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Comparing mechanical ventilation control strategies for indoor air quality: Monitoring and simulation results of a school building in northern Italy

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ABSTRACT

Demand-controlled ventilation systems and carbon dioxide monitoring are critical to ensure indoor air quality (IAQ) comfort conditions. Their importance has become significantly more evident since the COVID-19 pandemic crisis. Control strategies for mechanical ventilation based on CO_2 concentration are commonly used, although they are rarely applied in Italian and other Southern European country schools. Moreover, optimised ventilation systems can help maintain indoor air quality while reducing energy consumption for heating (i.e. exploiting heat recovery). The proposed paper aims to compare different remote-control strategies to manage three detached mechanical ventilation units (DMV) installed in a junior-high-school demo building in Torre Pellice (Northwest Italy), monitored with room detail since April 2021. Eight IAQ control logics are analysed considering both in situ tests, handling DMV accordingly to room sensors, and simulation tests using the Energy Management System of EnergyPlus in the neutral season. All different solutions are compared by considering air quality, temperature, and energy need indicators. Additionally, a yearly energy verification via hourly simplified analyses is performed by considering fan consumption and energy conservation. Threshold-based control logics result to be more effective than time-dependent ones, while all cases guarantee very high IAQ levels, although energy savings are limited. The choice of the correct control threshold(s) is site-dependent being influenced by user local habits.

1. Introduction

A well-ventilated indoor environment is crucial for building occupant health to avoid excessive pollutant concentrations and correlated diseases, such as sick building syndrome (SBS). Indoor air quality is recognised to be around 2 to 5 times worse concerning outdoor air conditions [1], while about 1/5 of the western population is affected by the mentioned SBS [2,3].

Focusing on the performance, various contaminants can be monitored to evaluate the health of indoor spaces. Those pollutants can be generated from indoor sources or come from the outside. Contaminants can be divided into two main categories: bio-effluents generated by the human body, like carbon dioxide (CO_2), odour, particulates, water vapour, biological aerosols, and pollutants produced by buildings and materials, like VOCs and TVOCs, which can be dangerous for the occupant health because suspected or known carcinogens, irritants or with an annoying smell [4,5]. In addition, the need for healthy indoor air quality has attracted increasing attention in recent years because of the spreading of SARS-CoV-2, whose principal transmission mode is due to infectious respiratory droplets in indoor environments air [6,7]. These droplets can be considered air pollutants and removed through ventilation [8]. Besides COVID-19, airborne transmission is among several other diseases' most relevant transmission modes. Hence, optimised ventilation solutions assume a vital role, especially in public buildings, such as schools, hospitals, and malls, to avoid spreading respiratory illness among occupants and, therefore, to their relatives.

Among human and building-generated volatile pollutants, carbon dioxide (CO_2) has been proven in the literature to be an excellent indicator to summarise air quality conditions in crowded buildings [9]. In typical building-occupied spaces, people are the most relevant source of CO_2, which can hence be considered a marker for all human-related contaminants as they are roughly correlated with emissions by breathing. A high CO_2 concentration is related to a reduction in occupants' attention and vigilance, negatively affecting memory and focus capacities, and these effects are of crucial importance if it is considered that people spend more than 90 % of their time indoors [10]. Hence, several States have introduced specific regulations supporting CO_2-based

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Nomenclature

CNV	Controlled Natural Ventilation
DMV	Detached Mechanical Ventilation
IAQ	Indoor Air Quality
MV	Mechanical Ventilation
SBS	Sick building syndrome
SOAP	Simple Object Access Protocol
VOC/TVOC	Volatile Organic Compounds/ Total Volatile Organic Compounds

control thresholds to detect IAQ performances in public buildings, including schools – see, for example, the ICONE approach [11]. In addition to IAQ control, building ventilation acts on space heat gain dissipation (heat losses) with a negative impact on the winter energy balance and a positive one on the summer energy balance, exploiting ventilative cooling potentialities – see, for example, EN ISO 52016–1:2017 [12]. The risk for excessive winter heat losses can be managed via mechanical ventilation by adopting heat recovery solutions in cold climates. Nevertheless, in temperate and hot climates, heat recovery systems may reduce their effectiveness not balancing the additional energy needed by the two fans with higher pressure drops. Using mechanical ventilation with an appropriate control strategy can lead to energy savings of up to 38 % [9,13], especially during winter, since it avoids heat dispersion due to excessive ventilation. Differently, ventilative cooling has been demonstrated to be very effective in several climates, including temperate ones [14–16], supporting, bypassing heat recovery solutions and adopting the proper control logic, low-energy cooling buildings [17–19]. Nevertheless, the SEER (Seasonal Energy Efficiency Ratio) of ventilative cooling may be very limited, especially when indoor and outdoor differences in temperature are low. Ventilation can be exploited by natural or mechanical flow activations, allowing controlled natural ventilation (CNV) and mechanically (MV) driven solutions [20]. With minor exceptions [21,22], i.e. the acceptance of any ventilation systems in regulations like EN 16798–1 [23] or the BS 5925 [24], the MV is the one that is generally considered in regulations due to the higher potential control of the inlet and/or outlet flows allowing to assure the minimal ventilation rate requirements. Despite the numerous advantages of mechanical ventilation (MV) solutions, they also show several disadvantages concerning controlled natural ventilation (CNV), including higher maintenance and installation costs [14,25]. To these costs, it also needs to be included the cost for the monitoring system, both in term of acquisition and of maintenance and recalibration. The inclusion of MV solutions can also negatively affect the acoustic comfort, resulting in disturbances during lecturing and activities. In addition to the latter issue, installing new MV systems in existing buildings, such as schools, may be complicated due to spatial configurations that do not include ducts and channels. Their diffusion is minimal in several countries, such as Italy. However, especially after the COVID-19 pandemic, the debate about installing IAQ monitoring solutions and correlated MV or CNV solutions in school buildings has become enormously significant – see Section 2.

1.1. Paper's objective and structure

This paper focuses on DMV application in school buildings with special regards to the addition of MV systems in existing buildings. The work bases on a demo case to test different control solutions exploiting the remote management of three detached mechanical ventilation (DMV) units installed in a school building in Torre Pellice (Northwest Italy). The building is very representative of Italian schools and is located in a temperate-to-cold climate, typical of north Italian locations and compatible with similar sites in Europe. The main objective of this paper is to evaluate the potential of eight different strategies to improve indoor air quality (IAQ) by comparing control algorithms based on CO_2 concentration. Control approaches for indoor air quality are tested in the school by using the SOAP protocol to retrieve the current conditions of rooms from sensors and Modbus to send control signals to the units and simulated with the Energy Management System of EnergyPlus [26] using calibrated models of the school rooms.

The paper is structured as follows. i.) A "State-of-the-art" section (see Section 2) briefly focuses the paper on the general background. ii.) A "Methodology" section (see Section 3) introduces the case study, the adopted smart monitoring system, the installed DMV system and its control logic, the building simulation model, and model verification. Additionally, Section 3 also describes the eight adopted IAQ-CO_2 control strategies. iii.) A "Results" section (see Section 4) reports the obtained results, including monitoring and simulated ones, followed by iv.) a "Discussion" section (see Section 5), discussing energy needs and energy conservations from the heat recovery, and the limitations of the study. Finally, Section 6, reports the paper's "Conclusions", including strengths and limitations of each strategy.

2. State of the art

Different control strategies can be used to ventilate interior spaces through mechanical ventilation systems to ensure a healthy environment for occupants. One of the most basic strategies, mostly adopted for simplicity, consists of providing a constant air exchange from the outside with a given schedule designing the ventilation flow for the maximum load of expected air contaminants [9]. However, it may lead to over-ventilation during low occupation, energy waste, and under-ventilation if the space is more crowded than expected. These issues can be solved by adopting suitable control solutions and making decisions based on space monitoring [27]. The most basic CO_2-based strategy is developed by identifying a maximum allowable CO2 measurement threshold. The ventilation is started when the measured value is above the limit and stopped whenever it is below. Commonly, the threshold is set to 1000 ppm [10,13,27], although other values are also adopted, such as 1500 ppm [28]. Several standards support the definition of performance IAQ evaluation, such as EN 16798–1, which classifies CO_2 comfort categories (Cat. I, II, III, IV) according to threshold levels, e.g. based on the difference between the indoor and outdoor measured values [23]. Additionally, specific national recommendations and standards focus on CO_2 levels to evaluate IAQ and pollutant exposure. It is possible, for example, to refer to the French ICONE method to define the index of confinement [29] that is compulsory applied in French school buildings. This approach considers a multi-scale, starting from a value aligned with outdoor levels and by additional threshold levels, such as the current values of 800 ppm (air renovation is sufficient) and 1500 ppm (air renovation is not enough, requiring fast actions). Similarly, the Swiss norm SIA 180 [30] supports a general 1000–2000 ppm range for non-confined occupied spaces, while extreme values may also be considered for bedroom night conditions.

To limit the number of on/off cycles of the mechanical ventilation system, a double threshold approach can be used for activating and deactivating the ventilation flow [9,31]. The CO_2-based strategy can also be combined with a second parameter that indicates those pollutants not produced by the human body but dangerous to the health [13,32], like TVOC, specific VOCs, and radon. This dual mode is suggested to be composed of two different phases: the first is applied when the building is occupied and adopts CO_2 values to make decisions; the second is used when the building is empty and aims at removing all contaminants generated by space and materials before occupants enter the building using TVOC or radon values [27,33].

Regarding IAQ ventilation and ventilative cooling, several control strategies could be used to improve thermal comfort and reduce consumption [34,35]. Spontaneous random occupant manual ventilation is the most straightforward application, and it is based on windows opening according to occupants' perceptions of indoor comfort [18]. However, users' perceptions may not represent the changes in external and internal conditions [36,37]. Differently, the informed occupant manual ventilation supports user self-actuation by providing information about when to ventilate [38,39]. Performances are hence dependent on the responsiveness of occupants, and if the number of requests is high, it may be a burden for the user to follow instructions in the long term. Random ventilation is generally not considered for defining ventilative building performances in line with current standards and references, e.g. [14,40]. Fully automated controlled ventilation can provide better performance considering energy consumption and thermal comfort [39,41]. There are two possibilities to control ventilative cooling automatically: by using automatic control of windows opening – controlled natural ventilation (CNV) – through heuristics [42], advanced model predictive control [36], and machine-learning techniques [43] or by pumping air from outside using a mechanical ventilation system (MV) where the most common strategies also are heuristic controls [18]. Even if both are demonstrated to be effective, a lack of regulations is underlined in several national standards for ventilative cooling in general and for CNV in particular – see for example [21,22,44].

