Journal of Building Engineering 71 (2023) 106405

Contents lists available at ScienceDirect

Journal of Building Engineering

journal homepage: www.elsevier.com/locate/jobe

Comparison of indoor air quality and thermal comfort standards and variations in exceedance for school buildings

Francesco Babich *, Giulia Torriani, Jacopo Corona, Irene Lara-Ibeas

Institute for Renewable Energy, Eurac Research, Bolzano, Italy

ARTICLE INFO

Keywords:
School buildings
IAQ
Thermal comfort
Field measurements
Exceedance

ABSTRACT

Addressing indoor air quality (IAQ) and thermal comfort issues in school buildings is challenging but relevant. Firstly, their primary occupants are more vulnerable than adults. Secondly, school buildings are often inadequate being too old or designed to prioritise energy-efficiency targets. Thirdly, occupants have often little control over the indoor environmental quality (IEQ). Lastly, the SARS-CoV-2 pandemic highlighted the complexity and vulnerability of existing decision-making processes in relation to making timely and well-informed decisions about IEQ threats. Standards and guidelines vary over time and among similar countries despite targeting similar occupants, evaluate IAQ and thermal comfort independently, and do not include any specific adaptations to children. Thus, the aim of this research is to compare different available standards to evaluate IAQ and thermal comfort in school buildings. By analysing with different standards (EN16798, BB101, and ASHRAE 55 and 62.1) the data collected in schools in northern Italy, this research evaluated the consequences of different limits and approaches, and proposed improvements. The conclusions are that (i) thresholds and methods inconsistency within the same standard should be avoided; (ii) upper- and lower-bounded operative temperature scales are the most appropriate means to design and verify thermal comfort in classrooms; (iii) IAQ metrics that give an upper limit per a certain amount of consecutive time might prevent the build-up of indoor pollutants, even with high emissions from the building fabric; (iv) no standard proposes a combined IAQ and thermal comfort analysis which could enable more informed trade-off decisions considering IAQ, thermal comfort, and energy targets.

List of abbreviation

ACH	Air Change Rate
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BB101	Building Bulletin 101
BMR	Basal Metabolic Rate
EQ-OX	Environmental Quality bOX
HE	High Emitting
IAQ	Indoor Air Quality
IEQ	Indoor Environmental Quality

* Corresponding author.
E-mail address: francesco.babich@eurac.edu (F. Babich).

https://doi.org/10.1016/j.jobe.2023.106405
Received 24 October 2022; Received in revised form 27 February 2023; Accepted 26 March 2023
Available online 29 March 2023
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LE	Low Emitting
MRT	Mean Radiant Temperature
PMV	Predicted Mean Vote
PPD	Predicted Percentage of Dissatisfied
RH	Relative Humidity
VLE	Very Low Emitting
WHO	World Health Organization

1. Introduction

Over the past two decades numerous indoor environmental quality (IEQ) studies have been carried out in European school buildings, the majority of which have highlighted serious problems with the indoor air quality (IAQ) and thermal comfort [1–8]. The recent SARS-CoV-2 pandemic has further emphasised the role that poor IAQ in schools plays in the transmission of airborne viruses [9]. Despite the growing awareness of these issues and the impacts they exert on the lives of students and staff, both designers and later school management authorities are often unsure how to respond to such issues in a timely and effective manner due to unclear and sometimes contradictory indications and guidelines.

Addressing air quality and thermal comfort issues in educational buildings is particularly challenging but also relevant for several reasons. Firstly, pupils spend a relevant time in classrooms [10–12] which can have an occupancy density four times higher than office buildings [12,13]. Research has shown that the conditions in schools are often inadequate [14] being old school buildings sometimes in a poor state of repair and newly built or recently refurbished schools often designed to prioritise energy-efficiency targets, with scant attention paid to indoor environmental quality (IEQ) [15]. Secondly, schools' primary occupants are children and adolescents whose respiration rates are higher than adults and whose organs and immune systems are still developing, which means they are more vulnerable to indoor pollutants [5] and adverse thermal environments [16]. Thirdly, good IAQ and thermal comfort in classrooms are essential because they can affect students' learning performance and ability to concentrate [17,18]. Fourthly, pupils, but also teachers and other school personnel often have little or no control over the IEQ [19,20]. In particular, pupils may not actively adjust the classroom environment due to limited permission from their teacher and may not be able to change their activity level and clothing insulation because they are required to sit quietly and wear uniforms [21]. Lastly, the current SARS-CoV-2 pandemic has highlighted the complexity and vulnerability of existing school management and decision-making processes in relation to making timely and well-informed decisions about threats to IAQ [22]. Research has shown that adopting an efficient ventilation strategy is crucial in terms of IAQ and risk of airborne infections in schools [23]. On one hand, the top-level management structures are ill-prepared to address urgent needs, and on the other hand teachers frequently feel under too much pressure (due to their burgeoning workload) or confused by too much (and often contradictory) information.

Different methods and indications to design and assess IAQ and thermal comfort in school buildings are provided by standards such as the European standard EN16798-1 [24], the British Building Bulletin 101-BB101 [25], and the ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers) Standards 55 [26] and ASHRAE 62.1 [27]. These standards are based on the findings of studies with adult subjects [28–30] and assume that the determinants of IAQ and thermal comfort are similar in children and adults [31]. However, previous studies reported systematic discrepancies between the actual thermal perception reported by students and the predictions made according to the current thermal comfort standards [31–34]. The available evidence suggests that the thermal sensation of children and adults might be different, with a tendency in children towards a warmer sensation compared with what the models predict [35]. Mors et al. [36] reported that the Predicted Mean Vote (PMV) - Predicted Percentage of Dissatisfied (PPD) method underestimates thermal sensation for children by up to 1.5 point. Dias Pereira et al. [37] found that in general students accept temperature ranges higher than those which are given by the norms. Moreover, although the occupants of school buildings have comparable needs for healthy and comfortable indoor spaces, standard and guidelines vary considerably over time and among similar countries or even within the same country (with regional and local regulations) [14]. Metrics and their acceptability thresholds may be considerably different, and this often is a cause for confusion and uninformed decisions.

Furthermore, standards evaluate IAQ and thermal comfort independently although previous studies have highlighted the combined effects of environmental factors on human perception and especially how the occupants' perception of IAQ varies according to thermal environment [38]. Occupants' thermal sensation can change according to CO_2 concentration [39] and vice versa [40].

Thus, there is a need to evaluate the indications provided by the different standards to facilitate the design and management of school buildings. Many field studies assessed the classrooms' conditions according to one standard [8]. However, there is a lack of studies comparing the thresholds provided by standards. The aim of the research presented in this paper is to compare different available standards to evaluate IAQ and thermal comfort in school buildings by focusing especially on the possible alternative metrics and approaches to identify the most suitable options, on the possible inconsistency within the same standards or frameworks, and on the potential gaps that have not been covered by standards yet. This comparison is performed using several thermal and IAQ measurements conducted in four schools in South Tyrol (Italy) and simulating three contaminants' emission scenarios based on building materials with different level of emissions. The study concludes with a combined thermal comfort and IAQ analysis for real-time decision making.

2. Methods

This study comprises two main parts, namely the indoor environmental data collection in school buildings and the analysis of this data using different standards and metrics to evaluate IAQ and thermal comfort.

2.1. Field study

In this study, indoor environmental data was collected from February 2022 to April 2022 in four schools located in the province of Bolzano (northern Italy). To define the heating season (period in which the use of heating is allowed), Italy has been divided in six climatic zones,[1] and most of Bolzano province falls into zone F (the coldest; for locations with more than 3000 heating degree days) for which there are no limits for the use of heating systems in terms of dates and number of hours of per day. All schools included into this study fall into zone F, and therefore had the heating system active during the whole data collection period. All classrooms were naturally ventilated, and no mechanical ventilation system was available. Measurements were taken in two classrooms per school (Table 1 and Fig. 1).

Measurements were collected by using an in-house developed multi-sensor device called "Environmental Quality bOX" (EQ-OX). EQ-OX was conceived to be a portable low-cost device that enables to measure multiple IEQ parameters such as hygro-thermal parameters, lighting level, and some IAQ parameters. The case and the board for the sensors are tailor-made, while the single sensors have been selected among those currently available on the market. EQ-OX uses a low-power wide-area networking protocol connection, and this enables to save and check the data in real time. In this study, EQ-OX was used to measure air temperature (T_{air}), globe temperature (T_{globe}), relative humidity (RH), pressure (p_{air}) and CO_2 as IAQ indicator (Table 2).

To ensure the correctness of the measurements performed, prior to the monitoring campaign the sensors integrated into EQ-OX were tested. Air temperature sensors were tested in a climatic chamber in the range of 10–35 °C and compared to a high accuracy RTD Pt100 1/10 DIN sensor, whereas the RH sensors were tested in the range of 20–80% and compared to E + E EE060 previously calibrated by an accredited calibration laboratory. In both cases, correlations between the sensor and the reference instruments were high ($R^2 > 0.99$). CO_2 sensors were compared with a IAQ datalogger HD21ABE17 (Deltaohm, Italy) previously calibrated by monitoring the same room for a week. In this case, Pearson squared correlation coefficient (R^2) ranged from 0.91 to 0.92 whereas the mean absolute error varied between 42 and 44 ppm, demonstrating an acceptable performance of the K-30 CO_2 sensors used in this study.

The whole acquisition system comprises three essential components, namely the EQ-OX (i.e. the box which contains the sensors), a gateway which enables to connect multiple EQ-OX at the same time, and a 4G modem for internet connection (Fig. 2). Gateway and modem can be freely located within the building as long as the gateway has a reliable connection with the EQ-OX and the modem has a stable connection to the internet. In each school, one gateway and one modem were installed in a storage room or a corridor. On the other hand, the position of the EQ-OX is crucial to ensure high-quality and representative data. In this study, in all classrooms, it was located at a 0.7 m–1.5 m height (above the floor) to assess the sitting position of the students and attention was paid to avoid direct sunlight and proximity to other sources of interference (e.g. radiators). Furthermore, it was located considering points that did not disturb the normal operation of the classrooms, typically in one of the four corners of the classroom.

EQ-OX system gathers multiple readings within 1 min. However, for all analysis conducted in this study, data was previously resampled using 10-min average values. All calculations were performed using Python (version 3, Anaconda distribution) scripts developed by the authors using commonly used libraries such as Pandas and Matplotlib (for visualization).

2.2. IAQ and thermal comfort metrics and analysis

In this study, in order to evaluate IAQ and thermal comfort in classrooms, three regulatory frameworks were considered, namely European standard EN16798-1 [24], British guidelines on ventilation, thermal comfort and IAQ in schools (Building Bulletin 101 – BB101) [25], and the American standards ASHRAE 62.1 [27] (focused on ventilation for acceptable IAQ) and ASHRAE 55 [26] (for thermal comfort). The reasons for considering these three standards are that they all refer to Western northern-hemisphere countries (basically Europe and north America), and thus in principle comparable (climate and habits) and suitable for the analysis of data collected in northern Italy.

2.2.1. European standard EN16798-1

EN16798 provides indoor environmental input parameters for design and assessment of energy performance of buildings addressing different aspects of IEQ, namely IAQ, thermal environment, lighting, and acoustics. This standard replaced the previously used EN 15251 [41], and, like its predecessor, it provides different criteria for different types of buildings including schools. EN16798 includes two annexes, namely Annex A and B. The former presents all national recommended criteria for indoor environment, and therefore it varies from country to country in Europe. The latter contains default criteria and does not vary at national level. In most cases, the national variations included in Annex A enable to better capture national peculiarities and to harmonize EN16798 to other national regulations.

