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Ventilation rates in naturally ventilated primary schools in the UK; Contextual, Occupant and Building-related (COB) factors

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CO₂ levels
Open area
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A B S T R A C T

Indoor Air Quality (IAQ) in classrooms is assessed by CO₂ levels and Ventilation Rates (VRs). Factors affecting VRs fall into Contextual, Occupant and Building (COB) related factors. This study investigates how VRs are affected by COB factors in 29 naturally-ventilated classrooms in the UK during Non-Heating and Heating seasons. Building-related factors classify classrooms with high or low potentials for natural ventilation, with 45% of classrooms having high potentials. Contextual factors including season, operative temperature (T₀p), outdoor temperature (Tₒ), and air density can limit or increase VRs. Occupant-related factors classify occupant’s good or poor practice of environmental adaptive behaviours. ‘Open area’ as a reflection of all COB factors is strongly correlated with ventilation rates. Results show that 12% and 19% of variations in ventilation rates are explained by open areas during non-heating and heating seasons, respectively. Findings highlight that to have VR of 8 ± 1.28 l/s.p during non-heating seasons and VR of 8 ± 1.07 l/s.p during heating seasons, average open areas of 3.8 m² and 2 m² are required, respectively. This difference can mostly be explained by temperature difference between inside and outside. Results show COB factors need to be considered holistically to maintain adequate VRs. Classrooms in which all COB factors are met provide average VR of 11 l/s.p and classrooms in which none of COB factors are met provide average VR is 3.1 l/s.p. This study highlights that 40% of classrooms according to EN 13779 and 80% of classrooms according to ASHRAE Standard fail to provide adequate VRs.

1. Introduction

Children spend around 25–30% of their life in schools [1–3] and about 70% of their school time inside classrooms [3], therefore, it is vital to maintain appropriate indoor environmental conditions in schools [4]. Young children are more vulnerable to indoor air pollution compared to adults [5–8] as children breathe in more air into their developing lungs relative to their body weight [9–11]. Children have narrower airways [10] and their organs, tissues and immune system are still growing [7], therefore, they are less resilient to deal with toxic chemicals [8]. Reviewing factors influencing IAQ suggest influential factors fall into three main categories; Contextual [12–18], Occupant-related [19,20] and Building-related [21] (COB) factors. IAQ in classrooms is mainly assessed by CO₂ levels which is the surrogate index of VRs [21–25]. Therefore, to consider the integrated impact of COB factors on IAQ, Ventilation Rates (VRs) should be acknowledged.

Ventilation is simply the removal of stale indoor air from a building and its replacement with fresh ‘Outside air’ [20]. ‘Outside air’ used in standards and guidelines for describing ventilation rates may not be as ‘fresh’ as assumed [26,27], therefore, it would not benefit IAQ. Low VRs unavoidably build up CO₂ levels [1,28] and adequate VRs improve IAQ [29–31] in classrooms. The indoor carbon dioxide concentration usually increases unless the removal rate is higher than the CO₂ generation rate [32]. Increased VRs are associated with satisfaction in thermal environment as well as IAQ [31,33] through mitigating overheating [6]. Ventilation by increasing room’s air velocity increases convective heat transfer and decreases thermal stress in high temperatures [33]. Occupants perceive air to be fresher when the outdoor air supply rate is increased [31,34].

Studying VRs in schools is important for at least two reasons, firstly, its impact on IAQ, students’ health [35–37] and performance [22,38–43] and secondly its effect on energy use and heat loss [37,39]. In a study done on 550 subjects, aged 15–20, in 20 classrooms in Norwegian schools, lower VRs are associated with increase in neurologic and airways irritation symptoms [44]. By increase in VRs from 1.3 to 12.8 l/s.p, asthmatic symptoms in pupils decrease from 11.1 to 3.4% over two years [45]. Another review on 20 studies [20], including 350 buildings and

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30000 subjects suggests that VRs below 10 l/s.p have negative effects on health and perceived IAQ and increase the prevalence of Sick Building Syndrome (SBS) symptoms [20].

Academically, increasing VRs improves learning performance of a wide range of schoolwork, from typical rule-based logical and mathematical tasks to language-based tasks [30]. Several studies suggest that for VRs over 10 l/s.p, learning performance increases by at least 7% [25, 46, 47]. Increase in VRs from 6.5 to 15 l/s.p improves learning performance 1–3% [48]. By increase in VRs from 3.0 to 8.5–9.5 L/s per person, the speed at which the children perform mathematical and language-based tasks improve significantly [30, 49]. For VRs over 10 l/s.p, learning performance increases by at least 7% [25, 46, 47]. When VRs increase from 3 to 8.6 l/s.p speed for different tests increase by 3–35% [30]. Haverinen-Shaughnessy et al. (2011) found a linear correlation between VRs and students’ achieved scores [43]. Every 1 l/s.p rise in VRs increases the proportion of passing students by 2.9% for math and by 2.7% for reading [43].