Focusing on the specific background, the application of controlled ventilation strategies in Italian school buildings is minimal. Among the few studies, it is possible to mention the research on Orsini's school case in Imola [45], including the application of CNV solutions for night cooling combined with a diurnal MV IAQ system. Nevertheless, this work focuses on a new school building and not on integrating controlled ventilation solutions in an existing one where space and budget limitations are contingent on their applicability. Additionally, it doesn't compare any control logic or detailed measuring outcomes, focusing on the design integration of different bioclimatic and low-energy solutions. The recent work [46] analyses three naturally ventilated rooms in northern Italy for a focused period in the later winter. The paper suggests a minimal window opening area supporting the maintenance of acceptable CO_2 levels and underlines that ventilation is needed to control the infection risk in post-pandemic conditions. Unlike the above reference study, the present paper focused on natural ventilation and IAQ parameters, not comparing different control strategies and not considering ventilative cooling issues. Similarly, the work reported in [33] performs a series of pressurisation tests in 16 classrooms (from 7 schools) located in central Italy. The work also analyses CO_2 and radon concentration levels in 6 classes. Results show that, especially in winter, CO_2 levels are considerably high. Manual natural ventilation is insufficient, although MV solutions are not feasible due to the lack of potential installation spaces and budget restrictions. The authors suggest that defining a specific window opening scheme or exploiting CNV solutions may solve this issue, but additional studies are needed. This reference differs from the proposed work here, not comparing controlling strategies, considering ventilative cooling, or exploiting long-term monitoring solutions. Additionally, it doesn't use simulations.

Similarly, looking at the international context, the analysis reported in [47] focuses on design choices and suggestions for school buildings in the Swiss context. A specific school is analysed, simulated and studied post-intervention, underlining the positive impact of ventilative cooling and CNV solutions. This work doesn't compare different controlling strategies and mainly focuses on the ventilative cooling domain. Another study, concentrating on the design of a low-energy kindergarten in Norway, focuses on the performances of hybrid ventilation systems to increase IAQ levels while reducing heat losses in winter [48]. The installed mechanical ventilation systems are demand-controlled, while CNV combines cross- and stack ventilation. The analyses are based on simulations performed before the construction and show the positive impact of hybrid ventilation, underlining the need to avoid overcooling risks. Fixed control logics are set considering both temperature and CO_2 control. In winter, CNV activates only if the MV is not sufficient to maintain IAQ levels (900–1200 ppm as set points) and it is both temperature ($T_{in} > 19$ °C) and CO_2 controlled (950–1500 ppm). In summer, the CNV operates when T_{in} overpasses 21 °C during daytime, allowing night ventilation activated when the room overpass 23 °C and deactivated at 18 °C. Additional works on applying ventilative cooling solutions in school buildings are reported in [28]. Nevertheless, these works don't compare different control logics, underlining the need for additional studies on the topic.

Focusing again on the Italian context, although the interest in the school building ventilation topic has recently grown due to the pandemic period, as underlined by an extensive public debate, e.g. [49–55], an Italian Government Decree [56] and devoted documents by the Educational Ministry [57,58]. Focussing on the DPCM 26th July 2022, the Italian Government, in line with the COVID-19 OMS document [59], supports the need to guarantee sufficient space ventilation. Natural, intermittent cross-ventilation air changes between each teaching hour and controlled mechanical ventilation modes are accepted, suggesting adopting CO_2 measuring systems. All these aspects have also supported the diffusion of new market solutions devoted to school environments, such as the ones adopted in this paper.

However, the above-mentioned national and international sources underlined the need for extra studies in this specific context. Additionally, a lack is highlighted in the comparison among different control logics by considering measurement experiments in actual buildings and calibrated model simulations. This paper aims to cover this issue by comparing different control logics for IAQ and ventilative cooling adopting DMV in a school building, including both measured experiments and calibrated simulation studies.

3. Methodology

Section 3 illustrates the paper's methodology adopted to compare different IAQ DMV control approaches. These are detailed and applied to a school demo building, in which three detached mechanical ventilation units are installed for the study, using both monitored and simulated data. Firstly, Section 3.1 defines the chosen and adopted IAQ control strategies. Secondly, the demo building, a junior high school in northern Italy, is described including correlated information (DMV, monitoring, modelling and calibration). Section 3.2 focuses on the general description of the building, while Section 3.3 describes the installed monitoring systems, and Section 3.4 the adopted DMV units. Section 3.5 describes the energy simulation model's development, and Section 3.6 illustrates the model verification process.

3.1. Control strategies

In this paper, in line with the declared objective, eight different MV indoor air quality control algorithms have been tested considering both remote management and simulation of DMV units located in a school building. Indoor air quality strategies are tested in the demo building during limited occupied free-running periods to compare the results of the simulated approaches with the monitored ones. Furthermore, longer simulations have been used to expand the comparison among the different control approaches. Effects of indoor air quality control strategies are evaluated based on the electric energy need of the DMV units, the average indoor temperature, the average CO_2 concentration during lesson hours, the average CO_2 peak value, and the total number of on/off cycles of the units.

The considered CO_2-based strategies are: constant air flow rate and threshold control activation. The constant air flow rate is a simple control approach that does not require a correlated CO_2 measurement. This paper adopts for this strategy two ventilation rates suggested by internationally recognised standards:

)i) ASHRAE 62 [60] uses a ventilation rate proportional to the number of people and does not ventilate when the room is unoccupied. In this case, the ventilation rate per person is set to 8 l/s in line with the number suggested for classrooms by the same standard [61] – see the control flowchart in Fig. A1, Annex A;

)ii) ASHRAE 62.1 [62], which adds to the previous one a fixed ventilation rate per room square meter, active also during unoccupied periods, to dilute the non-human produced pollutants. In this case, the adopted ventilation rate per person is 5 l/s, while the airflow rate per room square meter is set to 0.6 l/s [63] – see Fig. A2, Annex A.

For the threshold-based activation instead, different controlling solutions are adopted in line with literature review studies [64]. These strategies combine some of the following CO_2 thresholds used to activate/deactivate and/or modulate the ventilation airflow control. The different assumed threshold values are summarised and described below, mentioning the strategies in which they are involved:

- (activating threshold – strategies iii. and v.) 600 ppm: under this value, CO_2 has a negligible effect on almost all health problems [64];
- (activating threshold – strategies iv. and vi.) 800 ppm: a value also adopted in existing commercial monitoring systems, such as [65];
- (maximum limit threshold – strategies iii.-vi. – and activating threshold – strategies vii. and viii.) 1000 ppm: higher values are associated with moderately severe diseases, like dry cough and rhinitis, specifically in children. Moreover, there could be a decrease in pupils' attention, but without affecting their school performances [60];
- (not-overpassing limit threshold – all threshold strategies) 1500 ppm: higher values are associated with a decrease in the number of correct answers given by students, also increasing the risk of more severe symptoms – a value that cannot be exceeded for a long time in several regulations, e.g. for maximum 20 min in the UK [66].

Focussing on the adopted strategies, three of them are based on a single minimum control activation value – see the control flow chart in Fig. A3, Annex A. All these strategies activate during occupation time, turning off the DMV during weekends and other non-occupied periods. A seasonal control is also included to activate/deactivate the heat recovery.

The first single minimum activation threshold strategy – ventilation strategy iii. – is based on the following principles:

- there is no injected air when CO_2 is under 600 ppm since room conditions are healthy and prevent overventilation, reducing energy needs;
- when the CO_2 level is between 600 and 1000 ppm, the ventilation rate is set to 180 m^3/h. A small amount of ventilation can slowly bring back environmental conditions to be healthy, given that conditions are still acceptable;
- when the CO_2 is between 1000 and 1500 ppm, the ventilation value is set to 500 m^3/h because conditions are worse, and a healthy environment should be restored in a shorter time;
- above 1500 ppm, the mechanical ventilation flow rate is the maximum allowed (800 m^3/h), trying to reduce CO_2 concentration as fast as possible.

The second one – ventilation strategy iv. – is the same as strategy iii., except that the minimum activation threshold is set to 800 ppm instead of 600 ppm. This solution will save energy needs, considering a CO_2 concentration between 600 and 800 is still excellent.

The third one – ventilation strategy vii. –, instead, is defined as below – see Fig. A4, Annex A.

- when the CO_2 concentration is below 1000 ppm, the ventilation is set to off;
- between 1000 to 1500 ppm, the ventilation rate is set to 500 m^3/h;
- above 1500 ppm, the ventilation rate is set to the maximum allowed value (800 m^3/h).

Additionally, three other threshold control strategies have been tested, adopting a double minimum control value threshold – see the control flowchart in Fig. A5, Annex A. In those cases, the assumed activation/deactivation CO_2 value fluctuates around two thresholds to reduce the number of on/off switches. The developed control algorithms follow the single threshold ones during the activation phase. Nevertheless, a lower deactivation threshold is assumed when the mechanical ventilation unit is already on. In particular, the ventilation strategy v. adopts a minimum activation threshold of 600 ppm and a deactivating threshold of 500 ppm, keeping the ventilation rate at 180 m^3/h till this second threshold value is reached. Similarly, ventilation strategy vi. considers an activation threshold of 800 ppm and a deactivation value of 650 ppm. Finally, ventilation strategy viii. follows the activation process of strategy vii., but deactivates the flow only when the CO_2 concentration falls below 600 ppm – see Fig. A6, Annex A.

3.2. Case study introduction (context and building typology)

The demo building adopted in this paper is a municipality school in Torre Pellice, a small city in the Pellice Valley (Northwest Italy, Piedmont region). The town, with its 4545 inhabitants, is very representative of small municipalities in the Italian context, being positioned about in the middle among the 7978 Italian Municipalities [67]. The climate is cold and classified in the Italian climate Zone F, thanks to its 3128 HDD20 (Heating-Degree-Days) – see [68] and further modifications –, although summer peak temperatures may surpass 30 °C. The characteristics of the location are representative of northern and central Italy and of similar climate European condition.

The school building represents Italian public-school constructions, as it was built around 1975 and features typical characteristics making it a representative demonstrator for the Italian context and for similar conditions in southern-to-central Europe. The building is a demonstrative demo case inside the EU co-founded H2020 project E-DYCE [69]. The school has a rectangular shape with four levels: three floors devoted to the junior high school, plus a semi-buried floor hosting a kindergarten. The main building façade is facing south. The structure comprises a skeleton of reinforced concrete and brick multi-layer walls with a curved metal roof. The under-roof space is not climatised and is used only for maintenance. Strip windows are adopted on all floors facing both north and south. The floors are similarly organised, with classrooms and offices facing south and distribution corridors along the north façade; bathrooms are on the west side, while the main stair is on the East. This paper focuses on the three floors devoted to the junior high school.

3.3. Monitoring system

During the E-DYCE project activities, an environmental and energy monitoring system has been installed in the school since April 2021, allowing room-detailed data acquisition. The system includes temperature, relative humidity, and CO_2 probes in all classrooms, while the other spaces are monitored for temperature and relative humidity. Additional extra parameters are also retrieved in limited rooms, such as TVOC and window opening status. Sensors and monitoring gateways are based on the Capetti WINECAP™ system [70]. Thanks to a SOAP-based API, the adopted solution allows access to data remotely and in almost real-time. Each sensor is controlled to retrieve measures each 10 min. The technical specifications of the probes used in this paper are reported in Table 1, focusing on the datalogger WSD00TH2C_S type, which is equipped with CO_2, temperature, and relative humidity probes. These sensors are based on long-duration batteries, not requiring a direct electric plug, allowing for an easier and cheaper installation in school contexts. Sensors have been installed on the wall opposite to the

Table 1
Technical specifications – WSD00TH2CO_S dataloggers (Temperature, RH, CO_2) [70].