For thermal comfort, this standard defines four categories based on PPD index (Table 3). The way in which categories are defined however implies that there is a fifth category for all points with PPD equal or higher than 25%. PPD is derived from the PMV calculated according to EN ISO 7730 [42]. Moreover, threshold values of the indoor operative temperature ($T_{operative}$) are given for different types of indoor spaces (values for classrooms in Table 4). These thresholds were defined assuming 50% relative humidity level, low air

[1] D.P.R. n. 412 del 26 agosto 1993 (reference Italian law).

Table 1
Classrooms' features.

Classroom ID	School	Pupils age	Average occupancy	Type of room heating system
0217	High school (Technical institute)	14	17	Underfloor radiant heating
07	Primary school	10	18	Heating radiators
08	Primary school	10	21	Heating radiators
09	High school	14–15	15–20	Heating radiators
11	High school	14–15	15–20	Heating radiators
15	High school (Technical institute)	15	16	Underfloor radiant heating
16	Middle school	11–13	20	Heating radiators
10	Middle school	11–13	20	Heating radiators

Fig. 1. Classrooms layout.

Table 2
EQ-OX sensors' specifications (* encapsulated into a 40 mm black globe).

Parameter	Sensor	Range	Accuracy
T_{Air}	Littlefuse 11492	−50 to 150 °C	±0.2 °C
T_{globe}	Littlefuse 11492*	−50 to 150 °C	±0.2 °C
RH	Sensirion SHT31	0 to 100 RH %	±2%
p_{air}	Bosch BMP388	300 to 1100 hPa	±0.5 hPa
CO_2	CO_2meter K30	0 to 10000 ppm	±(30 ppm ± 3% of reading)

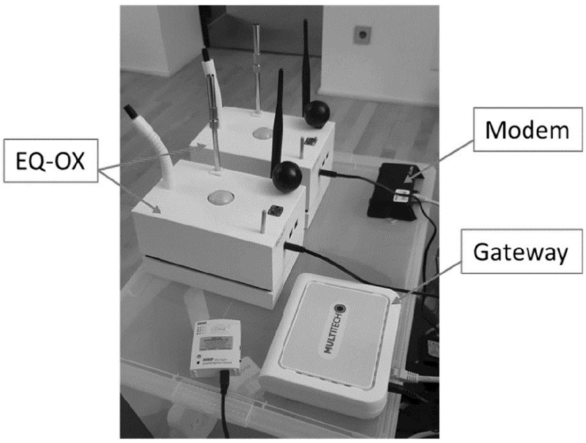

Fig. 2. Monitoring system which comprises three components (exemplary photo taken in our premises).

velocity level (<0.1 m/s), typical winter clothing (1.0 clo) and sedentary activity (1.1 met). Lastly, indoor operative temperature limits for energy calculations are also included in this standard. It is worth noting that the lower limit of Category IV in Table 5 is different (17 °C) from the corresponding value in Table 4 (18 °C).

A similar approach based on categories is used in EN16798 also for IAQ. The standard provides three different methods for the evaluation of the IAQ, and assumes complete air mixing in the room (concentration of pollutants is equal in extract and in occupied zone). In the first method, ventilation rates for sedentary, adults, non-adapted persons for diluting emissions (bio effluents) from people (Table 6) as well as ventilation rates for diluting pollution from the building and systems (Table 7) for different categories are

Table 3
Default categories for design of mechanical heated and cooled buildings.

Category	PPD [%]	PMV
I	<6	$-0.2 < PMV < +0.2$
II	<10	$-0.5 < PMV < +0.5$
III	<15	$-0.7 < PMV < +0.7$
IV	<25	$-1.0 < PMV < +1.0$

Table 4
Default design values of the indoor operative temperature in winter (values for classrooms).

Category	Minimum $T_{operative}$ for heating [°C]
I	21
II	20
III	19
IV	18

Table 5
Temperature ranges for hourly calculation of heating energy in four categories of indoor environment.

Category	$T_{operative}$ ranges for heating [°C]
I	21–23
II	20–24
III	19–25
IV	17–25

Table 6
Design ventilation rates for sedentary, adults, non-adapted persons for diluting bio-effluents.

Category	Expected percentage dissatisfied [%]	Air flowrate [l/(s person)]
I	15	10.0
II	20	7.0
III	30	4.0
IV	40	2.5

Table 7
Design ventilation rates for diluting emissions from different type of buildings.

Category	Very low polluting building, LPB-1 [l/(s m^2)]	Low polluting building, LPB-2 [l/(s m^2)]	Non low-polluting building, LPB-3 [l/(s m^2)]
I	0.50	1.0	2.0
II	0.35	0.7	1.4
III	0.20	0.4	0.8
IV	0.15	0.3	0.6

provided. The total design ventilation air flow rate for a room is calculated as the sum of both ventilation rates and can be expressed as l/s, l/(s person) and l/(s m^2). The second method establishes limits for CO_2 concentration above outdoor concentration (Table 7) for each category. The third method is based on predefined air flow rates. However, this standard only reports the values for an office, thus limiting its use for other spaces.

Furthermore, the standard says that the ventilation rate should always be higher than 4 l/s per person during occupied time. For the unoccupied time, two cases are considered. In case the ventilation is shut off, the minimum amount of air to be delivered prior to occupation of a given zone is 1 vol within 2 h. In case the ventilation is lowered for unoccupied periods, the total air flow rate for diluting emissions from building should be minimum 0.15 l/s m^2 of floor area in all rooms. No specific indications are given for schools nor for occupants different than adults. Like for thermal comfort, also for IAQ it is worth noting that Table 6 (and also Table 7) explicitly indicates four categories, but implies the existence of a fifth category. However, the same does not happen in Table 8 where the use of the same limit for category III and IV leaves in the latter all points in time above this limit.

Lastly, EN16798 remarks that the categories are related to the level of expectations the occupants may have. A normal level would be category II. A higher level may be selected for occupants with special needs (children, elderly, persons with disabilities, etc.). A lower level will not provide any health risk but may decrease comfort.

2.2.2. The UK Building Bulletin 101

BB101 [25] sets out regulations, standards and guidance on ventilation, thermal comfort and IAQ for school buildings. This

Table 8
Default design CO_2 concentrations above outdoor concentration.

Category	CO_2 concentration above outdoor [ppm]
I	550
II	800
III	1350
IV	1350

document considers different ventilation strategies ranging from a completely natural system to a completely mechanical system. For naturally ventilated spaces, the driving forces are the wind and the stack effect. It includes single sided ventilation, cross ventilation or stack ventilation systems, and openings can be manual, automatic or both. Mechanical ventilation systems are fan driven and can be either centralized or single-room systems. Hybrid or mixed-mode systems use both natural driving forces of the wind and the stack effect and fans to supplement these driving forces.

For teaching and learning spaces, BB101 sets different IAQ requirements for different ventilation strategies. For mechanical systems and hybrid systems when used in mechanical mode, sufficient outdoor air should be provided to achieve a daily average concentration of CO_2 of less than 1000 ppm during the occupied period. In addition, the maximum concentration should also not exceed 1500 ppm for more than 20 consecutive minutes each day during the occupied period.

For naturally ventilated spaces and for mixed-mode system when natural ventilation is used, the daily average concentration of CO_2 should not exceed 1500 ppm during the occupied period, and the maximum concentration should also not exceed 2000 ppm for more than 20 consecutive minutes each day. In addition, different design targets are given for new construction and refurbishments. In the former case, the system should be designed to achieve a CO_2 level for most of the time of less than 1200 ppm (800 ppm above the outside level, taken as 400 ppm) while this limit is raised at 1750 ppm for the latter case. This is equivalent to category II and category III of EN16798 (Table 7), respectively. In BB101, both average and maximum thresholds are always specified adding that they apply only when occupancy is equal to design occupancy or lower.

In BB1010, no specific ventilation rates are given based on the different emissions levels from building materials. Nevertheless, this bulletin states that the removal of pollution sources is more effective to maintain an acceptable IAQ than diluting the pollutant concentrations by ventilation and recommends the use of low-polluting building materials or products such as glass, stone and ceramics or other materials which have one of the recognised labels for low emissions in the European Union (i.e. European Ecolabel,[2] EMICODE®,[3] etc).

For thermal comfort, BB101 still refers to category descriptions from EN15251. Like in EN16798, there are four categories, namely I (the highest level - recommended for spaces occupied by very sensitive and fragile persons with special requirements like some disabilities, sick, very young children and elderly persons), II (normal), III (moderate expectation level), and IV (low level of expectation – acceptable only for a limited part of the year). Furthermore, BB101 says that for refurbished buildings, the minimum standard is category IV where category III cannot be met for reasons of practicality and due to the extent of refurbishment. However, after refurbishment the criteria should not be worse than before refurbishment in any aspect affecting thermal comfort.

For spaces with normal level of activity, including teaching, study, exams, admin and staff areas, and computer suites, the recommended operative temperatures during the heating season are 20 °C (normal maintained operative temperature) and 25 °C (maximum operative temperature during the heating season at maximum occupancy). These values should be measured at seated head height (1.1 m for primary schools; 1.4 m for secondary schools) in the centre of the room.

2.2.3. ASHRAE standards

ASHRAE reference standards for thermal comfort and for ventilation requirements are standard 55 “Thermal Environmental Conditions for Human Occupancy” [26] and 62.1 “Ventilation for Acceptable Indoor Air Quality” [27], respectively.

For thermal comfort, compliance is achieved if $-0.5 < PMV < +0.5$. ASHRAE 55 includes two different ways to calculate the PMV according to average air speed. For low air speed values (below 0.2 m/s) the PMV calculation is identical to the ISO 7730 calculation. On the other hand, if the occupants have activity levels result in average metabolic rates between 1.0 and 2.0 met, clothing insulation is between 0.0 and 1.5 clo, and average air speed is greater than 0.2 m/s, then it is permissible to apply the elevated air speed comfort zone method. This method better captures the effect of elevated air movement on thermal comfort.

For IAQ, the minimum ventilation rates based on people in the breathing zone in classrooms is 5 l/(s person). The limit is the same regardless of the ventilation system (natural, mechanical or mixed-mode) and the age of pupils. This ventilation rate must then be increased by an additional term (0.6 l/(s m^2)) that is based on the surface of the classroom. In Italy, the minimum classroom floor-area per pupil is 1.80 m^2 (from preschool to middle school) and 1.96 m^2 (high school),[4] and thus the additional term becomes 1.1 l/(s person) and 1.2 l/(s person), respectively.

ASHRAE 62.1 has not contained a limit value for indoor CO_2 since the 1989 edition of the standard. ASHRAE has intentionally removed the previously used threshold (1000 ppm) to avoid an overestimate of the significance of this limit as an indicator of acceptable IAQ in general, while this concentration is at best an indicator of outdoor air ventilation rate per person [43]. Comparing

[2] https://environment.ec.europa.eu/topics/circular-economy/eu-ecolabel-home_en.

[3] www.emicode.com.

[4] Decreto Ministeriale del 18/12/1975 (reference Italian law).

ASHRAE 62.1 with EN16798, it appears that the current ASHRAE minimum ventilation rate for classrooms is half the EN threshold (5 as opposed to 10 l/(s person)). On the other hand, the old and no longer in-use 1000 ppm value would be approximately equivalent to EN16798 Category I limit (950 ppm assuming 400 ppm outdoor concentration).

2.2.4. Application of the international standards

In the present study, for EN16798 application, values from Annex B were adopted. Values from Tables 3 and 4 were used for the analysis of the thermal comfort, while values from Table 8 were used to evaluate IAQ. A 400 ppm outdoor CO_2 concentration was assumed [44]. Moreover, category I was assumed to be the target for classrooms, and the percentage of occupied time in each category was calculated.