Considering the significance of VRs on students’ health and performance and building’s energy use, this study aims to investigate how Contextual, Occupant-related and Building-related (COB) factors impact VRs and consequently IAQ in classrooms. The main objectives of the study are: 1) reviewing building-related factors to classify classrooms with high or low potentials for natural ventilation. 2) examining how contextual factors facilitate or restrict natural ventilation. 3) classifying occupants’ adaptive behaviours into good or poor practice for providing natural ventilation and 4) evaluating classrooms’ VRs and IAQ against Standards.

### 2. Methodology

To investigate how IAQ is affected by VRs, following steps are carried out in this methodology: 1. Sampling climate and buildings. 2. Acquiring data on occupants’ Adaptive Behaviours (ABs), occupancy patterns, and environmental measurements. 3. Calculating hourly air change rates (ACR) and ventilation rates (VRs) in classrooms. 4. Reviewing Standards. 5. Overviewing recorded data.

### 2.1. Sample selection

In this study, samples were selected with specific attention to climate and school buildings.

#### 2.1.1. Climate

Schools were selected in mild climate of UK for two main reasons; 1) Mild or temperate climates where outside temperature is lower than indoor temperature can provide opportunities for buildings’ natural ventilation, as supported in Ref. [50–52]. As supported in Ref. [51], outdoor temperature in the UK is lower than indoor temperature for most of the year during both day and night, therefore, window opening can ventilate and cool the building. 2) Mild or temperate climates can reduce the biased impact of one extreme climate to let investigate window operation in NV buildings during both heating and non-heating scenarios. Therefore, the study was carried out in Coventry, West Midlands, with a mild climate according to Koppen classification [53] from July 2017 until May 2018 to represent all climatic conditions.

Fig. 1 shows the distribution of outdoor temperature in boxplots for each classroom during schools’ occupancy period. In boxplots, bars show all values from the minimum to maximum, lines in boxes show median values, crosses show mean values and boxes show interquartile ranges.

Fig. 2 shows the distribution of air-speed in boxplots for each classroom during schools’ occupancy period. Table 1 shows descriptive statistics of outdoor variables that were taken from Met office local weather stations [54]. Measurements show that mean outdoor temperature, humidity and air-speed are 17.6 °C, 80.5% and 7.1 m/s during non-heating seasons and are 7.1 °C, 80.5% and 2.8 m/s during heating seasons.

#### 2.1.2. Buildings

To select school buildings in which environmental adaptive behaviours for natural ventilation are varied and not restricted by contextual factors, selected schools met 5 criteria. Selected buildings in this study are 1) naturally ventilated (NV), 2) located in quiet areas, 3) located in low-polluted areas 4) different in architectural characteristics and 5) a...
mix of renovated and existing schools.

1) Selected schools in this study are naturally ventilated as the main source of ventilation in most UK schools is windows. Variations in temperature, relative humidity and indoor pollutants from mechanical ventilation and air-conditioning (MVAC) [55–57] can limit the understanding of building-related factors on VRs, therefore naturally ventilated buildings are selected for the aim of this study. 2) Buildings were selected in quiet areas to not restrict window operation due to high background noise level [51, 58–63]. Selected schools are within a considerable distance to the main road to have the regional Road Noise, LAeq 16h, less than 55 dB according to England Noise Map Viewer [64]. 3) Schools were selected in areas with low Daily Air Quality Index (DAQI) according to Air pollution Forecast by the Met Office [65], because window operation can be limited due to pollution or odour [21, 51, 55, 60, 61, 66]. 4) Buildings were selected with different architectural features so that different potentials for ABs and natural ventilation are provided. There is evidence that buildings’ design affects IAQ and VRs [12, 17, 19, 21]. Range of architectural features including classroom area (50–70 m²), volume (130–252 m³), classrooms’ depth to height ratio (2–4), ratio of window area to classroom area (0–13%) and ratio of opening area to classroom area (0–13.6%) are presented in Table 6. 5) Schools were selected among both renovated and existing buildings because buildings have different potentials for maintaining IAQ and VRs according to their age and design [6, 7, 12, 67]. Furthermore, the required VRs are different for renovated and existing buildings [68]. Schools 1, 2 and 6 (13 classrooms) are renovated and schools 3, 4, 5, 7 and 8 (16 classrooms) are not renovated.