Connection	*Wireless, USB.*
Indoor Temperature – transducer type	*NTC10KΩ*
Indoor Temperature – measure range	*−10 °C ÷ +60 °C*
Indoor Temperature – measure precision	*±0,2°C whole range*
Indoor Temperature – measure resolution	*0,01 °C*
Relative humidity – transducer type	*CMOSens® technology*
Relative humidity – measure range	*0 ÷ 100 %*
Relative humidity – measure precision	*±2,0% (typical) from 0 % to 90 %*
Relative humidity – measure resolution	*0,05 %RH*
CO_2 concentration – Measure Range	*0 ÷ 5,000 ppm*
CO_2 concentration – Measure Resolution	*1 ppm*
CO_2 concentration – Measure Accuracy	*0 ÷ 5,000 ppm: < ± 50 ppm (+3% of* measured value*)*

windows and checked to not receive direct radiation. Installation eight is at 2 m from the ground to avoid damages and to not interfere with school activities. Differently, the gateways are plugged and include a SIM to transmit data autonomously from local internet connections. The gateway communicates with each datalogger via the LuPo protocol. The system is conceived to be redundant, avoiding data losses thanks to the triple storage level: in each datalogger, in the gateways and in the cloud winecap service. Additionally, data are also stored in the research unit server via a self-developed script using the SOAP access.

A meteorological station is installed nearby – less than 300 m – on an accessible flat roof not influenced by obstacles. The station transmits in real-time data to collect weather variables needed to feed a dynamic building energy simulation with actual boundary conditions. The station is composed of a Thiess US climate sensor monitoring temperature, humidity, atmospheric pressure, sky brightness, wind (direction and velocity), and precipitation data, and a Spectrally Flat Class B (First Class) pyranometer (LPPYRA02) made by Delta OHM which measures global horizontal solar radiation. To split global irradiation into direct and diffuse components, the Boland-Ridley-Lauret model [71,72] has been applied. All the meteorological measured data are retrieved by our server via REST and, thanks to a self-developed code, filtered, hourly aggregated and translated into an EPW format (EnergyPlus Weather) to feed EnergyPlus simulations [73–75].

3.4. Detached mechanical ventilation units

Due to the lack in spaces and to the excess in costs for the installation of a centralise MV system, mechanical ventilation in the demo case has been provided by installing detached units per room level. The choice of the type of units is based on main technical specifications: i.) allow a flow-rate in line with school requirements, ii.) support simple installation not requiring long channels and allowing a proper integration in the school spaces, iii.) support the possibility to manage different control logics. Hence, three DMV Flow M800 units by Helty [76] have been installed in three rooms – one per floor – of the junior high school in January 2022. These units, conceived explicitly for school and other public spaces requiring high air exchanges, are inserted within a closet – see Fig. 1 – and can exchange indoor air by pumping up to 800 m^3/h of fresh air. The system has a double channel with inlet and exhaust fans and is equipped with a heat recovery that may be bypassed when the specific request is set on the control board. The declared absorbed power at maximum speed is 188 W. Fans are allowed to be set with ten different rates, while the producer gives related absorption powers to retrieve the fan energy consumptions. These units can be controlled on-site through a control panel within the closet. Nevertheless, these machines are designed to also allow for the development of personalised remote-control solutions by exploiting the Modbus RS485 protocol. To test in this demo building the control strategies above-mentioned, a hardware setup based on a Raspberry Pi equipped with a B6RS485 can hat is set up for each unit in June 2022. The Raspberry Pi board behaves as a Modbus Master to send control signals to the mechanical ventilation units through four wires copper shielded cable to change flow rates and heat recovery states. The Modbus Master simulator implemented on Raspberry Pi has been coded using the Pymodbus Python library [77]. In addition, Raspberry Pi's boards have been equipped with SEK-SCD41 CO_2 sensors by Sensirion [78], adopting the I^2C interface. These high-accuracy sensors measure CO_2 within the 400–5000 ppm range with an accuracy of ± 50 ppm (+2.5 % of the reading till 1000 ppm and + 3 % till 2000 ppm). These additional sensors are needed to allow a real-time control of the units, without waiting for the transmission of the data via SOAP. Nevertheless, the Capetti monitoring system is used for retrieving and analysing the results and the room IAQ, while the unit-

Fig. 1. (a) one of the installed DMV units; (b) the system controlling board; (c) a moment of the installation.

coupled fast sensors are adopted for the control logic.

3.5. Simulation model

The considered school is a large building simulated in EnergyPlus according to different modelling approaches – see [79,80]. In addition to the complete model, smaller models – one per floor – have been developed to keep simulation time reasonable without losing model calibration performances. Fig. 2 illustrates the outside and inside view of the school model, initially created by using Design Builder, showing the junior-high school plan views. Modelling was done considering detailed inspection results, including a detailed geometrical relief, an in-situ U-value measurement campaign, and existing building construction data by the Municipality. Furthermore, during the installation of the DMV machines, external walls have been perforated with the consequent identification of the correct stratigraphy – see Fig. 1(c). Vertical walls are composed by a double layer of bricks with an interposed insulation layer (rock wool) of 6 to 7 cm (U-values from 0.68 to 1st floor – to 0.59 W/(m^{2}K) – 3rd floor), while windows are double glazing systems with a wooden frame with thermal break (U-value 1.782 W/(m^{2}K), SHGC 0.553). Schedules are following the situ inspection, including student occupation from 8:00 to 14:00. Specific modelling inputs and details are given in the references mentioned above, including inspection information, systems' descriptions, and modelling choices.

Focusing on the paper's contents, the model has been provided with mechanical ventilation for the rooms underlined in Fig. 2. Specifically, for modelling the DMV units, the characterisation of the power absorption curve bases on the data provided by the Helty manufacturer. Data re given by reference fan-speed points and are interpolated linearly to create a curve that shows the power absorption as function of the amount of fan-injected air. The obtained curve is tested in four points by using inspection sensors. Due to the scheme's simplicity, the building is simulated with the EnergyPlus simple HVAC approach. However, the DMV airflows are controlled via a Python script and exploit the EMS (energy management system) functions of EnergyPlus [81]. Simulations are performed via the EnergyPlus interface PREDYCE [75] based on Python libraries.

3.6. Model verification process

Since on each floor, just one classroom is equipped with a mechanical ventilation unit, data from those rooms are used as ground truth to check the accuracy of the model calibration. Differently, the other rooms are used as boundary conditions during verification by aligning them with the measured conditions via the PREDYCE IDF coding. Hence, boundary rooms are maintained at the measured temperatures via an automatic control of their set points (heating and cooling) exploiting the digital twin functionalities of the mentioned EnergyPlus interface. This choice has been made to be as precise as possible in calibrating the specific rooms with DMV installed since the verification process of the CO_2 concentration is deeply room dependent. In fact, concerning natural ventilation, each room is handled by different teachers with different habits, requiring to define adapted conditions which are not valid for other rooms. The developed micro-service software structure, managing data flow to retrieve measure data for calibrations, is shown in Annex B, Fig. B1.

Firstly, once both measured data and original models are defined, the temperature of the three rooms with the DMV is calibrated by acting on the school envelope parameters, internal mass, and air infiltration under building-controlled conditions (summer holidays) with the help of the PREDYCE Python library – semi-automatic calibration usage scenario – [75]. Secondly, the calibration validity over time is tested. Thirdly, carbon dioxide and mechanical ventilation air rates are also calibrated based on occupancy and ventilation parameters and schedules.

The quality of the model has been investigated by applying the calibration signature approach [82] and using different well-known statistical metrics: root mean squared error (RMSE), mean bias error (MBE), the combination of the two (RMSE_MBE), mean absolute percentage error (MAPE), and peak error metric – see eq. (1). The latter indicator is newly introduced for this study, and it is based on the difference between simulated daily peaks and measured ones. It is used because high carbon dioxide levels are dangerous for the occupants' health, so the calibrated model must imitate not only the average CO_2 levels, but also peaks.

$$\text{peak error} = \frac{1}{N_d}\sum_{k=1}^{N_d}\frac{|\text{peak\_predicted}_k - \text{peak\_true}_k|}{\text{peak\_true}_k}.100 \quad (1)$$

where:

The parameters "peak_predicted_k" and "peak_true_k" are the daily maximum measured and forecasted carbon dioxide values for each day in which its concentration reaches a maximum value greater than 450 ppm, an indicator of the room occupation. In this way, just the days someone is in the room are considered. N_d is the total number of considered peaks. Model verification is although based on all the mentioned parameters – see results in the following Section.

3.6.1. Verification results

Firstly, indoor air temperature is calibrated in the three rooms considering the period of July 2021, when the absence of people removes uncertainties due to daily usage. Different envelope characteristics are considered in the process, notably: U-value of opaque envelope, U-value and solar heat gain coefficient (SHGC) of windows, air infiltration, internal mass, and shadings position. Allowed variations are defined following data coming from inspection. Fig. 3 shows the calibration signatures with hourly definition at the end of the calibration process: the percentage error is always less than 5 %, in line with ASHRAE 14–2014 acceptable ranges [83,84]. Secondly, calibration validity over time is tested over the whole scholar year 2021–2022. Results are shown in Table 2. As expected, from RMSE MBE, it is possible to see that long-term test predictions are slightly worse than the ones in the calibration period, considering that the yearly cases also include

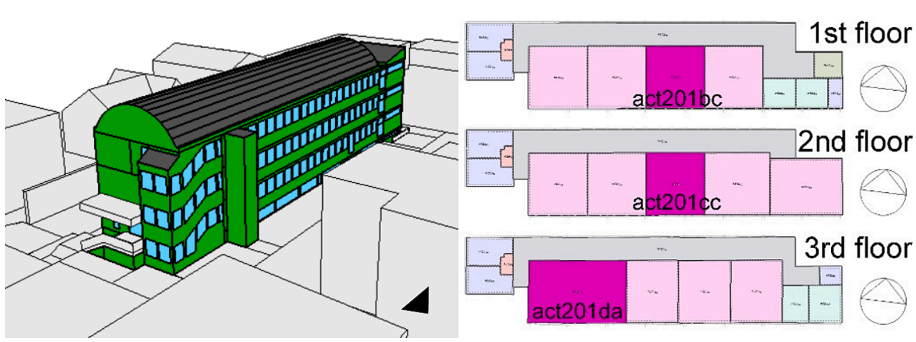

Fig. 2. The considered school building: (a) comprehensive view and (b) the plans of the junior high school with underlined the rooms with DMV.