For the IAQ analysis according to BB101, average and maximum CO_2 limit values only for naturally ventilated buildings are used as none of the analysed classrooms had mechanical ventilation systems. Furthermore, an estimation of the indoor pollutant concentration when using building materials with different levels of emissions was performed to highlight the impact of building material selection on IAQ. To evaluate thermal comfort, in this study, the percentage of occupied time with operative temperature below 20 °C, between 20 °C and 25 °C, and above 25 °C is calculated.

ASHRAE thermal comfort analysis is based on PMV whose calculation includes air speed as an input. However, this was not directly measured. Moreover, multiple measurement points would have been required to have an acceptable estimate of the values in the different parts of the room due to the erratic nature of air speed, but this type of measurements is not feasible in occupied classrooms for long periods. As the focus was on winter conditions and anecdotal evidence did not suggest any issues about elevated air speed, PMV was calculated assuming a constant value of 0.1 m/s. Clothing and metabolic rate were assumed to be 1.0 clo (typical winter value) and 1.1 met (reading and writing), respectively. For IAQ analysis, since ASHRAE does not provide any CO_2 threshold, but the aim of this study is to evaluate IAQ applying different standards, two limit values were chosen, namely 1000 ppm and 1320 ppm. The latter was defined assuming that 6.2 l/(s person) (which is 5 plus 1.2 l/(s person)) is in between EN16798 Category II and III limits (whose respective CO_2 limits are 1200 ppm and 1750 ppm – see Table 7).

In this study, for the numerical calculations performed according to the standards, classrooms were assumed to be occupied from 7:00 to 18:00 and from Monday to Friday. Thus, night and weekend data was not considered in the analysis.

2.2.5. Additional thermal calculations

A key parameter to evaluate thermal comfort in indoor environments is the operative temperature which considers both the convective and radiative heat transfer between a person and the surrounding thermal environment [45]. In most practical cases, including the current study, if the relative velocity is small (0.2 m/s or less) or where the difference between the mean radiant temperature (MRT) and air temperature (T_{air}) is small (up to 4 °C), the $T_{operative}$ can be calculated as the mean value of MRT and T_{air} according to EN ISO 7726 [46]:

$$T_{operative} = \frac{MRT + T_{air}}{2}$$

In this study, the T_{air} was directly measured, while the MRT was calculated from the measured values of air and globe temperature according to EN ISO 7726 [46] (temperatures in Celsius; diameter of the globe D = 0.04 m; emissivity of the globe $\epsilon_{globe} = 0.95$ for matt black paint):

$$MRT = \left[\left(T_{globe} + 273\right)^4 + \frac{0.25 \times 10^8}{\varepsilon_{globe}} \left(\frac{\left|T_{globe} - T_{air}\right|}{D} \right)^{1/4} \times \left(T_{globe} - T_{air}\right) \right]^{1/4} - 273$$

2.2.6. Simulation of different emission scenarios

CO_2 concentrations provided in standards are generally related to the perception of human bioeffluents and the level of acceptance of their odors. However, there are many other relevant indoor air pollutants that are not related to number of occupants, and CO_2 concentration is not a good indicator of those contaminants [43]. To evaluate the potential implications that different CO_2 concentration thresholds have on the levels of other indoor pollutants, three exposure scenarios were simulated for each classroom using building materials and furniture with different levels of emissions. Formaldehyde (HCHO) was selected as model pollutant to represent emissions from materials due to its frequent occurrence in school buildings and known carcinogenic effects [47].

To simulate the different scenarios, the air change rate (ACH) in each classroom was estimated using the CO_2 decay method. This method was selected to estimate the ACH over other methods such as build-up methods because of the lack of accurate hourly occupancy data or methods based on the blower door test due to budget restrictions. The decay method is based on the decrease of CO_2 levels after the occupation period. Since the ACH in the classrooms can be affected by time-varying factors (i.e. wind speed and direction, outdoor-indoor temperature difference, etc.), this method was applied using data from different days of the monitoring period to obtain an average air exchange for each classroom representative of the ACH over the whole monitoring period. Assuming a single and well mixed zone, the sequence of CO_2 concentrations over a time interval of the decay period is described by the equation [48]:

$$C_t = (C_{ss}\ C_{out})\exp(-A_D t) + C_{out}$$

where C_t is the CO_2 concentration at the time t, C_{out} is the background CO_2 concentration (assumed to be 400 ppm), A_D is the estimated air exchange rate, t is the time and C_{ss} is the steady-state CO_2 concentration. This equation can be easily linearized to calculate the air exchange rate as follows:

Table 9
CO_2 generation rates at 273 K and 101 kPa for ranges of ages and level of physical activity.

Age (years)	Mean body mass (kg)	BMR (MJ/day)	Physical activity (met)	CO_2 generation rate (l/s)
Females				
6 to < 11	31.7	4.73	1.1	0.0025
11 to < 16	55.9	6.03	1.1	0.0032
21 to < 60	75.3	6.23	1.2	0.0036
Males				
6 to < 11	31.9	5.14	1.1	0.0028
11 to < 16	57.6	5.02	1.1	0.0038
21 to < 60	88.0	8.00	1.2	0.0047

$$ln(C_t - C_{out}) = -A_D t + \ln\,(C_{ss} - C_{out})$$

For each classroom, CO_2 and formaldehyde concentrations over time were estimated considering the classroom occupation (number and age of the pupils), building characteristics (room volume, air infiltration) and building materials with different levels of emissions.

The simulation of both CO_2 and formaldehyde levels over time served to associate the real CO_2 levels measured in the classrooms with a formaldehyde concentration depending on the type of building materials and furniture used in the three scenarios. To estimate CO_2 and HCHO concentrations, the following contaminant mass balance equation based on a single zone fully mixed mass balance model was used [49]:

$$V\frac{dC}{dt} = Q(C_{out} - C) + E$$

where V is the volume of the classroom (m^3), C is the concentration of the contaminant in the room (mg/m^3), C_{out} is the concentration of the contaminant in outdoor air (mg/m^3), Q is the flow rate of outdoor air (m^3/h), and E is the emission rate of indoor sources (mg/h). Note that CO_2 concentration in outdoor air levels was assumed to be 400 ppm whereas for formaldehyde, the average outdoor concentration was assumed to be 5 ppb according to previous studies on long-term measurements of formaldehyde at European monitoring sites [50].

By using the previous, several assumptions were made. This single zone mass balance equation ignores sorption and desorption processes into and from sinks, and also the concentration differences between building zones and the contaminant transportation between zones. Q, C_{out}, and E are generally functions of time, although here they are assumed to be constant. Furthermore, air density differences between indoors and outdoors are neglected and the same value of Q was assigned for the airflow into and out of the room. Considering these assumptions, the analytical solution of the previous equation is:

$$C(t) = C(0)e^{-\frac{Q}{V}t} + C_{ss}\left(1 - e^{-\frac{Q}{V}t}\right)$$

where C(t) is the indoor concentration at t = t, C(0) is the indoor concentration at t = 0 and C_{ss} is the steady-state indoor concentration. Assuming steady-state conditions, in a ventilated space with a uniform contaminant concentration, the ventilation rate and contaminant concentration are related as follows [49]:

$$C_{ss} = C_{out} + \frac{E}{Q}$$

The CO_2 generation rate in each classroom was estimated using the approach proposed by Persily and de Jonge that considers the basal metabolic rate of the individuals of interest combined with their level of physical activity [51]. For these calculations, the pupils were assumed to be 50% females and 50% males with a level of physical activity equal to 1.1 met corresponding to activities performed while sitting such as reading or writing whereas the teacher was assumed to have an age between 21 and 60 and a level of activity of 1.2 met. Based on the generation rates for people in that age range, an average CO_2 generation rate was calculated. The CO_2 generation rate employed in this study are listed in Table 9.

Building materials are the main source of formaldehyde in indoor air. Formaldehyde levels were not directly measured this study. However, to evaluate the potential implications different CO_2 thresholds have on the levels of other indoor pollutants, three exposure scenarios were simulated for each classroom by using building materials and furniture with different levels of emissions, namely high-emitting (HE), low-emitting (LE), and very low-emitting (VLE) building. The materials employed in each scenario are presented in Table 10.

Formaldehyde emission rates of each material were extracted from data obtained in schools with similar air exchange rates 0.03–0.22 h^{-1} [52]. In this study, the emission rates were assumed to be constant over time. The selection of the different configurations was made based on the classification of formaldehyde emission according to the M1 building materials labelling system (the voluntary Finnish emission classification of building materials[5]). This system was chosen because it classifies the materials directly by

[5] https://cer.rts.fi/.

Table 10
Emission rates from building materials and furniture used in the calculation of formaldehyde levels (a Floor and ceiling surface in classrooms 7, 8, 9 and 11 b Floor and ceiling surface in classrooms 0217 and 15).

Materials	Formaldehyde emission rate (μg/m^{2}h)			Surface (m^2)
	VLE Building	LE Building	HE Building	
Ceiling	14	114	252	30[a]/40[b]
Furniture	15	15	15	12
Wooden chairs	15	39	66	7
Floor	5	5	5	30[a]/40[b]

their emission rates instead of the concentration measured in a test chamber after 28 days. According to that system, materials can be classified in three categories: M1, M2 and M3, whose formaldehyde emission thresholds are <50 μg/m^{2}h (M1), <125 μg/m^{2}h (M2) and >125 μg/m^{2}h (M3), respectively. Furniture and flooring were low emitting materials (M1 class) in every scenario whereas the ceiling and wooden chairs emissions increased from one scenario to another, being both M1 class in the LE building and M3 and M2 class, respectively, in the HE building scenario. As the occupancy in the investigated classrooms were similar, the same surface of furniture and chairs was selected for each classroom while the surface of the floor and the ceiling was adjusted according to the dimensions of the classroom. The total HCHO emission rate for each scenario in each classroom was calculated by multiplying these emission rates by the material surface.

3. Results

3.1. Overview of the measured indoor environmental parameters

As opposed to what previous research in classrooms from the same region found [53], in this case, in all classrooms CO_2 was below 1000 ppm for most of the time and below 2000 ppm for over 95% of the time in six out of eight classrooms (all apart from classrooms 7 and 10). For both CO_2 and operative temperature, the maximum values appear to be outliers that are likely to be due to unwanted interactions by the occupants with the measurement device (e.g. breathing intentionally on it). For operative temperature, peak values are particularly elevated especially in classroom 8, and they occurred all in three mornings in February approximately from 8am to 11am. As the air temperature during the same time was considerably lower (around 10–12 °C less), these picks are likely to be due to the usage of some very hot devices in the view field of the globe sensor. Fig. 3 shows CO_2 (above) and operative temperature (below) trends for one week in classroom 8. The time between 18:00 and 7:00 is assumed to be unoccupied and was not considered in any analysis. (periods marked in blue in Fig. 3).

It is also worth noting the reliability of the entire monitoring system. During the three-month period, considering occupied and unoccupied time, measurements are missing in less than 4% of the time for most classrooms. Only in two classrooms (15 and 0217) the percentage is considerably higher being nearly 40%, and this was due to manual interference of the occupants with the devices. During unoccupied time, the system never stopped to work in any classrooms.

3.2. Results according to the international standards

3.2.1. European standard EN16798-1

In all classrooms, the majority of occupied time is in category I (Table 11). However, in three classrooms (7, 8 and 10) this happens

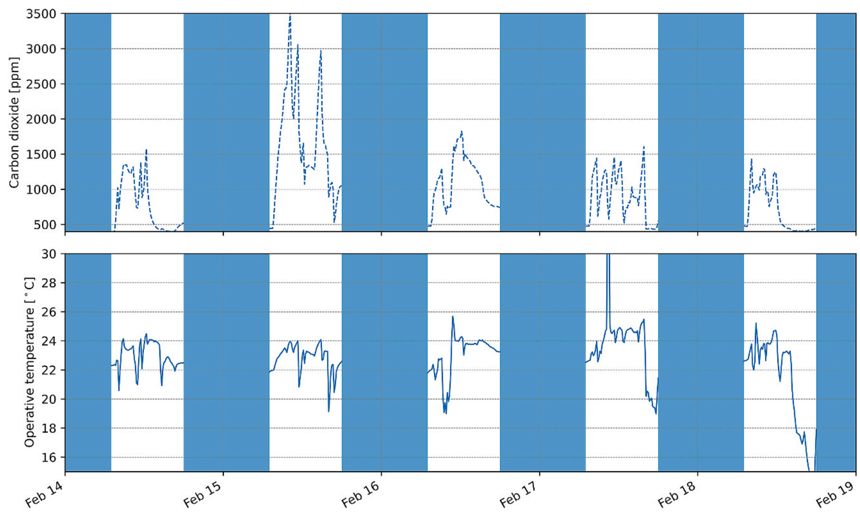

Fig. 3. CO_2 (above) and operative temperature (below) trends for one week in classroom 8. The time between 18:00 and 7:00 is assumed to be unoccupied and was not considered in any analysis.

Table 11
CO_2 EN16798 categories during occupied time (percentage of time in each category).

Parameter	Classroom ID							
	7	8	9	11	15	16	10	0217
EN16798 – Cat I (<950 ppm) [%]	56	56	90	75	81	83	54	71
EN16798 – Cat II (950–1200 ppm) [%]	13	18	6	11	9	7	12	9
EN16798 – Cat III (1200–1750 ppm) [%]	19	19	4	11	9	8	16	15
EN16798 – Cat IV (>1750 ppm) [%]	12	7	0	3	1	2	18	5

just slightly above 50% of the time, and in two of them (7 and 10) the CO_2 concentration exceeded 1750 ppm in over 10% of the time. All other classrooms are at least in category II for over 80% of the time. Thus, no classrooms fully met the EN16798 target (that is category I), but the exceedance distribution varies considerably among the classrooms.

Focusing on thermal comfort, results obtained from the analysis of temperature (Table 12) and PMV (Table 13) are considerably different. Looking at categories based on operative temperature, the results are very good for 7 out of 8 classrooms. In these classrooms, most time is in category I, and the remaining part is mostly in category II. Only classroom 10 has only 49.1% of values in category I, but still most of the others in II (34.2%) and III (11.2%). For all classrooms, there are times in which the operative temperature was below 18 °C.

PMV results (Table 13) seem instead to present a less comfortable situation as the percentage of time in category I is much lower (compared with Table 12). However, the main difference is that category I based on temperature includes whatever was at least equal to 21 °C, while category I based on PMV has an upper limit. A possible means to enable a better comparison is combining together all values that are in category I or above (last line of Table 13), but this would still not match the figures of Table 12 for category I.

The main advantage of PMV based categories is that they enable to evaluate both too cold and too hot situations, while operative temperature categories give information only on the cool-to-cold side of the scale. On the other hand, PMV calculations are affected by the choice of clothing and metabolic rate values which cannot be measured directly in real time during a lecture, and may vary among pupils and school personnel. Combining this with the fact that these PMV-based categories are quite narrow, even small variations in the clothing and metabolic rate values might imply the change from one category to another. Thus, it is worth noting that most values are in category I or II also in a PMV-based analysis.

3.2.2. The UK Building Bulletin 101

The analysis of CO_2 levels according to BB101 limits for naturally ventilated buildings shows that in 6 out of 8 classrooms the daily average during occupied time was always not greater than 1500 ppm (Table 14). Only in two classrooms this target was not met, but for a small number of days (6% and 4%). This means that 6 out 8 classrooms fully met the first criterium set by BB101.

However, only one classroom (number 9) also meets completely the other requirement (Table 15). In other three classrooms (11, 15, 16) CO_2 concentrations exceed 2000 ppm for more than 20 min, but only in a very limited number of occasions. This might be due to special circumstances such as severe rain, external uncommon noises or an examination that caused a delay in opening the windows. Classrooms 7 and 8 are instead those with the most critical situations having several and long periods above 2000 ppm, and the likelihood that this could be due to special events is very low.

The analysis of the temperature (Table 16) shows that the classrooms were thermally comfortable during the monitored period according to BB101. However, two classrooms often suffered from overheating (9 and 0217) while two from being too cold (10 and 16). Likewise the previous PMV categories, the main advantage of having upper and lower limits is that it is possible to have a more sound picture of the thermal situation in both directions.

3.2.3. ASHRAE standards

Using the CO_2 thresholds derived from ASHRAE approach to IAQ design and evaluation, classrooms can be split into three groups (Table 17). Classrooms 9, 15 and 16 have the best values being CO_2 lower than 1000 ppm for over 80% of the time and lower than 1320 ppm for over 90% of the time. The situation is a little worse in classrooms 11 and 0217, while it drops in 7, 8 and 10 (with 40% of more time above 1000 ppm).

ASHRAE uses fewer but wider PMV bands (compared to EN16798) to evaluate thermal comfort, and as a result the percentage of values in the desired central band is higher (Table 18). The most critical classrooms are 16 and 10 which were too cold in 25.5% and 35.0% of the time respectively, and the 9 which was overheated for 17.9% of the monitored period. In the remaining classrooms, the

Table 12
Operative temperature EN16798 categories during occupied time (percentage of time in each category).

Parameter	Classroom ID							
	7	8	9	11	15	16	10	0217
EN16798 - Cat I (>21 °C) [%]	89.4	90.8	98.4	85.2	88.3	71.9	49.1	91.1
EN16798 - Cat II (20–21 °C) [%]	5.9	4.3	1.2	6.3	5.6	14.7	34.2	5.2
EN16798 - Cat III (19–20 °C) [%]	1.7	2.1	0.3	4.3	3.2	5.9	11.2	1.4
EN16798 - Cat IV (18–19 °C) [%]	1.2	0.8	0.1	2.3	1.8	3.7	3.5	1.2
Below 18 °C [%]	1.8	2.0	0.0	1.9	1.1	3.8	2.0	1.1

Table 13
PMV EN16798 categories during occupied time (percentage of time in each category).

Parameter	Classroom ID							
	7	8	9	11	15	16	10	0217
PMV < −1.0 [%]	2.8	2.7	0.1	3.9	2.5	6.2	3.3	2.2
EN16798 - Cat IV (−1.0 < PMV < −0.7) [%]	2.2	2.5	0.8	5.8	4.1	6.9	10.7	1.8
EN16798 - Cat III (−0.7 < PMV < −0.5) [%]	5.9	3.8	1.1	5.4	5.2	12.4	21.0	4.8
EN16798 - Cat II (−0.5 < PMV < −0.2) [%]	21.4	11.5	4.8	16.5	23.4	33.6	43.8	17.2
EN16798 - Cat I (−0.2 < PMV < +0.2) [%]	44.2	45.8	27.3	41.5	54.2	29.0	21.2	30.9
EN16798 - Cat II (0.2 < PMV <0.5) [%]	17.3	28.8	48.1	20.7	9.5	9.8	0.0	31.2
EN16798 - Cat III (0.5 < PMV <0.7) [%]	4.2	2.8	14.0	4.4	1.0	1.9	0.0	10.1
EN16798 - Cat IV (0.7 < PMV <1.0) [%]	1.8	0.6	3.3	1.6	0.0	0.0	0.0	1.7
PMV >1.0 [%]	0.2	1.5	0.6	0.1	0.0	0.0	0.0	0.0
PMV > -0.2 [%]	*67.7*	*79.5*	*93.3*	*68.3*	*64.7*	*40.7*	*21.2*	*73.9*

Table 14
CO_2 BB101 daily average vales: percentage of days in which the average was above the threshold.

Parameter	Classroom ID							
	7	8	9	11	15	16	10	0217
Daily average above 1500 ppm [%]	6	4	0	0	0	0	0	0

Table 15
CO_2 BB101 time intervals above 2000 ppm (number of occurrences).

Duration (time)	Classroom ID							
	7	8	9	11	15	16	10	0217
20 min	10	8	0	4	1	0	3	4
30 min	15	4	0	2	1	0	1	2
40 min	6	5	0	2	0	0	2	2
50 min	10	2	0	0	1	0	1	1
60 min	3	2	0	0	0	1	3	0
70 min	2	0	0	0	0	0	0	0
80 min	3	0	0	0	0	0	1	0
90 min	1	2	0	0	0	0	1	1
100 min	2	0	0	0	0	0	1	0
110 min	1	2	0	0	0	0	2	0

Table 16
BB101 operative temperature distribution during occupied time (percentage of time in each category).

Parameter	Classroom ID							
	7	8	9	11	15	16	10	0217
BB101 – above 25 °C [%]	8.4	5.9	34.8	9.6	2.0	3.3	0.0	17.4
BB101 – 20–25 °C [%]	86.9	89.2	64.8	81.9	91.8	83.3	83.3	78.9
BB101 – below 20 °C [%]	4.7	4.9	0.4	8.6	6.2	13.4	16.7	3.7

Table 17
ASHRAE: CO_2 concentration distribution during occupied time (percentage of time in each category).

Parameter	Classroom ID							
	7	8	9	11	15	16	10	0217
CO_2 < 1000 ppm [%]	59	60	91	78	83	85	58	74
1000 ppm < CO_2 < 1320 ppm [%]	16	22	6	12	10	8	12	10
CO_2 > 1320 ppm [%]	25	18	3	10	7	7	30	16

thermal environment was within comfortable ranges for most of the time, and mainly too cold (PMV < −0.5) in the remain time.

3.3. *Estimated CO_2 and formaldehyde levels in the different emission scenarios*

CO_2 and formaldehyde levels (Fig. 4) were estimated over time based on the occupancy in the classrooms and the different emission scenarios. To illustrate the results, a 60min period was selected as it is the typical duration of a lesson in Italian schools. As shown in

Table 18
ASHRAE: PMV distribution during occupied time (percentage of time in each category).