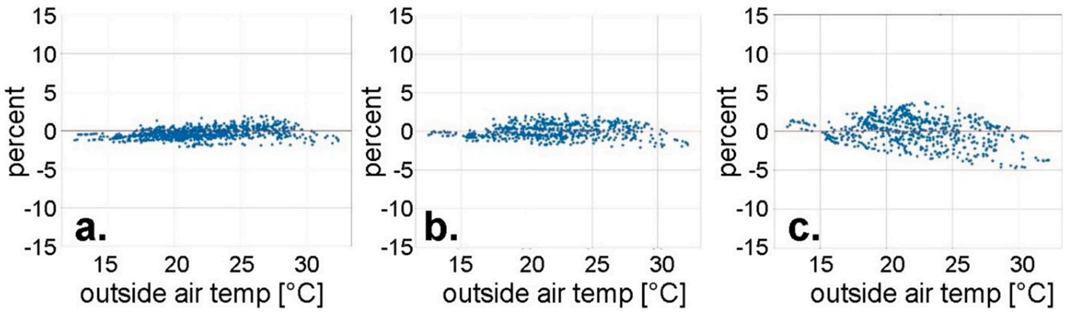

Fig. 3. Calibration signatures at the end of the temperature calibration process in the three rooms (left: act201bc; centre: act201cc; right: act201da).

Table 2
Error results for indoor temperature during the calibration and testing periods.

	Calibration period 2021			Testing period 2021				Testing period 2022			
	RMSE	MBE	RMSE_MBE	RMSE	MBE	RMSE_MBE	MAPE	RMSE	MBE	RMSE_MBE	MAPE
Room1	0.23 °C	0.10 °C	0.26 °C	1.44 °C	1.04 °C	1.78 °C	5.90	1.61 °C	0.50 °C	1.27 °C	4.65
Room2	0.26 °C	−0.01 °C	0.26 °C	1.40 °C	0.98 °C	1.70 °C	5.44	1.17 °C	0.29 °C	1.20 °C	4.30
Room3	0.51 °C	−0.01 °C	0.51 °C	1.13 °C	0.41 °C	1.20 °C	4.19	1.60 °C	−0.55 °C	1.69 °C	5.43

system activation in winter and occupation periods, including people's random actions (e.g. window openings in the measured conditions). However, the calibration is highly accurate, and the statistical results aligned with given ranges. Additionally, MAPE is always under 10 showing that predictions accurately follow the actual building behaviour for 2021 and 2022 – see the sample plots in Fig. 4.

Thirdly, CO_2 verification is performed. In this case, model fitting actions were mainly focused on adapting occupancy (i.e. number of people in the room), ventilation parameters, and schedules. The considered fitting period is spring 2021. Error metrics are shown in Table 3. Obtained results are feasible: MAPE of less than 10 indicates that the simulation is highly accurate, and the percentage of the peak error is relatively small, leading to a reasonable forecast of the CO_2 trend and maximum CO_2 values. In 2022, after the DMV units' installation, the model was updated with the integration of the units. Verification results in spring 2022 before and after the addition of the mechanical ventilation in the model are shown in the same Table 3. The updated model includes DMV units and accurately reflects the measured temperature and CO_2 behaviours, given that MAPE is smaller than 10 – see also the sample plots in Fig. 5. Moreover, the accuracy of both CO_2 trends and peak behaviours increases if compared with the model without the DMV units since a more stable operational scheme is applied in mechanically ventilated rooms in the actual building.

Table 3
Error results for CO_2 during the calibration and testing periods.

Year	MAPE	Peak Error
2021	6.64	13.48
2022 – without DMV	8.85	18.94
2022 – with DMV	6.83	17.59

4. Results

Measured physical tests were performed in the school in September-October 2022 (neutral season) by testing all the eight defined control approaches. CO_2 Strategies vii. and viii. where only tested in this latter analysis. An additional test, considering strategies i., iv. and vi., is also performed during an occupied period in April 2023. Additionally, CO_2-based control strategies have been simulated under actual weather conditions on the calibrated models over the period ranging from 25/04/2021 to 02/06/2021 (neutral season), which is characterised by a very high CO_2 fitting during the model verification phase. Clearly, in the real environment, boundary conditions are less controlled than in simulations due to the presence of people who may use manual window operation, although the model verification process included average impact of random ventilation by adapting room parameters. In the discussion Section, a simplified extension to the entire school year is performed without considering user behaviours to discuss energy aspects of the different strategies including also winter heat recovery.

4.1. CO_2-based strategies – Monitoring results

This section reports the results obtained by the in-situ tests on the

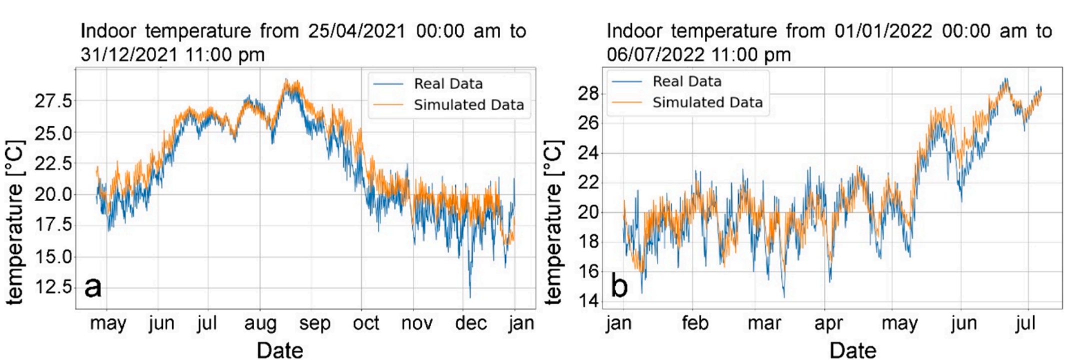

Fig. 4. Comparison between simulated and measured temperature data for room act201bc in (a) 2021 and (b) 2022.

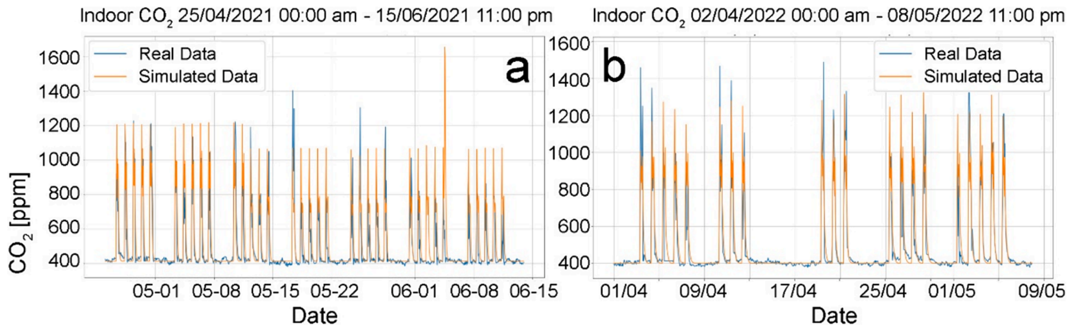

Fig. 5. Comparison between simulated and measured CO_2 data for room act201bc (a) before the DMW installation (spring 2021) and (b) after the installation (spring 2022). Room act201. Statistical data for the whole verification analysis is given in Table 3.

installed DMV units. The results of the monitored tests performed in September-October 2022 are shown in Table 4. These tests also include strategies vii. and viii. Each strategy is tested for 3 days at the end of the neutral season starting from September 14th' being not possible to apply all the strategies at the same moment. A reference room, with the same or more similar boundary conditions of the mechanically ventilated room but without DMV, is assumed for each floor of the building to consider the impact of the DMV concerning typical randomly ventilated spaces.

The two constant airflow strategies i. and ii. demonstrate to be the more energy-consuming ones. Both cases demonstrate the ability to control CO_2 peak concentrations firmly. However, the constant airflow is detached by the specific actual conditions, allowing the identification of focalised higher peaks or over-ventilation periods when, for some reason, windows are opened for an extended period – see, for example, Fig. 6.

Looking at the 600-ppm single activation threshold strategy iii., the DMV unit's measured switches are higher than the following simulation results. The occupants' behaviour can explain this result. They ventilate more than expected during this period since it is still hot, as confirmed by the installed windows opening sensors. Hence, CO_2 concentration oscillates more around the 600-ppm threshold instead of the 800-ppm one like it was during simulations. Nevertheless, this difference may be expected in neutral seasons, while it will be reduced during the winter months. Similar considerations can also be made for the 800-ppm single activation threshold strategy iv. Both cases are effective, especially the 800-ppm one that maintains peaks below 600 ppm. The days in which the 1000-ppm single activation threshold strategy vii. is tested are atypical since the average CO_2 concentration and its peaks in the reference room are significantly smaller than the ones recorded in the other days of the period, so this comparison is not here reported. Nevertheless, this strategy is effective, even if the obtained CO_2 concentrations, both the average during the occupation and the average peak, are higher than in the other cases, based on a higher limit value. It can be noted that with the single activation threshold approach, the number of switches of the unit is relevantly higher when the CO_2 concentration oscillates around the threshold. This outcome justifies adopting a double activation/deactivation threshold approach, although

Table 4
Results of the indoor air quality monitored strategies in September-October 2022 – each strategy is run for 3 days.

	Strategy i.	Strategy ii.	Strategy iii.	Strategy iv.	Strategy v.	Strategy vi.	Strategy vii.	Strategy viii.
	ASHRAE 62	ASHRAE 62.1	600 ppm activation threshold	800 ppm activation threshold	600–500 ppm act./ deactivation thresholds	800–650 ppm act./ deactivation thresholds	1000 ppm activation Threshold	1000–600 ppm act./ deactivation Threshold
DMV units electric consumption	2.49 kWh	3.14 kWh	0.29 kWh	0.08 kWh	0.69 kWh	0.41 kWh	0.59 kWh	1.07 kWh
DMV electric energy needs (average daily values)	0.83 kWh	1.05 kWh	0.1 kWh	0.03 kWh	0.23 kWh	0.14 kWh	0.2 kWh	0.36 kWh
Average indoor temperature	22.6 °C	22.2 °C	26.6 °C	27.2 °C	22.7 °C	25.9 °C	21.8 °C	22.3 °C
Average indoor CO_2 – occupied	858 ppm	593 ppm	638 ppm	454 ppm	605 ppm	460 ppm	776 ppm	668 ppm
Average indoor CO_2 peak value	1118 ppm	707 ppm	795 ppm	594 ppm	649 ppm	703 ppm	1000 ppm	811 ppm
Total on/off cycles of the DMV unit	3	1	10	5	3	3		
	9	3						
Average indoor temperature reduction	0.1 °C	0.3 °C	0.3 °C	0.2 °C	0.5 °C	0.3 °C	0 °C	0.3 °C
Average indoor CO_2 reduction ratio – occupied	8.72 %	14.68 %	1.08 %	26.54 %	35.50 %	22.30 %		30.12 %
Average indoor CO_2 peak value reduction ratio	35.93 %	32.21 %	11.67 %	25.38 %	33.78 %	12.56 %		52.04 %
Reference room av. CO_2 – occupied	940 ppm	695 ppm	645 ppm	618 ppm	938 ppm	592 ppm		956 ppm
Reference room av. CO_2 peak value	1745 ppm	1043 ppm	900 ppm	796 ppm	980 ppm	804 ppm		1691 ppm

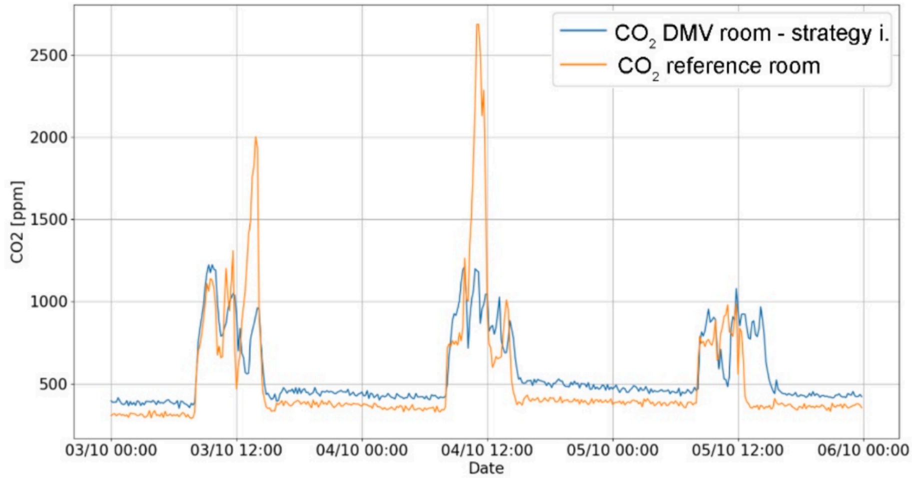

Fig. 6. measured CO_2 concentrations – room applying Strategy i. (ASHRAE 62) vs the reference nearer room.

the latter is more energy-requiring. By comparing, for example, strategy viii. with strategy vii., the average CO_2 concentration is reduced by about 100 ppm during lesson time while peaks are decreased by about 200 ppm. The high energy needs observed in the strategy viii. together with the reduced on/off cycles, can be explained by the elevated CO_2 concentration during the testing days due to a limited random ventilation with a consequent higher request in airflows.

A second test is performed in April 2023 – see Table 5, including the number of occupied testing days. During this period, the most relevant strategies identified above – strategies i., iv. and vi. – are replicated to confirm the previous results in a different season. Results show that the three strategies are still effective: the higher CO_2 levels due to the lowest outdoor temperature – beginning of April is still in the winter season for the local climate – and reduced random use of the windows due to the post-COVID conditions. In particular, adopting an 800-ppm threshold, especially in case vi., is more performative, maintaining the average occupied CO_2 concentration considerably below 1000 ppm, in line with KPIs, and the average peak considerably below 1500.

Table 5
Results of the indoor air quality monitored strategies in April 2023.

	Strategy i.	Strategy iv.	Strategy vi.
	ASHRAE 62	800 ppm activation threshold	800–650 ppm act./ deactivation thresholds
Number of testing days (occupied)	6	8	7
DMV units electric consumption	2.99 kWh	2.59 kWh	2.31 kWh
DMV electric energy needs (average daily values)	0.5 kWh	0.32 kWh	0.33 kWh
Average indoor temperature	21.1 °C	21.6 °C	21.0 °C
Average indoor CO_2 – occupied	924 ppm	854 ppm	881 ppm
Average indoor CO_2 peak value	1360 ppm	1233 ppm	1276 ppm
Total on/off cycles of the DMV unit	7	17	6
Average indoor temperature reduction	−0.1 °C	−0.3 °C	−0.1 °C
Average indoor CO_2 reduction ratio – occupied	48.69 %	50.66 %	49.35 %
Average indoor CO_2 peak value reduction ratio	32.98 %	36.16 %	36.13 %

4.2. CO_2-based strategies – Simulation results

At first, the model is simulated in the neutral season without controls to assess the free-floating building behaviour that acts as the baseline. The obtained relevant environmental parameters are shown in Table 6, offering a slightly cold outdoor environment and comfortable indoor conditions. CO_2 values show acceptable average concentration levels, although peaks during occupation time exceed 1000 ppm. Results of simulations are reported in Table 7, assuming the different tested control strategies. In all cases, indoor air quality is higher in the DMV cases concerning the free-floating one, considering the average CO_2 levels during the entire period and for the sole occupational hours. Additionally, the DMV is also able to reduce CO_2 peak values. Looking at the energy needs, the two constant air flow solutions, i.e. strategies i. and ii., result in the more consuming ones, confirming the monitoring tests. In contrast, the threshold-controlled strategies can save respectively from 4 to 8 times the ASHRAE 62 constant airflow needs and from 2 to 16 times the ASHRAE 62.1 ones.

Although the ASHRAE 62 strategy i. is quite consuming in terms of energy needs, it reaches the second minor values for global CO_2 concentrations and the absolute lowest values during occupational periods. It can also be noted that this strategy also activates on the 30th of April (Friday), even if pupils are not present due to a local holiday (simulated in the occupation schedule), being based on a weekday and weekend schedule rule. Strategy i. has 28 total on/off cycles aligned with the number of weekdays in the simulated period. The ASHRAE 62.1 strategy ii., since it also implies unoccupied ventilation, has the highest energy needs, more than doubling the previous strategy i., but also the lowest average CO_2 concentration during the entire period. It also shows the second lowest occupational CO_2 concentration – see Fig. 7 (a). Nevertheless, due to the continuous ventilation flow, this strategy also leads to a drop in indoor temperature due to the implicit night ventilative cooling exploitation. During the simulation, the room reaches the morning lowest peaks below 18 °C during the occupational periods and differences in temperature concerning the baseline free-floating case up to 2 °C – see Fig. 7 (b). This specific condition is not reached in any of the other tested strategies, where the baseline and the DMV cases are almost

Table 6
Results of the free-floating building simulation.

Average outdoor temperature	14.3 °C
Average indoor temperature	19.6 °C
Average indoor CO_2 (entire period)	524 ppm
Average indoor CO_2 – occupied hours	748 ppm
Average indoor CO_2 peak value	1179 ppm

Table 7
Results of the indoor air quality simulated strategies in spring 2021 – from the 25th of April to the 2nd of June (28 operational weekdays. The 30/04 is without occupancy due to local holidays).

	Strategy i.	Strategy ii.	Strategy iii.	Strategy iv.	Strategy v.	Strategy vi.
	ASHRAE 62	ASHRAE 62.1	600 ppm activation threshold	800 ppm activation threshold	600–500 ppm act./ deactivation thresholds	800–650 ppm act./ deactivation thresholds
DMV unit's electric consumption (entire period)	8 kWh	19 kWh	2 kWh	1 kWh	2 kWh	2 kWh
DMV electric energy needs (average week-day daily values)	0.29 kWh	0.68 kWh	0.07 kWh	0.04 kWh	0.07 kWh	0.07 kWh
Average indoor temperature	19.5 °C	19.1 °C	19.5 °C	19.5 °C	19.5 °C	19.5 °C
Average indoor CO_2 (entire period)	460 ppm	453 ppm	490 ppm	500 ppm	490 ppm	497 ppm
Average indoor CO_2 – occupied hours	593 ppm	624 ppm	669 ppm	690 ppm	669 ppm	678 ppm
Average indoor CO_2 peak value	713 ppm	742 ppm	913 ppm	918 ppm	913 ppm	918 ppm
Total on/off cycles of the DMV unit	28	1	27	92	27	58

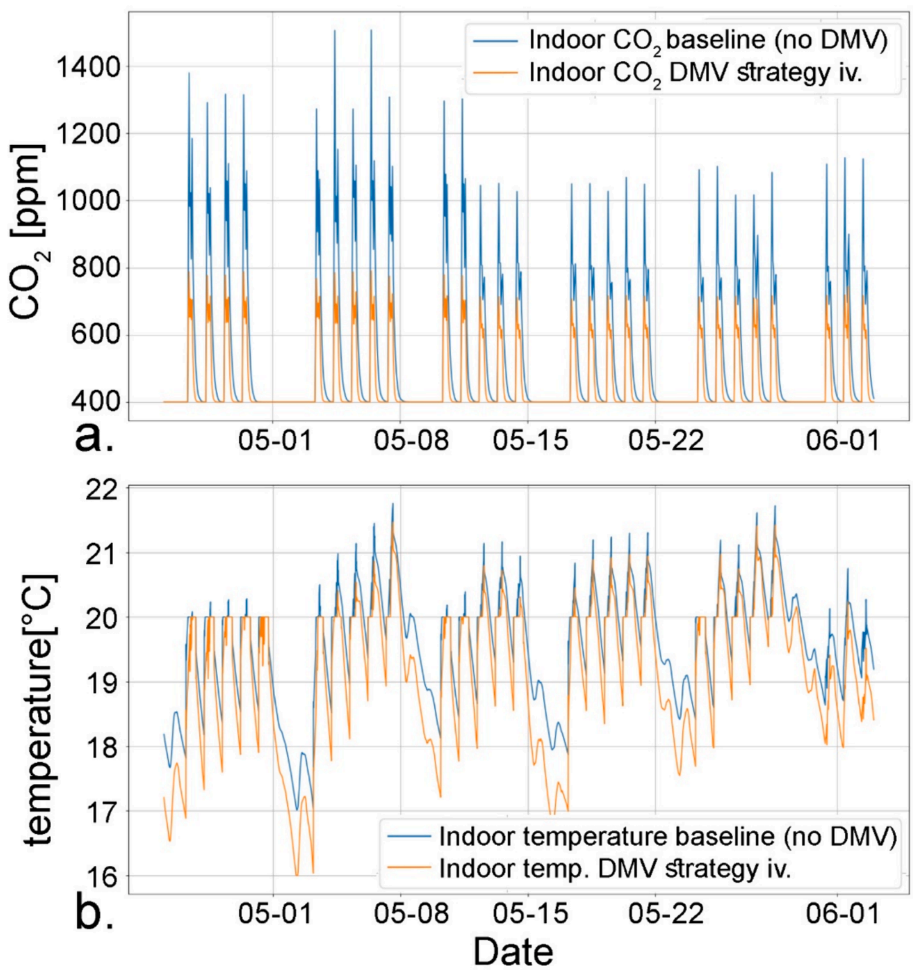

Fig. 7. Strategy ii. (ASHRAE 62.1) vs the baseline case: (a) simulated indoor CO_2 behaviours; (b) simulated indoor temperatures.

aligned in terms of temperatures – see Fig. 8 (b) reporting the results of the strategy iv.