Parameter	Classroom ID							
	7	8	9	11	15	16	10	0217
PMV < −0.5 [%]	10.9	9.0	2.0	15.1	11.8	25.5	35.0	8.8
−0.5 < PMV < +0.5 [%]	82.9	86.1	80.1	78.7	87.1	72.6	65.0	79.4
PMV >0.5 [%]	6.2	4.9	17.9	6.2	1.1	1.9	0.0	11.8

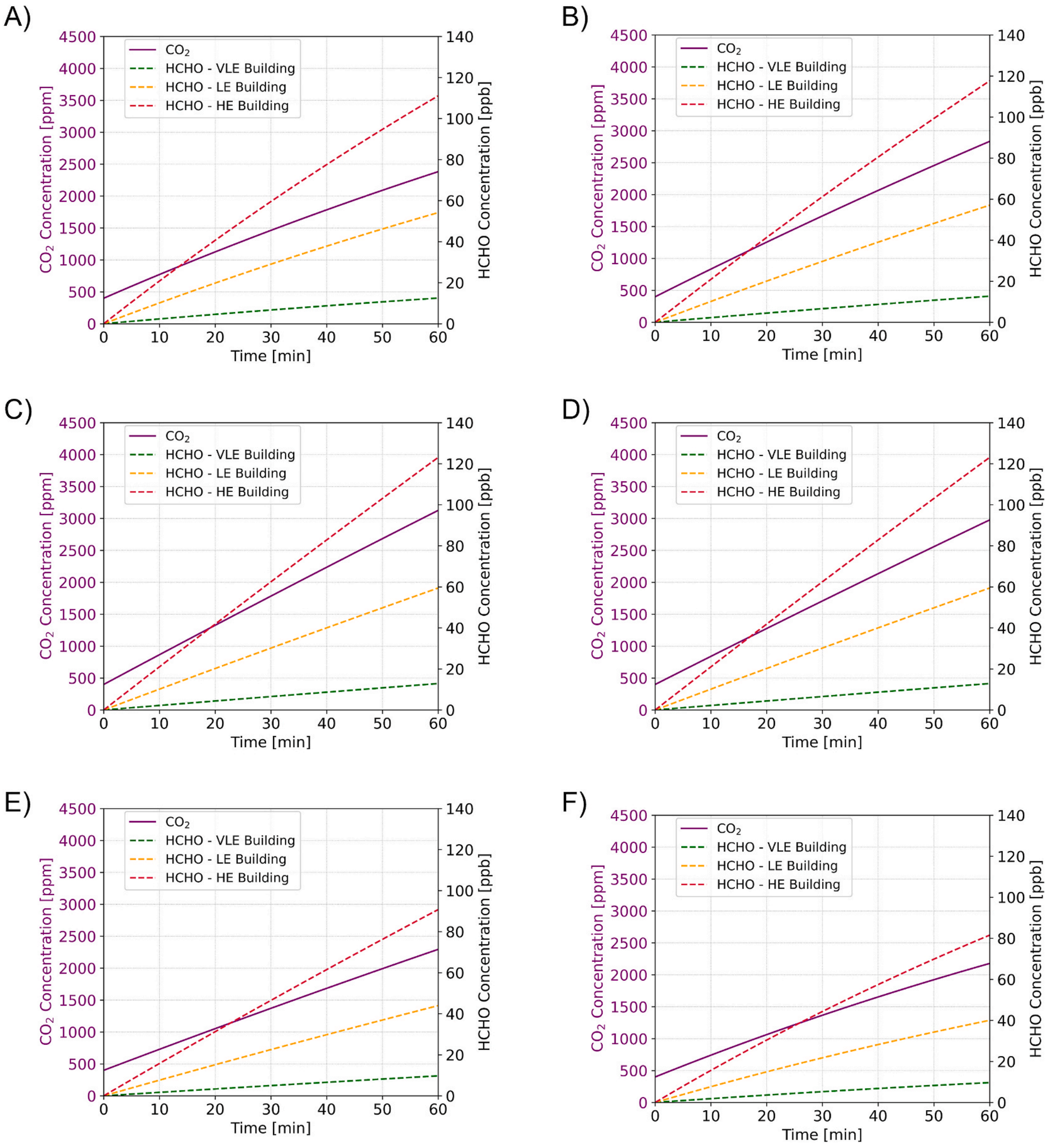

Fig. 4. CO_2 and HCHO concentrations in the different emission scenarios in classrooms 7 (A), 8 (B), 9 (C), 11 (D), 15 (E) and 0217 (F).

Fig. 4, when the classrooms are not ventilated during the whole duration of a lesson, CO_2 levels could exceed 2000 ppm (classrooms 7, 8, 15 and 0217) or even 3000 ppm (classrooms 9 and 11). The CO_2 threshold of 1000 ppm could be reached after 13–18 min without any ventilation whereas 1500 ppm might be exceeded after 23–35 min for all the schools if no ventilation is conducted. The CO_2 concentrations measured in the classrooms were below 1000 ppm for most of the time: >85% in classrooms 9 and 16, >74% and classrooms 0217, 11 and 15 and 58% in classrooms 7, 8 and 10. Comparing these CO_2 concentrations with the ones estimated, it is very likely that doors or windows were often opened 2–4 times per lesson. The CO_2 threshold of 2000 ppm was rarely exceeded (0–2% in classrooms 9, 11, 15, 16 and 0217 and 4–13% in classrooms 7, 8 and 10) indicating that classrooms were ventilated at least once per lesson.

As expected, CO_2 levels increased faster in classrooms 9 and 11 than in other classrooms with similar occupancy since their size was smaller or had more aged pupils which have higher CO_2 generation rates.

Formaldehyde levels estimated according to the different emission scenarios were fairly similar in all the classrooms. However, in a certain classroom, the levels can be completely different depending on the emission level of the building materials and furniture used. In the scenario with high emission materials, formaldehyde concentrations can reach up to more than 110 ppb in most cases (classrooms 7, 8, 9, 11) and up to 80–90 ppb for classrooms 2 and 15. For the low emitting scenario, formaldehyde levels are between 40 and 60 ppb in all schools whereas in the very low emitting scenario, they were always below 20 ppb.

Appendix A lists the estimated formaldehyde concentrations obtained for the CO_2 thresholds proposed in each standard according the three emission scenarios. As can be observed, the values obtained for EN16798 Class I limit (950 ppm) and the old threshold from ASHRAE (1000 ppm) are fairly similar ranging from 2.6 to 3.7 ppb (very low emission), 12.1–16.0 ppb (low emission) and 24.6–32.8 ppb (high emission). For EN16798 Class II limit (1200 ppm), formaldehyde concentrations are slightly higher varying from 3.7 to 5.0, 17.2–21.7 ppb and 35.6–44.5 ppb for very low, low and high emission scenarios, respectively, and similar to the second CO_2 threshold from ASHRAE (1320 ppm) where the formaldehyde levels range from 4.6 to 5.9 ppb in the very low emission scenario, 20.2–25.4 ppb in the low emission scenario and 41.4–52.1 ppb in the high emission scenario. At the threshold of 1500 ppm set in the BB101 standard for naturally ventilated classrooms, the formaldehyde concentrations slightly increase varying from 5.3 to 6.9 ppb, 24.2–29.9 ppb and 50.1–61.4 ppb for very low, low and high emission scenarios, respectively. Significantly higher values are observed at a CO_2 threshold of 1750 ppm (EN 16798 Cat III) and 2000 ppm (BB101) where the formaldehyde concentrations ranged from 7.6 to 10.1 ppb (very low emission), 35.1–43.7 ppb (low emission) and 72.6–89.7 ppb (high emission).

4. Discussion

Different standards prescribe different limits and methods for thermal comfort and IAQ evaluation, and therefore the analysis provided comparable but not identical results. Thus, the aim of this section is to address three main aspects, namely (i) a critical comparison among thermal comfort evaluation approaches, (ii) comparison of indoor air quality approaches and their impact on occupant's exposure, and (iii) a combined thermal comfort and IAQ analysis for real-time decision-making.

4.1. Comparison among thermal comfort evaluation approaches

This study focuses on the approaches that are commonly used to design and later evaluate thermal comfort in school buildings at room level. The thermal environment is evaluated either by using the operative temperature or the PMV/PPD as in almost all previous field studies [8]. The former explicitly considers air and mean radiant temperatures, and indirectly also the air speed since the calculation varies according to the air speed (with the radiant part becoming less relevant as the air speed increases). The latter calculation instead also includes the relative humidity, clothing insulation and metabolic rate as inputs. It potentially is a more accurate comfort metric since it gives the most likely thermal sensation, but the use of too narrow bands might become a limiting factor. Even minor variations in the clothing or metabolic rate values might lead to a shift from one band to another (e.g. PMV from 0.15 to 0.25), and this is even more critical in schools for two reasons. Firstly, the PMV algorithm was originally developed for adults [30] and none of the standards considered in this study includes any means to adapt this to pupils, although previous studies have highlighted the importance to adjust the metabolic rate using correction factors such as students' body surface area [34,54,55]. Moreover, due to a lack of research, it is unclear the applicability of adults' clo values to pupils. Secondly, even assuming that adults' values are applicable to younger people, depending on the type of activity (e.g. examination vs normal lecture) the metabolic rate is likely to slightly varies (e.g. 1.2 vs 1.0) and this might cause the change of band. In general, the limits of the PMV method to predict students' thermal sensation found in this study further support previous research. When comparing PMV with the actual thermal sensation, previous comparable studies reported under estimation in primary classrooms [55,56] while over estimation was mainly reported in secondary and high schools [57,58] and a better compatibility was only observed in universities [59,60].

Considering the two metrics, this study therefore suggests that the application of the PMV/PPD method should be carefully considered. In absence of evidence-based modifications to adapt the calculation to pupils, the use of very narrow categories (e.g. in EN16798) looks a forcing. Wider bands (e.g. in ASHRAE 55) partially limit this issue.

Operative temperature thresholds are also not specially developed for pupils. ASHRAE 55 and BB101 do not provide specific limits according to the students' age, although there can be large differences in neutral temperatures between the different educational stages [8,15] and EN16798 does not even differentiate between children and elderly. Furthermore, using acceptability bands could be confusing. In particular, EN 16987 recommends $T_{operative} > 21$ °C, and BB 101 recommends 20 °C $> T_{operative} > 25$ °C, even if literature reports lower thermal neutral temperatures for younger students (e.g. even less then 18 °C in some European primary schools studies [15]). However, EN 16987 at least uses wider acceptability bands, and this partially limit the overestimate of the thermal discomfort. In this case, especially in the EN16798, the main limits are the lack of an upper threshold (Table 4), and the fact that there is a very considerable difference in distribution of measured values in the categories depending on whether this is done using the operative temperature or the PMV/PPD.

Operative temperature thresholds are also easier to verify in real buildings. In many cases, research showed that the different between mean radiant and air temperature is negligible [61–63]. In the others, periodic short-term more accurate monitoring can enable the calculation of the MRT from the air temperature, and hence of a more accurate operative temperature. In both cases, a long-term (ideally permanent) measurement would eventually be sufficient to estimate the operative temperature and thus the comfort level. Thus, upper- and lower-bounded operative temperature scales seem to be the most appropriate means to design and verify (in the actual classroom) thermal comfort in classrooms. Very narrow limits should be carefully evaluated.

4.2. Comparison of indoor air quality approaches and their impact on occupant's exposure

Indoor air quality in school buildings is commonly assessed through a variety of methods. The goal of this study is to compare the different methods used for building design and evaluation of IAQ and their impact on the occupant's exposure to indoor pollutants. Current norms and guidelines for the ventilation of schools differ among countries and regions [14]. However, IAQ is often designed and evaluated by defining minimum ventilation rates for a specific room or CO_2 concentration thresholds. Minimum ventilation rates are typically defined per person and/or per-unit floor area based on the space type or application (educational, residential, etc.), number of occupants and their characteristics (age, adapted/non-adapted) [64]. The former is meant to dilute human bio effluents while the latter aims at diluting emissions from building materials. These emissions are variable depending on the material, thus ventilation rates per-unit floor area need to be adapted according to the emissions of the building materials used, which are often unknown. In some cases, buildings are categorized according different level of emissions (very low, low and non low-polluting buildings) and ventilation rates per square meter are defined based on these categories (e.g. EN16718 – Method 1) but sometimes