Differently, the threshold-based approaches, thanks to their on-demand nature, lead to energy savings by aligning the fan-speed control with current CO_2 concentrations. Hence, in all these cases, the DMV units do not activate during the unoccupied sample weekday (30th of April), saving unneeded ventilation. Considering the 600-ppm activation threshold cases, i.e. strategies iii. and v., the DMV unit switches 27 times during the simulation test, underlining that once the DMV unit first activates during the morning of a given school day, it remains on till the end of the occupation period. Hence, the CO_2 concentration never returns under 600 ppm in occupied hours for these cases. Results of the 800-ppm activation threshold approaches, i.e. strategies iv. and vi., are characterised by a higher number of on/off cycles being their specific deactivation thresholds underpasses during simulations. By comparing the single and the double activation/deactivation strategies for 800 ppm (strategies iv. and vi.), it is possible to see that the latter case has a smaller number of on/off cycles but higher energy needs. In those two cases, the CO_2 peaks are the same, adopting the same strategy above 800 ppm, while the average values are slightly better for strategy vi. although strategy iv. is more convenient. Fig. 8 shows the results of strategy iv. compared with the baseline ones. Comparing the CO_2 trends with the one in Fig. 7 (a), it is possible to show how concentrations during occupational periods are higher even if the baseline peaks are

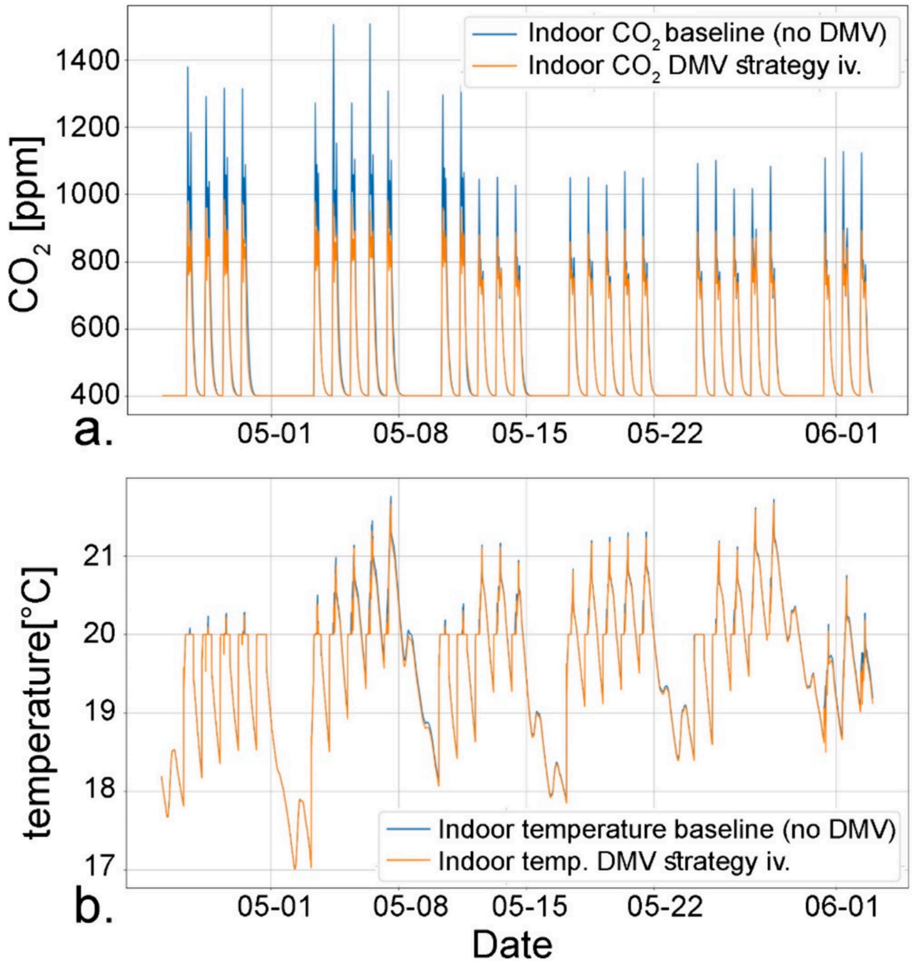

Fig. 8. Strategy iv. (single activation threshold 800 ppm) vs the baseline case: (a) simulated indoor CO_2 behaviours; (b) simulated indoor temperatures.

avoided in the threshold-controlled scenario. In all tested DMV scenarios, the average CO_2 during the occupation never surpasses 800 ppm, straying below 700 ppm, while peaks never reach 1000 ppm. Hence, those strategies guarantee high air quality in the considered classrooms. An even slight downscaling of the assumed airflow may be considered to limit energy needs slightly.

5. Discussion and limitations

The results focus on neutral periods, or in boundary periods in which the heating systems is mainly not activating. Additionally, the demo school building does not have a single room heating set point control, being the system working with a single thermostat for the whole block (while a second heating line is used only for the small offices). Hence, these analyses do not allow to study the energy conservation potential of DMV, being eventually the single DMV room temperature varying with respect to CNV-driven ones. For this reason, a discussion section has been developed to include yearly energy reflections and calculation about DMV energy conservation – see §5.1. For this additional analysis, well-known simpler calculation methods are applied and described below. Furthermore, section 5.2 reports strengths and limitations for the different control logics, while Section 5.3 discusses the limitations of the study.

5.1. Energy needs and conservation

Differently by controlled natural ventilation strategies, DMV is strongly correlated with energy needs, considering on the one side the electricity consumptions of fans and, on the other side, the potential heating energy saving due to the adoption of heat recovery systems. Even if this paper focuses on neutral season applications, a simplified analysis of the whole year energy needs has been performed by testing the impact of all the eight control strategies.

Focusing on the fan energy needs, the calculation is based on the application of the well-known mass balance equation, assuming a well-mixed air, – see eq. 2, e.g. [85] –, by calculating, with a 10-minute interval – the same used during the tests –, progressive CO_2 concentrations and corresponding ventilation rates via the DMV. Defined the ventilation rates ($\dot{m}$), energy needs by the fans are defined in line with the producer absorption curve. School days are defined looking at the scholastic year 2020–21, considering the standard effective number of 207 school days assuming the Regional calendar [86]. For time-scheduled strategies (i. and ii.), days of activation rise to 211, not considering interrupting the operation during single day holidays. The CO_2 emission rate per person (G) is 3.82E-8 $m^2/(sW)$, in line with ASHRAE standard [62], that, assuming a metabolic rate of 1.2 Met, CO_2 gas characteristics at 20 °C, the 18 people per room, and a typical atmospheric pressure of 101325 Pa, corresponds to 570659.4 mg/h per class during occupation (Mon-Sat, from 8:00 to 12:59). Infiltration rate is not changed with respect to the one derived by the calibrated model.

$$C_{fin} = C_o + (C_i - C_o)e^{-\frac{\dot{m}\Delta t}{V}} + \frac{G}{\dot{m}}\left(1 - e^{-\frac{\dot{m}\Delta t}{V}}\right) \tag{2}$$

Where: C_{fin} is the indoor concentration after the Δt period, C_o is the external CO_2 concentration [ppm], C_i is the starting internal CO_2

concentration [ppm], G is the emission rate by people, V the volume of the space [m^3], and ṁ the airflow. The G/ṁ term is expressed in mg/m^3 and further transferred to ppm by adopting the 24.055/44.01 conversion for the carbon dioxide at 20 °C.

Focusing on the heat recovery effect, a simple hourly based analysis on energy conservation is performed by calculating the difference in the ventilation energy losses considering a fixed internal set point of 20 °C ($\vartheta_{in\text{-}set}$) and an external hourly temperature (ϑ_{ext}) variation of the typical local climate derived by the Meteonorm tool v7 [87]. The calculation is hourly conducted, assuming the well-known eq. 3, aligned with energy labelling calculation schemes [12,40], where the hourly airflow (ṁ) is derived, for each strategy, by the previous IAQ fan-energy analysis. For air density (ρ) and for the specific air heat capacity (c) are assumed the reference values of 1.2 [kg/m^3] and 0.28 [W/(kgK)]. To define the energy conservation potential, the calculation is performed twice, with and without the heat recovery, to retrieve the difference between the two results (DMV vs CNV). The heat recovery efficiency is set to 80 % (η), in line with the DMV technical datasheet. CNV is assumed to be controlled via a 1000 ppm limit, in line with Section 2 analysis, and eq. 3 is applied without the heat recovery. CNV airflows are precautionary limited to a maximum of 2.5 ACH, corresponding to the single-side ventilation potential – see BS 5925:1991 [24] – for the local average wind velocity, assuming a 20 min window opening time per hour and the window opening area of the testing building. This CNV logic allows to maintain, the internal CO_2 concentration during occupation hours at an average of 1026 ppm (aligned with threshold-base cases – see Table 8), thanks to an average airflow of 345 m3/h (1.92 ACH). Ventilation losses are hence transformed to final energy, by applying the COP of the school heating system (98 %), a Viessman Vitocrossal 200 CM2-620, a gas condensing boiler with 620 kW of nominal power, and to primary energy using the natural gas factor of 1 [88], compatible with the UNI/TS 11,300 method [89]. Heating is considered active from the 1st of October to the 30th of April, in line with the typical local activation period, with a set-point schedule from 6:00 to 16:00 (including washing time) from Monday to Saturday. During single day-holidays the system is set to on, but is off during Christmas, carnival, and Easter periods. Infiltrations are not considered, being looking at DMV-CNV differences.

$$Q_{H-net} = \sum \left(\dot{m}\, c\, \rho \left(\vartheta_{in_{set}} - \vartheta_{ext} \right) \eta \right) \quad (3)$$

These calculations differ from the tests being:

i. based on a simplified calculation methodology;
ii. focused on DMV, not considering random ventilation and user behaviours or other calibration data;
iii. referred to a school time organisation based on the regional calendar, not including the choices of the local school (autonomy) – i.e. school time from 8:00 to 13:00, from Monday to Saturday, not considering gym and visit un-occupations –;
iv. referred to simplified room dimensions of 60 m^2, 3 m in height and 0.3 people/m^2 of density (18 people/room); and.
v. based on the local typical meteorological year.

Looking at fan energy needs, yearly results are shown in Table 8, by also defining the final energy needs per square meter. It can be possible to report the data to primary energy, considering a non-renewable electrical mix factor of 2.17 [86], compatible with the UNI/TS 11,300 method [87]. Results show that all strategies of MV can impact on a building with a very high energy class, i.e. between A and B, with the risk, especially for the constant airflow ones, to worsen the building class. Nevertheless, threshold activated solutions are less impacting.

A significative difference in energy needs is underlined for threshold-based strategies between these results and the testing ones. This is because, for this simplified approach, windows are never activated, while in detailed simulations and monitoring the user random behaviours are considered, positively impacting on the DMV fan energy needs of threshold-based solutions. Nevertheless, for the same principle, the difference between strategy i. and threshold-based strategies may be also reduced in cases in which window retrofitting actions would drastically reduce the infiltration rate. Additionally, this calculation refers to simplified conditions, including all the differences listed before.

Looking at the energy conservation, Table 9 reports the calculated ventilation energy losses. Additionally, the CNV losses are also reported for comparison, considering both the CNV case describe above, and a CNV ventilation with the same airflow of the compared DMV control logic. By comparing the energy conservation potential due to DMV heat recovery with the fan energy consumptions – all reported to primary energy for comparison –, it is possible to see that DMV is slightly more convenient, although for time scheduled ventilation, this is true only when the CNV flow is the same of the DMV control logic. Results suggest that DMV is mainly convenient in terms of automatic control potentialities, allowing for a sure activation of air exchanging under request, avoiding to ask teachers and students in constantly manage windows' openings for ventilation.