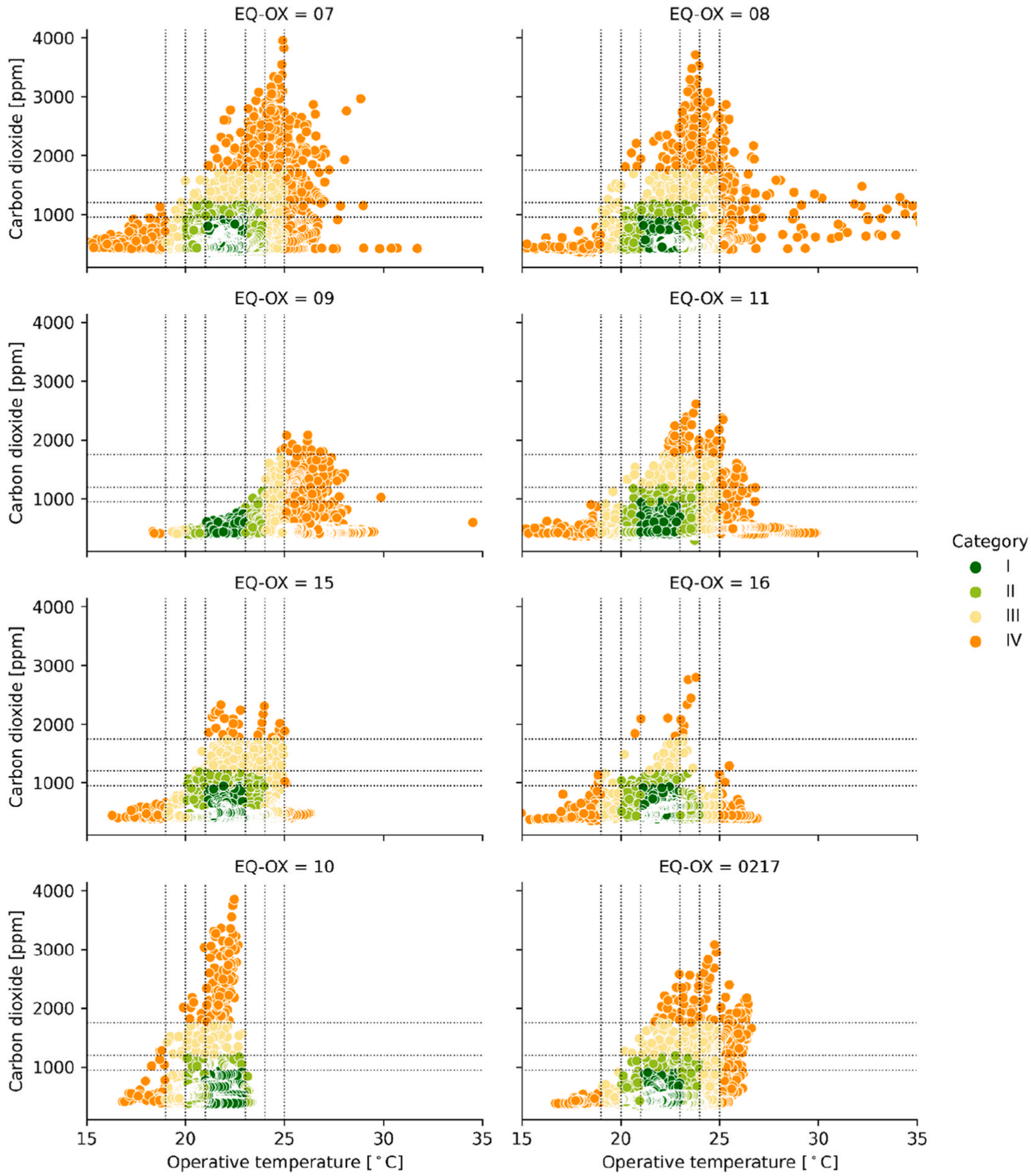

Fig. 5. Combined CO_2 and operative temperature categories. The dotted lines represent the category limits for operative temperature (vertical lines) and CO_2 (horizontal lines). EQ-OX is the monitoring device that was installed in each classroom (e.g. EQ-OX 10 was installed in classroom 10).

only a single value is provided depending on the space type and occupants (e.g. ASHRAE 62.1 – Ventilation rate procedure), being higher for building with vulnerable occupants such as a day-care, or where activities conducted might result in additional emissions such as an art classroom. More detailed calculations to dilute an individual substance are also used (e.g. EN16718 – Method 2, ASHRAE 62.1 – IAQ procedure). Nevertheless, this requires knowing the emission rates from all the building materials, which could be likely in the case of new buildings whereas it might be not possible in existing buildings. Using ventilation rates may be convenient during building design, but its verification during building operation requires measurement techniques that are intrusive and imply the use of specific equipment by qualified professionals.

Alternatively, CO_2 thresholds remain the primary indicator for IAQ in buildings, even if other pollutants or respiratory airborne transmission contaminants pose higher risks to the occupants [14]. These thresholds are calculated based on similar design ventilation rates based using the mass balance equation (e.g. EN16718, BB101). Surprisingly, the ventilation rates equivalent to these thresholds seem only to consider emissions from occupants and no additional CO_2 thresholds are given based on building materials emissions. CO_2 thresholds are expressed in different ways and the maximum concentration might vary by different standards, however, the upper threshold is always about 1000 ppm. In some cases, categories are defined based on the percentage of time that CO_2 concentration exceeds a certain level (e.g. EN16718) while in some others, the requirements are expressed as daily average concentration (e.g. BB101), both during the occupied periods. Both thresholds differ 500 ppm in the case of naturally ventilated schools which could result in significantly higher exposures in case of high emission scenarios. Also, a maximum CO_2 concentration not to exceed for more than 20 consecutive minutes is defined. This metric might prevent the build-up of indoor pollutants, even in case of high emission scenarios (Fig. 4), limiting pupils exposure and facilitating the compliance with the guideline value set by the World Health Organisation (WHO) for formaldehyde indoors (100 μg/m^3 (≈80 ppb) for 30 min).

Although minimum ventilation rates that consider occupant-related and building materials emissions are probably the most appropriate method to consider IAQ during building design, the recent emergence of CO_2 low-cost sensors [65] make the use of CO_2 thresholds a most practical approach to verify IAQ in classrooms during operation. However, their use requires to carefully consider several parameters such as the classroom geometry, outdoor ventilation rate and number of occupants and their characteristics and ideally, to have a general idea on the materials emissions.

4.3. Combined thermal comfort and IAQ analysis for real-time decision-making

Anecdotal evidence suggests that school personnel balances the need for acceptable IAQ and thermal comfort, and acts accordingly. In the last two school years (2020-21 and 2021–22) IAQ often was prioritized to minimize the risk of SARS-CoV-2. In certain cases, the use of higher ventilation rates led to an increase in energy consumption but with a limited impact on thermal comfort [64]. In other cases, when this was not possible for reasons such as a limited heating power available, either a lower temperature or a higher risk of infection was accepted. Fabric-related air contaminants' sources can be removed in new construction and during renovation projects, but this is clearly not possible for occupant-driven contaminants (either generated or brought inside by people). Thus, balancing IAQ and thermal comfort will be essential also beyond SARS-CoV-2 pandemic. The main issue is that school personnel typically is not IAQ and hygro-thermal experts, and hence is likely to struggle in presence of separate (IAQ vs thermal comfort) or inconsistent (operative temperature vs PMV evaluation) indications.

Since thermal comfort and IAQ are both mutually affected by the way in which heating, cooling and ventilation (mechanical, natural or mixed-mode) systems are operated, the use of visual means to combine both IEQ components might be effective in guiding school personnel. Moreover, evidence shows that CO_2 concentration can influence occupants' thermal sensation [39] and that the thermal environment can influence air quality perception [40].

A possible combination of IAQ and thermal comfort levels is presented in Fig. 5. For thermal comfort, operative temperature was chosen over PMV as is easier to understand and to be measured in real buildings. In many cases, it can be approximated with the air temperature (thus, directly measurable at limited costs), and, for more accuracy, periodic checks with the support of experts can be performed. Upper and lower limits were defined according to Table 5 instead of Table 4 since the latter does not set upper thresholds which are important to avoid overheating problems in classrooms. All points beyond Category III boundaries were classified as Category IV. For IAQ, CO_2 was selected as it is widely used as indicator for occupancy-related air contaminants, and also for its ease to be measured compared with other contaminants. In the current graphs, CO_2 thresholds were defined according to Table 8. In Fig. 5, points are in Category I if both IAQ and thermal comfort are in this category (dark green). Otherwise, a certain point falls into the lower category according to either IAQ or thermal comfort.

The main advantage of this approach is that it enables school personnel to make informed trade-off decisions. Depending on the context, either IAQ or thermal comfort might be maximised (so targeting Category I), but the combined analysis shows the extent to which the other gets worse and which implications this has on health and comfort. For instance, using the data collected in Bolzano, the combined analysis highlights immediately how only a minor part of points with IAQ in Category II or worse (threshold is 950 ppm) have also a low temperature, being only a few below 20 °C and very few below 19 °C. This means that, in these classrooms, IAQ might have been improved by ventilating more without any additional energy consumption as temperature could have been decreased (due to the higher ventilation rates) without reducing thermal comfort, and perhaps even improving it when the classroom was overheated.

In Fig. 5, the thresholds (i.e. the vertical and horizontal dotted lines) were defined according to the EN16798 Annex B values. However, this approach could be applied in different geographical regions by adapting the boundaries of each category with evidence-based robust thresholds defined for that specific area. Likewise, categories' thresholds might also need to be adapted over time as preferences (e.g. thermal preferences) or needs might be different in the future, but this would not modify the overall approach (i.e. doing a combined evaluation of IAQ and thermal comfort).

5. Conclusions

The aim of study was to compare different available standards to evaluate IAQ and thermal comfort in school buildings, to evaluate the consequences of different limits and approaches, and to propose possible improvements. The main conclusions are as follows.

- Thresholds and methods inconsistency within the same standard should be avoided to minimize confusion. EN16798-1 includes both operative temperature and PMV thresholds leading to different thermal comfort results, and different operative temperature limits for different purposes. Moreover, four IEQ categories are defined, but the given thresholds imply the existence of a fifth band in certain cases.
- For thermal comfort, upper- and lower-bounded operative temperature scales seem to be the most appropriate means to design and verify thermal comfort in classrooms. If PMV is used for thermal comfort assessment, the use of too narrow bands might make the calculation too dependent on assumptions such as clo, met and MRT, and thus lead to overestimate discomfort. Moreover, no means to adapt PMV calculation to children is included in any standards.
- For IAQ, having metrics that give an upper limit per a certain amount of consecutive time (e.g. 2000 ppm of CO_2 for no longer than 20 min – BB101) might prevent the build-up of indoor pollutants, even in case of high emission from the building fabric, limiting pupils exposure and facilitating the compliance with the WHO guideline values.
- No standard proposes a combined IAQ and thermal comfort analysis. The main advantage of this approach would be to enable to take more informed trade-off decisions considering IAQ, thermal comfort, but also energy targets.

5.1. Limitations

This study focused on the evaluation of the indications provided by the different standards, and on the consequences of different limits and approaches. None of the considered standards currently explicitly suggest or impose the use of building simulation methods (e.g. dynamic thermal modelling coupled with air flow modelling for evaluating long-term average room performances, computational fluid dynamics for finer spatial resolution, etc.), and therefore simulations were not included in this study. However, research is needed to provide guidelines for the use of simulations both in the design phase and potentially in the operational phase.

Moreover, this study did not aim at providing an overview of current levels of IAQ and thermal comfort in schools. Data from four schools was used only to exemplify the consequences of using different methods and means to treat exceedance. Data enables to make considerations on the current situation in those four schools, but not to draw any broader conclusions on current levels of IAQ and thermal comfort in schools in general for which a larger sample of cases studies would have been required.

Author statement

•**Francesco Babich:** Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Project administration; Resources; Supervision; Visualization; Roles/Writing - original draft; Writing - review & editing.

•**Giulia Torriani:** Conceptualization; Writing - review & editing.

•**Jacopo Corona:** Data curation; Resources;

•**Irene Lara Ibeas:** Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Resources; Visualization; Roles/Writing - original draft; Writing - review & editing.

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

Data will be made available on request.

Acknowledgements

The authors thank the Department of Innovation, Research and University of the Autonomous Province of Bozen/Bolzano for covering the Open Access publication costs.