This outcome underlines how DMV performances can be underestimated in terms of fan-consumptions, when applied to traditional existing buildings, where summer and neutral season climate and user expectations do not allow to apply higher window controls. Nevertheless, the defined energy conservation due to heat recovery is at the contrary overestimated, being the same random typical ventilation acting on the results. Furthermore, this type of buildings rarely has a room-temperature control, while thermostat is generally one per floor or even one per building, moving the potential energy conservation to a simply increase in the specific room temperature. In the specific demo building, for example, the heating system has a single thermostat for classrooms, located in the corridor of one of the three floors, while a second thermostat is applied for offices. It is hence clear that DMV not

Table 8
Yearly reported DMV electric needs assuming the simplified mass balance equation (10-min intervals) and expanding reference daily results to the 2020–21 school calendar (207 school days for threshold-based strategies, and 211 for time-scheduled ones) – occupation Mon-Sat from 8:00 to 13:00.

	Strategy i.	Strategy ii.	Strategy iii.	Strategy iv.	Strategy v.	Strategy vi.	Strategy vii.	Strategy viii.	CNV
	ASHRAE 62	ASHRAE 62.1	600 ppm activation threshold	800 ppm activation threshold	600–500 ppm act/deact threshold	800–650 ppm act/deact threshold	1000 ppm activation Threshold	1000–600 ppm act/deact threshold	
Single DMV unit electric needs	48.53 kWh	98.24 kWh	35.59 kWh	35.16 kWh	35.59 kWh	35.16 kWh	34.91 kWh	35.89 kWh	–
Single DMV unit electric needs per m^2	0.81 kWh/m^2	1.64 kWh/m^2	0.59 kWh/m^2	0.59 kWh/m^2	0.59 kWh/m^2	0.59 kWh/m^2	0.58 kWh/m^2	0.60 kWh/m^2	–
Primary energy single DMV unit needs per m^2	1.76 kWh_{PE}/m^2	3.55 kWh_{PE}/m^2	1.29 kWh_{PE}/m^2	1.27 kWh_{PE}/m^2	1.29 kWh_{PE}/m^2	1.27 kWh_{PE}/m^2	1.26 kWh_{PE}/m^2	1.30 kWh_{PE}/m^2	–
av. CO_2	551 ppm	542	568	591	586	591	590	583	605
av. $CO_{2\ occupation}$	881 ppm	932	1001	1001	1001	1001	1036	1008	1026
Max CO_2	920 ppm	980	1120	1118	1120	1118	1223	1172	1223

Table 9
Yearly reported DMV ventilation energy losses (1 h intervals) assuming the 2020–21 school calendar (207 school days for threshold-based strategies, and 212 for time-scheduled ones) – occupation Mon-Sat from 8:00 to 13:00, heating season from 1st of October to the 30th of April. The energy conservation includes DMV fan energy needs.

	Strategy i.	Strategy ii.	Strategy iii.	Strategy iv.	Strategy v.	Strategy vi.	Strategy vii.	Strategy viii.
	ASHRAE 62	ASHRAE 62.1	600 ppm activation threshold	800 ppm activation threshold	600–500 ppm act/deact threshold	800–650 ppm act/deact threshold	1000 ppm activation Threshold	1000–600 ppm act/deact threshold
vent. losses $kWh_{nat\text{-}gas}$ y (final energy) 1 room	1352	1605	946	927	946	927	883	935
PE vent. losses kWh_{PE}/m^2 y	22.54	26.75	15.76	15.45	15.76	15.45	14.71	15.58
$CNV_{1000ppm}$ vent. losses kWh_{PE}/m^2 y	18.4 (211 days)	18.4	18.11 (207 days)	18.11	18.11	18.11	18.11	18.11
Energy conservation (PE and final energy) DMV-$CNV_{1000ppm}$	−5.42	−9.62	1.07	1.39	1.07	1.39	2.14	1.23
$CNV_{DMV\text{-}airflow}$ vent. losses kWh_{PE}/m^2 y	28.17	33.43	19.70	19.31	19.70	19.31	18.39	19.48
Energy conservation (PE and final energy) DMV-$CNV_{DMV\text{-}airflow}$	4.35	5.40	2.65	2.58	2.65	2.58	2.39	2.61

only requires a high initial investment for machine acquisition and installation, plus the maintenance cost and service, but may also requires to invest in the heating system control logic. This reduces its potential application in the wide context due to high costs, especially if compared with the ones of CNV ventilation based on sensors and user-self activation via luminous or acoustic alerts.

5.2. *Comparing the eight control logics: pros, and cons*

This section reports the main outcomes of the paper, underlining the main positive and negative aspects of the different considered control logics. Considering the time-dependent strategies i. and ii., it is possible to underline that:

- (pro) have the lowest CO_2 concentration values, both in averages and peaks;
- (pro) have a low number of activation cycles;
- (pro) do not require a CO_2 sensor to be managed, nor a remote-control logic, reducing installation and maintenance costs;
- (cons) have the highest energy needs for fans;
- (cons) define a continuous activation of the fan during the occupation period with a consequent production of noises;
- (cons) are not aligned with CO_2 levels, remaining active also during unoccupied hours (e.g. gym time), when random ventilation occurs, or during smart holidays when the operators would not act on the system ON/OFF;
- (cons) the high airflows impact on the energy conservation potential, limiting the potential savings.

Regarding thresholds dependent strategies it is possible to underline that:

- (pro) CO_2 concentrations are below 800 ppm during the whole testing, and around 1000 for the standard yearly calculation approach, supporting very good indicator values;
- (pro) peak CO_2 levels are always lower than 1000 ppm in the demo testing, and lower than 1250 for the standard yearly calculation;
- (pro) airflows are lower with respect to the time-dependent strategies increasing the potential energy conservation in winter and reducing the fan energy needs;
- (pro) they do not activate during unoccupied periods, allowing to reduce manual interventions for defining ON/OFF periods due to holidays;
- (pro) they positively consider random window opening contribution to IAQ;
- (cons) require CO_2 sensor connected to the DMV units, with a consequent increase in installation and maintenance costs;
- (pro/cons) high number of on/off cycles for cases with a single threshold, near the fluctuations of classroom levels – see especially the simulated tests with a threshold of 800 ppm, strategies iv. and vi. –, may reduce the energy needs, but can shorten unit's lifetime or generate fast changes in the acoustic perception.

Threshold control logics are the most suitable, although the definition of the threshold can influence the performance according to the specific room occupation density and to local typical behaviours (e.g. manual window schedules), avoiding excessive on/off cycles or over ventilations. This point is underlined when comparing the 800 ppm activation threshold strategy iv., the most interesting during the real tests, with the standard year analysis in which all threshold approaches are more similar.

An additional point to be mentioned is that the installation and management of this type of controlled machine need to be discussed with teachers, students, school masters and managers to support the proper use of the DMV, avoiding excessive random manual window openings and discussing the potential impact on the acoustic perception. In this study, we faced a very high level of collaboration that will be deepened in devoted work, although the acoustic effect of the machines was only sometimes positively accepted.

5.3. *Limitations and future studies*

The paper refers to a specific demo building, located in the temperate area of Europe, in Italy. Although the building is very representative for the specific context and for general southern-to-central European cases (Torre Pellice is a piedmont area with cold winter and temperate to hot summers – TMY has 7 tropical nights and 50 frost days, calculated in line with [90]), results may differ from the ones obtained in northern countries and in different climatic contexts. The school is a real building, including unpredictable user behaviours and the need to not interfere with typical school activities. Additionally, it is a traditional building without a ventilation system, not allowing for a centralised MV, but referring to single DMV units per class. The main analyses with in situ measurements and tests and the adoption of calibrated models refers to neutral seasons, although the energy conservation potential and the whole year impact of DMV is analysed by an alternative approach, allowing to expand the discussion to a wider context. The specific school, in fact, doesn't allow to perform these analyses not having a room-detailed heating control, but only a single thermostat located in the main corridor and serving all the classrooms, and being the number of installed DMV limited to three.

Looking at the results, the single activation threshold strategy that adopts 800 ppm as an activation threshold is the most effective for the testing analysis, consuming at least half of the other approaches. Nevertheless, looking at the different measured results, the choice of the threshold can be influenced by the specific room occupation density or by manual window schedules that can generate CO_2 fluctuations when the DMV is active near a particular threshold, requiring double activation/deactivation choices. The latter can be re-set during maintenance or post-intervention optimisations or defined on a seasonal basis to take advantage of summer manual window operation. In addition, from the tests, it emerges that even the high 1000 ppm single activation threshold strategy can be considered, although higher average CO_2 values are retrieved in this latter case. These results are, although, visible in the in-situ tests and in the calibrated simulation results, while the standard yearly discussion show how all threshold-based strategies are very similar for the considered steady-state conditions. This point underlines how, confirmed in all the analyses the main results, the identification of the best strategy is quite site-dependent, and may require adjusting over the years the activation thresholds to potential variations in local habits, or the adoption of smart control logics. Nevertheless, this study doesn't include predictive control logics or trend-based controls, being referring to time-dependent schedules and to threshold-based ones, considering also the limited potential budget of schools for maintaining the systems. Further analyses may be conducted in future to expand the number of control logics. Similarly, the study refers to CO_2 control optimisation and not includes other target variables in the analysis, such as energy savings in winter and/or ventilative cooling in summer. Installing DMV units in crowded school spaces has a tangible potential to improve and maintain the correct IAQ levels in classrooms. In addition, the tested DMV units could also help contain heating energy needs in room-controlled systems thanks to the heat recovery. However, this point needs to be deeply investigated in further analyses considering also other demo cases in which a room-temperature control is available. Additionally, a future study will focus on the ventilative cooling potential, comparing DMV with CNV approaches. Finally, the comparison between DMV and CNV is not performed in this study with measurements, although a large citizen science is under development for another project.

6. Conclusions

The paper analyses the differences between different CO_2 airflow control strategies applied to detached mechanical ventilation units (DMV) in a school building. Based on both constant airflow and CO_2 threshold levels, eight main different DMV control strategies are analysed to study their impact on indoor air quality performances. These strategies are physically tested in the school building via measurements for shorter periods (3–6 days) to verify their impact under actual occupied conditions. These tests are based on both a detailed monitoring system and the development of a remote-control approach for the DMV units. Additionally, main strategies are also simulated via EnergyPlus for a long time using a calibrated school-building model. The on-site tests' overall results confirm the simulation analyses' outcomes. Finally, a whole year application of the eight DMV control logics is developed using well-known simpler models to analyse fan energy needs and energy conservations.