Appendix A

Table 19
Estimated HCHO levels in each classroom obtained for the CO_2 thresholds set in EN16798

CO_2 Threshold	Building Emissions	Estimated HCHO concentration in each classroom [ppb]					
		07	08	09	11	15	0217
EN16798 - Cat I (950 ppm)	Very Low	3.5	2.9	2.6	2.9	2.9	2.9
	Low	15.1	13.2	12.2	13.2	12.9	12.1
	High	30.9	27.1	25.2	27.3	26.7	24.6
EN16798 - Cat II (1200 ppm)	Very Low	5.0	4.3	3.7	4.0	4.2	4.3
	Low	21.7	19.1	17.2	18.2	8.9	17.7
	High	44.5	39.3	35.6	37.7	38.9	36.1
EN16798 - Cat III (1750 ppm)	Very Low	8.5	7.0	6.3	6.8	6.9	7.4
	Low	37.0	31.6	29.2	31.2	31.2	30.7
	High	75.8	65.1	60.4	64.5	64.5	62.5

Table 20
Estimated HCHO levels in each classroom obtained for the CO_2 thresholds set in BB101 for naturally ventilated classrooms

CO_2 Threshold	Building Emissions	Estimated HCHO concentration in each classroom [ppb]					
		07	08	09	11	15	0217
BB101 (1500 ppm)	Very Low	6.9	5.8	5.3	5.5	5.6	6.1
	Low	29.9	25.9	24.2	25.2	25.5	25.0
	High	61.4	53.3	50.1	52.2	52.6	51.0
BB101 (2000 ppm)	Very Low	10.1	8.3	7.6	8.0	8.2	8.7
	Low	43.7	37.2	35.1	37.1	36.9	36.1
	High	89.7	76.7	72.6	76.8	76.3	73.4

Table 21
Estimated HCHO levels in each classroom obtained for the CO_2 thresholds according to ASHRAE 62.1

CO_2 Threshold	Building Emissions	Estimated HCHO concentration in each classroom [ppb]					
		07	08	09	11	15	0217
ASHRAE (1000 ppm)	Very Low	3.7	3.2	2.9	3.1	3.0	3.3
	Low	16.0	14.1	13.2	14.2	13.7	13.5
	High	32.8	29.2	27.3	29.4	28.2	27.5
ASHRAE (1320 ppm)	Very Low	5.9	4.9	4.4	4.6	4.7	4.9
	Low	25.4	22.0	20.2	21.2	21.1	20.4
	High	52.1	45.3	41.9	43.9	43.5	41.6

References

[1] P. Wargocki, J.A. Porras-Salazar, S. Contreras-Espinoza, W. Bahnfleth, The relationships between classroom air quality and children's performance in school, Build. Environ. 173 (2020), 106749, https://doi.org/10.1016/j.buildenv.2020.106749.

[2] D.L. Johnson, R.A. Lynch, E.L. Floyd, J. Wang, J.N. Bartels, Indoor air quality in classrooms: environmental measures and effective ventilation rate modeling in urban elementary schools, Build. Environ. 136 (2018) 185–197, https://doi.org/10.1016/j.buildenv.2018.03.040.

[3] J. Madureira, I. Paciência, C. Pereira, J.P. Teixeira, E. de O. Fernandes, Indoor air quality in Portuguese schools: levels and sources of pollutants, Indoor Air 26 (2016) 526–537, https://doi.org/10.1111/ina.12237.

[4] S. Gaihre, S. Semple, J. Miller, S. Fielding, S. Turner, Classroom carbon dioxide concentration, school attendance, and educational attainment, J. Sch. Health 84 (2014) 569–574, https://doi.org/10.1111/josh.12183.

[5] I. Annesi-Maesano, N. Baiz, S. Banerjee, P. Rudnai, S. Rive, Indoor air quality and sources in schools and related health effects, J. Toxicol. Environ. Health Part B Crit. Rev. 16 (2013) 491–550, https://doi.org/10.1080/10937404.2013.853609.

[6] M.J. Mendell, E.A. Eliseeva, M.M. Davies, M. Spears, A. Lobscheid, W.J. Fisk, M.G. Apte, Association of classroom ventilation with reduced illness absence: a prospective study in California elementary schools, Indoor Air 23 (2013) 515–528, https://doi.org/10.1111/ina.12042.

[7] P.N. Pegas, C.A. Alves, M.G. Evtyugina, T. Nunes, M. Cerqueira, M. Franchi, C.A. Pio, S.M. Almeida, M.C. Freitas, Indoor air quality in elementary schools of Lisbon in spring, Environ. Geochem. Health 33 (2011) 455–468, https://doi.org/10.1007/s10653-010-9345-3.

[8] Z.S. Zomorodian, M. Tahsildoost, M. Hafezi, Thermal comfort in educational buildings: a review article, Renew. Sustain. Energy Rev. 59 (2016) 895–906, https://doi.org/10.1016/j.rser.2016.01.033.

[9] J. Zhang, Integrating IAQ control strategies to reduce the risk of asymptomatic SARS CoV-2 infections in classrooms and open plan offices, Sci. Technol. Built Environ. 26 (2020) 1013–1018, https://doi.org/10.1080/23744731.2020.1794499.

[10] R.A. Parinduri, Do children spend too much time in schools? Evidence from a longer school year in Indonesia, Econ. Educ. Rev. 41 (2014) 89–104, https://doi.org/10.1016/j.econedurev.2014.05.001.

[11] M.J. Mendell, G.A. Heath, Do indoor pollutants and thermal conditions in schools influence student performance? A critical review of the literature, Indoor Air 15 (2005) 27–52, https://doi.org/10.1111/j.1600-0668.2004.00320.x.

[12] R.S. McLeod, M. Mathew, D. Salman, C.L.P. Thomas, An investigation of indoor air quality in a recently refurbished educational building, Front. Built Environ. 7 (2022) 156, https://doi.org/10.3389/fbuil.2021.769761.

[13] M.C. Katafygiotou, D.K. Serghides, Indoor comfort and energy performance of buildings in relation to occupants' satisfaction: investigation in secondary schools of Cyprus, Adv. Build. Energy Res. 8 (2014) 216–240, https://doi.org/10.1080/17512549.2013.865554.

[14] S. Sadrizadeh, R. Yao, F. Yuan, H. Awbi, W. Bahnfleth, Y. Bi, G. Cao, C. Croitoru, R. de Dear, F. Haghighat, P. Kumar, M. Malayeri, F. Nasiri, M. Ruud, P. Sadeghian, P. Wargocki, J. Xiong, W. Yu, B. Li, Indoor air quality and health in schools: a critical review for developing the roadmap for the future school environment, J. Build. Eng. 57 (2022), 104908, https://doi.org/10.1016/j.jobe.2022.104908.

[15] M.K. Singh, R. Ooka, H.B. Rijal, S. Kumar, A. Kumar, S. Mahapatra, Progress in thermal comfort studies in classrooms over last 50 years and way forward, Energy Build. 188–189 (2019) 149–174, https://doi.org/10.1016/j.enbuild.2019.01.051.

[16] P. Wargocki, D.P. Wyon, The effects of moderately raised classroom temperatures and classroom ventilation rate on the performance of schoolwork by children (RP-1257), HVAC R Res. 13 (2007) 193–220, https://doi.org/10.1080/10789669.2007.10390951.

[17] H.W. Brink, M.G.L.C. Loomans, M.P. Mobach, H.S.M. Kort, Classrooms' indoor environmental conditions affecting the academic achievement of students and teachers in higher education: a systematic literature review, Indoor Air 31 (2021) 405–425, https://doi.org/10.1111/ina.12745.

[18] D. Twardella, W. Matzen, T. Lahrz, R. Burghardt, H. Spegel, L. Hendrowarsito, A.C. Frenzel, H. Fromme, Effect of classroom air quality on students' concentration: results of a cluster-randomized cross-over experimental study, Indoor Air 22 (2012) 378–387, https://doi.org/10.1111/j.1600-0668.2012.00774.x.

[19] N. Bernardi, D.C.C.K. Kowaltowski, Environmental comfort in school buildings, Environ. Behav. 38 (2006) 155–172, https://doi.org/10.1177/0013916505275307.

[20] G. Torriani, G. Lamberti, F. Fantozzi, F. Babich, Exploring the impact of perceived control on thermal comfort and indoor air quality perception in schools, J. Build. Eng. 63 (2023), 105419, https://doi.org/10.1016/J.JOBE.2022.105419.

[21] R. de Dear, J. Xiong, J. Kim, B. Cao, A review of adaptive thermal comfort research since 1998, Energy Build. 214 (2020), 109893, https://doi.org/10.1016/j.enbuild.2020.109893.

[22] L. Stabile, A. Pacitto, A. Mikszewski, L. Morawska, G. Buonanno, Ventilation procedures to minimize the airborne transmission of viruses in classrooms, Build. Environ. 202 (2021), 108042, https://doi.org/10.1016/j.buildenv.2021.108042.

[23] M. Shrestha, H.B. Rijal, G. Kayo, M. Shukuya, An investigation on CO2 concentration based on field survey and simulation in naturally ventilated Nepalese school buildings during summer, Build. Environ. 207 (2022), 108405, https://doi.org/10.1016/J.BUILDENV.2021.108405.

[24] CEN, EN 16798-1, Energy Performance of Buildings - Ventilation for Buildings - Part 1: Indoor Environmental Input Parameters for Design and Assessment of Energy Performance of Buildings Addressing Indoor Air Quality, Thermal Environment, Lighting and Acoustic, 2019. Bruxelles, Belgium.

[25] R. Daniels, BB 101: Ventilation, Thermal Comfort and Indoor Air Quality, 2018.

[26] ASHRAE, Standard 55 - Thermal Environmental Conditions for Human Occupancy, 2017. Atlanta, GA, USA.

[27] ASHRAE, Standard 62.1 - Ventilation for Acceptable Indoor Air Quality, 2016. Atlanta, GA, USA.

[28] R. de Dear, G. Brager, Developing an adaptive model of thermal comfort and preference, Build. Eng. (1998) 145–167. https://escholarship.org/uc/item/4qq2p9c6. (Accessed 25 August 2022).

[29] J.F. Nicol, M.A. Humphreys, Adaptive thermal comfort and sustainable thermal standards for buildings, in: Energy Build, Elsevier, 2002, pp. 563–572, https://doi.org/10.1016/S0378-7788(02)00006-3.

[30] P.O. Fanger, Thermal Comfort. Analysis and Applications in Environmental Engineering, 1970.

[31] D. Teli, M.F. Jentsch, P.A.B. James, Naturally ventilated classrooms: an assessment of existing comfort models for predicting the thermal sensation and preference of primary school children, Energy Build. 53 (2012) 166–182, https://doi.org/10.1016/j.enbuild.2012.06.022.

[32] N.H. Wong, S.S. Khoo, Thermal comfort in classrooms in the tropics, Energy Build. 35 (2003) 337–351, https://doi.org/10.1016/S0378-7788(02)00109-3.

[33] J. Kim, R. de Dear, Thermal comfort expectations and adaptive behavioural characteristics of primary and secondary school students, Build. Environ. 127 (2018) 13–22, https://doi.org/10.1016/j.buildenv.2017.10.031.

[34] R.M.S.F. Almeida, N.M.M. Ramos, V.P. De Freitas, Thermal comfort models and pupils' perception in free-running school buildings of a mild climate country, Energy Build. 111 (2016) 64–75, https://doi.org/10.1016/j.enbuild.2015.09.066.

[35] M. te Kulve, R.T. Hellwig, F. van Dijken, A. Boerstra, Do Children Feel Warmer than Adults? Overheating Prevention in Schools in the Face of Climate Change, Routledge, 2022, https://doi.org/10.4324/9781003244929-11.

[36] S. ter Mors, J.L.M. Hensen, M.G.L.C. Loomans, A.C. Boerstra, Adaptive thermal comfort in primary school classrooms: creating and validating PMV-based comfort charts, Build, Environ. Times 46 (2011) 2454–2461, https://doi.org/10.1016/J.BUILDENV.2011.05.025.

[37] L. Dias Pereira, D. Raimondo, S.P. Corgnati, M. Gameiro da Silva, Assessment of indoor air quality and thermal comfort in Portuguese secondary classrooms: Methodology and results, Build. Environ. 81 (2014) 69–80, https://doi.org/10.1016/J.BUILDENV.2014.06.008.

[38] S. Torresin, G. Pernigotto, F. Cappelletti, A. Gasparella, Combined effects of environmental factors on human perception and objective performance: a review of experimental laboratory works, Indoor Air 28 (2018) 525–538, https://doi.org/10.1111/ina.12457.

[39] H. Shin, M. Kang, S.H. Mun, Y. Kwak, J.H. Huh, A study on changes in occupants' thermal sensation owing to CO_2 concentration using PMV and TSV, Build. Environ. 187 (2021), 107413, https://doi.org/10.1016/j.buildenv.2020.107413.

[40] L. Lan, P. Wargocki, D.P. Wyon, Z. Lian, Effects of thermal discomfort in an office on perceived air quality, SBS symptoms, physiological responses, and human performance, Indoor Air 21 (2011) 376–390, https://doi.org/10.1111/j.1600-0668.2011.00714.x.

[41] CEN, EN 15251, Indoor Environmental Input Parameters for Design and Assessment of Energy Performance of Buildings Addressing Indoor Air Quality, Thermal Environment, lighting and acoustics, 2007.

[42] CEN, EN ISO 7730, Ergonomics of the Thermal Environment — Analytical Determination and Interpretation of Thermal Comfort Using Calculation of the PMV and PPD Indices and Local Thermal Comfort Criteria, 2005.

[43] A.K. Persily, C. Mandin, W. Bahnfleth, C. Sekhar, H. Kipen, P. Wargocki, J. Lau, L.C.N. Weekes, ASHRAE Position Document on Indoor Carbon Dioxide, 2022. Atlanta, GA, USA.

[44] M. Raitzsch, J. Bijma, T. Bickert, M. Schulz, A. Holbourn, M. Kučera, Atmospheric carbon dioxide variations across the middle Miocene climate transition, Clim. Past 17 (2021) 703–719, https://doi.org/10.5194/cp-17-703-2021.

[45] ASHRAE, Handbook of Fundamentals, 2021. Atlanta, GA, USA.

[46] CEN, EN ISO 7726, Ergonomics of the Thermal Environment - Instruments for Measuring Physical Quantities, 2001.

[47] R.M. Baloch, C.N. Maesano, J. Christoffersen, S. Banerjee, M. Gabriel, É. Csobod, E. de Oliveira Fernandes, I. Annesi-Maesano, P. Szuppinger, R. Prokai, P. Farkas, C. Fuzi, E. Cani, J. Draganic, E.R. Mogyorosy, Z. Korac, G. Ventura, J. Madureira, I. Paciência, A. Martins, R. Pereira, E. Ramos, P. Rudnai, A. Páldy, G. Dura, T. Beregszászi, É. Vaskövi, D. Magyar, T. Pándics, Z. Remény-Nagy, R. Szentmihályi, O. Udvardy, M.J. Varró, S. Kephalopoulos, D. Kotzias, J. Barrero-Moreno, R. Mehmeti, A. Vilic, D. Maestro, H. Moshammer, G. Strasser, P. Brigitte, P. Hohenblum, E. Goelen, M. Stranger, M. Spruy, M. Sidjimov, A. Hadjipanayis, A. Katsonouri-Sazeides, E. Demetriou, R. Kubinova, H. Kazmarová, B. Dlouha, B. Kotlík, H. Vabar, J. Ruut, M. Metus, K. Rand, A. Järviste, A. Nevalainen, A. Hyvarinen, M. Täubel, K. Järvi, C. Mandin, B. Berthineau, H.J. Moriske, M. Giacomini, A. Neumann, J. Bartzis, K. Kalimeri, D. Saraga, M. Santamouris, M.N. Assimakopoulos, V. Asimakopoulos, P. Carrer, A. Cattaneo, S. Pulvirenti, F. Vercelli, F. Strangi, E. Omeri, S. Piazza, A. D'Alcamo, A. C. Fanetti, P. Sestini, M. Kouri, G. Viegi, S. Baldacci, S. Maio, V. Franzitta, S. Bucchieri, F. Cibella, M. Neri, D. Martuzevičius, E. Krugly, S. Montefort, P. Fsadni, P.Z. Brewczyński, E. Krakowiak, J. Kurek, E. Kubarek, A. Wlazło, C. Borrego, C. Alves, J. Valente, E. Gurzau, C. Rosu, G. Popita, I. Neamtiu, C. Neagu, D. Norback, P. Bluyssen, M. Bohms, P. Van Den Hazel, F. Cassee, Y.B. de Bruin, A. Bartonova, A. Yang, K. Halzlová, M. Jajcaj, M. Kániková, O. Miklankova, M. Vítkivá, M. Jovsevic-Stojanovic, M. Zivkovic, Z. Stevanovic, I. Lazovic, Z. Stevanovic, Z. Zivkovic, S. Cerovic, J. Jocic-Stojanovic, D. Mumovic, P. Tarttelin, L. Chatzidiakou, E. Chatzidiakou, M.C. Dewolf, Indoor air pollution, physical and comfort parameters related to schoolchildren's health: data from the European SINPHONIE study, Sci. Total Environ. 739 (2020), 139870, https://doi.org/10.1016/j.scitotenv.2020.139870.

[48] S. Batterman, Review and extension of CO2-based methods to determine ventilation rates with application to school classrooms, Int. J. Environ. Res. Publ. Health 14 (2017), https://doi.org/10.3390/ijerph14020145.

[49] A. Persily, B.J. Polidoro, Residential application of an indoor carbon dioxide metric, in: 40th AIVC - 8th TightVent - 6th Vent, Conf. - Ghent, Belgium, 2019, pp. 1–13.
[50] S. Solberg, C. Dye, S.E. Walker, D. Simpson, Long-term measurements and model calculations of formaldehyde at rural European monitoring sites, Atmos. Environ. 35 (2001) 195–207, https://doi.org/10.1016/S1352-2310(00)00256-9.
[51] A. Persily, L. de Jonge, Carbon dioxide generation rates for building occupants, Indoor Air 27 (2017) 868–879, https://doi.org/10.1111/ina.12383.
[52] G. Poulhet, S. Dusanter, S. Crunaire, N. Locoge, V. Gaudion, C. Merlen, P. Kaluzny, P. Coddeville, Investigation of formaldehyde sources in French schools using a passive flux sampler, Build. Environ. 71 (2014) 111–120, https://doi.org/10.1016/j.buildenv.2013.10.002.
[53] F. Babich, A. Belleri, I. Demanega, C. Peretti, L. Verdi, G. Fulici, The Indoor Environmental Quality in Schools in South Tyrol: Insights from the Field Measurements, and Initial Design of the Improvements, ASHRAE Top. Conf. Proc., Atlanta, GA, USA, 2021.
[54] G. Havenith, Metabolic rate and clothing insulation data of children and adolescents during various school activities, Ergonomics 50 (2007) 1689–1701, https://doi.org/10.1080/00140130701587574.
[55] S. ter Mors, J.L.M. Hensen, M.G.L.C. Loomans, A.C. Boerstra, Adaptive thermal comfort in primary school classrooms: creating and validating PMV-based comfort charts, Build, Environ. Times 46 (2011) 2454–2461, https://doi.org/10.1016/j.buildenv.2011.05.025.
[56] W. Zeiler, G. Boxem, Effects of thermal activated building systems in schools on thermal comfort in winter, Build. Environ. 44 (2009) 2308–2317, https://doi.org/10.1016/j.buildenv.2009.05.005.
[57] S.P. Corgnati, R. Ansaldi, M. Filippi, Thermal comfort in Italian classrooms under free running conditions during mid seasons: assessment through objective and subjective approaches, Build. Environ. 44 (2009) 785–792, https://doi.org/10.1016/j.buildenv.2008.05.023.
[58] L. Dias Pereira, D. Raimondo, S.P. Corgnati, M. Gameiro da Silva, Assessment of indoor air quality and thermal comfort in Portuguese secondary classrooms: Methodology and results, Build. Environ. 81 (2014) 69–80, https://doi.org/10.1016/j.buildenv.2014.06.008.
[59] M.A. Nico, S. Liuzzi, P. Stefanizzi, Evaluation of thermal comfort in university classrooms through objective approach and subjective preference analysis, Appl. Ergon. 48 (2015) 111–120, https://doi.org/10.1016/j.apergo.2014.11.013.
[60] X. Wang, L. Yang, S. Gao, S. Zhao, Y. Zhai, Thermal comfort in naturally ventilated university classrooms: a seasonal field study in Xi'an, China, Energy Build. 247 (2021), 111126, https://doi.org/10.1016/j.enbuild.2021.111126.
[61] V. Földváry Ličina, T. Cheung, H. Zhang, R. de Dear, T. Parkinson, E. Arens, C. Chun, S. Schiavon, M. Luo, G. Brager, P. Li, S. Kaam, M.A. Adebamowo, M. M. Andamon, F. Babich, C. Bouden, H. Bukovianska, C. Candido, B. Cao, S. Carlucci, D.K.W. Cheong, J.H. Choi, M. Cook, P. Cropper, M. Deuble, S. Heidari, M. Indraganti, Q. Jin, H. Kim, J. Kim, K. Konis, M.K. Singh, A. Kwok, R. Lamberts, D. Loveday, J. Langevin, S. Manu, C. Moosmann, F. Nicol, R. Ooka, N. A. Oseland, L. Pagliano, D. Petráš, R. Rawal, R. Romero, H.B. Rijal, C. Sekhar, M. Schweiker, F. Tartarini, S. ichi Tanabe, K.W. Tham, D. Teli, J. Toftum, L. Toledo, K. Tsuzuki, R. De Vecchi, A. Wagner, Z. Wang, H. Wallbaum, L. Webb, L. Yang, Y. Zhu, Y. Zhai, Y. Zhang, X. Zhou, Development of the ASHRAE global thermal comfort database II, Build. Environ. 142 (2018) 502–512, https://doi.org/10.1016/j.buildenv.2018.06.022.
[62] J. Woolley, S. Schiavon, F. Bauman, P. Raftery, J. Pantelic, Side-by-side laboratory comparison of space heat extraction rates and thermal energy use for radiant and all-air systems, Energy Build. 176 (2018) 139–150, https://doi.org/10.1016/j.enbuild.2018.06.018.
[63] M. Dawe, P. Raftery, J. Woolley, S. Schiavon, F. Bauman, Comparison of mean radiant and air temperatures in mechanically-conditioned commercial buildings from over 200,000 field and laboratory measurements, Energy Build. 206 (2020), 109582, https://doi.org/10.1016/j.enbuild.2019.109582.
[64] W.J. Fisk, The ventilation problem in schools: literature review, Indoor Air 27 (2017) 1039–1051, https://doi.org/10.1111/ina.12403.
[65] I. Demanega, I. Mujan, B.C. Singer, A.S. Anđelković, F. Babich, D. Licina, Performance assessment of low-cost environmental monitors and single sensors under variable indoor air quality and thermal conditions, Build. Environ. 187 (2021), https://doi.org/10.1016/j.buildenv.2020.107415.