Results underline that the choice of the best strategy could be different based on the intended goal and specific boundary conditions. All strategies are able to maintain the CO_2 concentration level in the crowded classes inside the expected boundaries, although results differ especially between time-dependent schedules and threshold-based ones, such as underlined in the discussion. In conclusion:

- the performance of DMV is demonstrated to be effective for IAQ control, although their installation may result in spatial and budget limitations, by also considering that their total impact on energy needs is limited, considering fan consumptions and heating energy savings;
- Time-dependent control logics are able to minimise the CO_2 levels, although their consumptions are higher;
- Threshold-dependent controls are more interesting, although threshold definition may be a critical issue to be considered to balance activation cycles, energy conservation and energy needs;
- existing schools may not have the space to install centralised ventilation systems, requiring, like in the case here investigated, room-per-room DMV units. This may impact the management complexity and the operative costs because each room will have an independent system that needs to be controlled and maintained individually;
- units are directly positioned in the rooms, including potential acoustic and space occupation issues, i.e. in one class, there wasn't the volumetric space to install a unit;
- sensor system installation and maintenance costs need to be considered from the beginning, to allow the application of the most energy-effective solutions.

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CRediT authorship contribution statement

Giacomo Chiesa: Conceptualization, Data curation, Funding acquisition, Methodology, Supervision, Writing – original draft, Writing – review & editing. **Manuela Vigliotti:** Data curation, Methodology, Software, Writing – original draft.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that has been used is confidential.

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Appendix A. – control logic flowcharts

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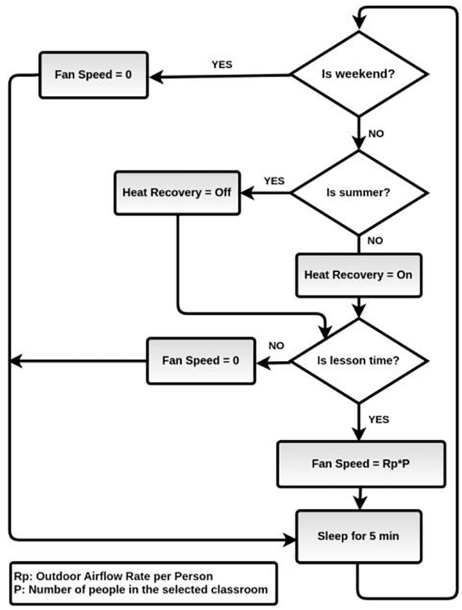

Fig. A1. the CO_2 constant airflow ventilation control algorithm recommended by the ASHRAE 62 [60].

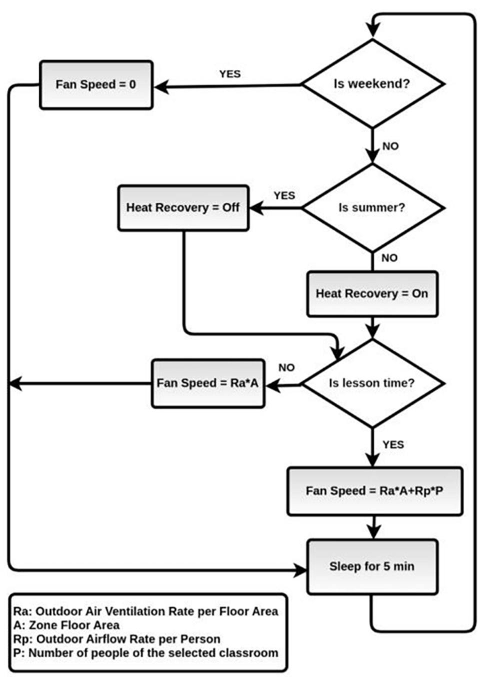

Fig. A2. the CO_2 constant airflow ventilation control algorithm recommended by the ASHRAE 62.1 [63].

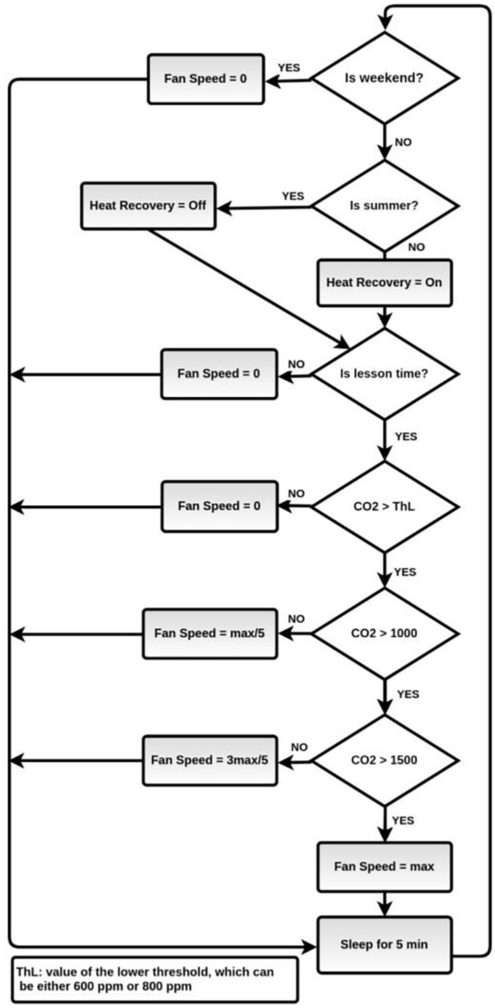

Fig. A3. the CO_2 ventilation control algorithm adopting a single minimum activation threshold (ThL) – control strategies iii. and iv.

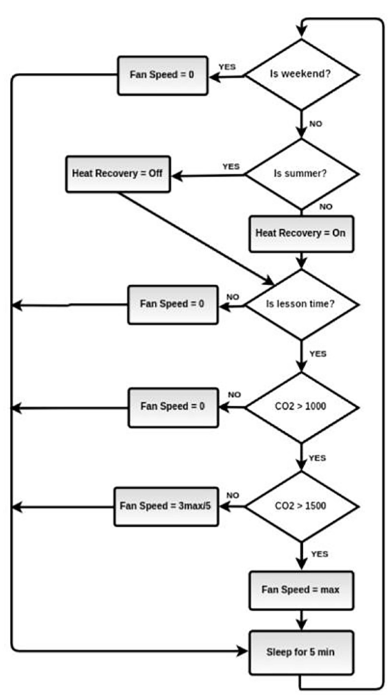

Fig. A4. the CO_2 ventilation control algorithm adopting a single minimum activation threshold of 1000 ppm – control strategy vii.

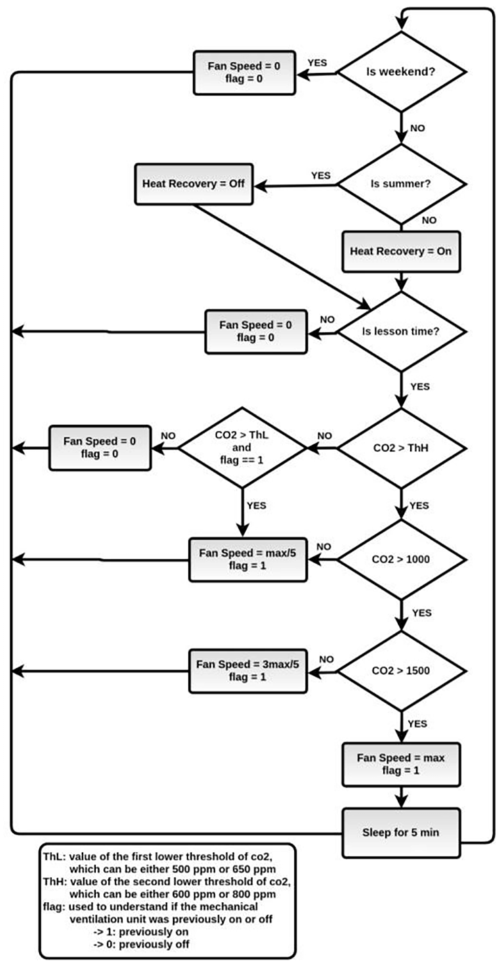

Fig. A5. the CO_2 ventilation control algorithm adopting a double minimum activation/deactivation threshold (ThH and ThL) – control strategies v. and vi.

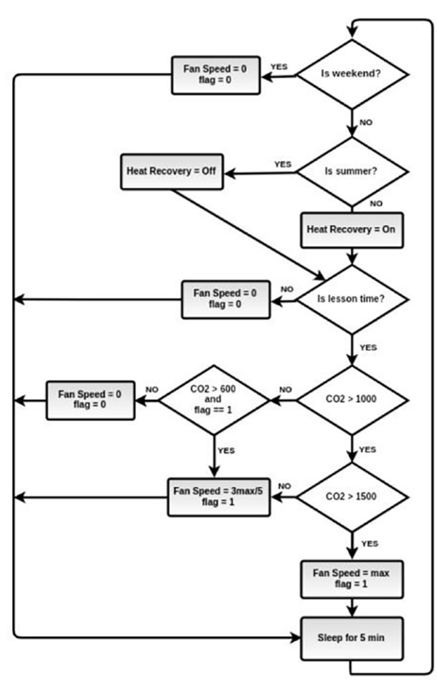

Fig. A6. the CO_2 ventilation control algorithm adopting a minimum activation threshold of 1000 ppm and a deactivation threshold of 600 ppm – control strategy viii.

Appendix B

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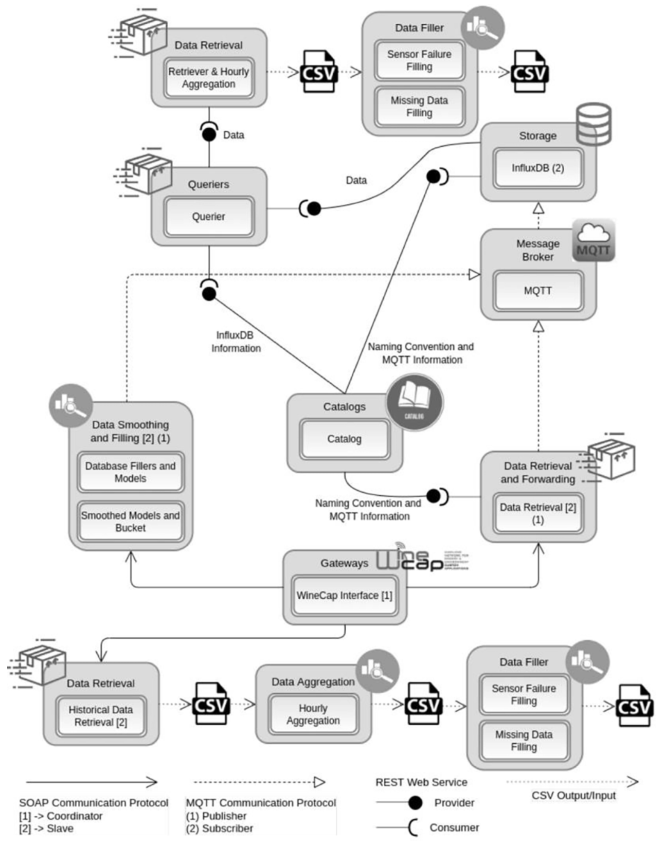

Fig. B1. General flowchart of the coded software structure to retrieving data to calibrate the models.

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