In total, 29 NV classrooms in eight primary schools, as listed in Tables 5 and 6, were selected and studied during non-heating (NH) and heating (H) seasons. Seasons are separated in this study because variations in temperature and humidity from the heating systems can impact occupants’ interaction with the building and consequently VRs.

### Table 1
Descriptive statistics of outdoor variables.

<table>
<thead>
<tr>
<th>Mode</th>
<th>Outdoor variables</th>
<th>Minimum</th>
<th>Maximum</th>
<th>Mean</th>
<th>Std. Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-heating</td>
<td>T_{out}(°C)</td>
<td>9.6</td>
<td>25.1</td>
<td>17.6</td>
<td>3.7</td>
</tr>
<tr>
<td></td>
<td>RH (%)</td>
<td>43.0</td>
<td>94.0</td>
<td>73.0</td>
<td>15.5</td>
</tr>
<tr>
<td></td>
<td>V (m/s)</td>
<td>0.0</td>
<td>7.7</td>
<td>3.0</td>
<td>1.8</td>
</tr>
<tr>
<td>Heating</td>
<td>T_{out}(°C)</td>
<td>0.7</td>
<td>14.6</td>
<td>7.1</td>
<td>3.1</td>
</tr>
<tr>
<td></td>
<td>RH (%)</td>
<td>50.0</td>
<td>94.0</td>
<td>80.5</td>
<td>9.9</td>
</tr>
<tr>
<td></td>
<td>V (m/s)</td>
<td>0.0</td>
<td>9.6</td>
<td>2.8</td>
<td>1.9</td>
</tr>
</tbody>
</table>

![Fig. 1. Outdoor temperature for each classroom during school’s occupancy.](image1)

![Fig. 2. Outdoor airspeed for each classroom during school’s occupancy.](image2)
CO occupancy patterns and controls by authors [80] is used to obtain information on architectural features, data acquisition and observations were carried out in 29 different Adaptive Behaviours (ABs) and simultaneous environmental variables.

2.2. Data acquisition

The study acquires data on children’s occupancy patterns, their Adaptive Behaviours (ABs) and simultaneous environmental variables.

2.2.1. Adaptive behaviours and occupancy patterns

This study applies transverse method to collect data because most of the behavioural studies [69-79] use transverse sampling. Therefore, data acquisition and observations were carried out in 29 different classrooms on 29 distinct school days throughout one year.

An observation form, Table 2, that was validated in an earlier study by authors [80] is used to obtain information on architectural features, occupancy patterns and controls’ operation. Occupancy patterns affect CO2 levels generated in the classrooms [17,81] and operation of windows and external doors influence VRs [2,18,82,83]. Information on occupant’s Schools’ occupancy period is divided into teaching, non-teaching and total occupied period (09:00–15:30). Observations on occupancy patterns and window operations are done at 10-min intervals.

2.2.2. Environmental measurements

Environmental variables affecting VRs were recorded at 5-min intervals by multi-functional SWEMA equipment, standalone data loggers and CO2 meter (TGE-0011, accuracy:±50 + 2% of the reading). Measurement station was located away from the main airflows (e.g. windows), away from heat sources (e.g. projectors) and also away from sun patches at a height of 1.1 m as recommended by ISO 7726 [84]. Further details on specifications of the measuring equipment including range, resolution, accuracy and location are found in earlier studies by authors [80,85]. Time-lapse cameras were installed inside the classrooms to record state of windows, blinds and external doors at 5-min intervals.

2.3. Determination of air change rates and ventilation rates

This study has applied transient mass balance method for estimating Air Change Rates (ACRs) and Ventilation Rates (VRs), as used by many other studies [1,15,17,19,29,86,87]. VRs derived from the transient mass balance method are more reliable than VRs derived from other methods, such as steady-state, decay and build-up methods [19,86,88]. These methods have limitations for calculation of ACRs [19], therefore, they result in inconsistent and unstable data that is not relevant to the occupied time [86]. Steady-state method requires CO2 concentrations at equilibrium [86,88], however, plotting data suggests that equilibrium was seldom achieved in studied classrooms. The decay method is ideal for empty classrooms after children have left the classroom [1,88]. Build-up method assumes a constant generation rate during occupancy [86,88], however, generation rates are varied in schools due to diverse occupancy patterns. The transient mass balance method does not require steady-state conditions, and it can be used for different occupancy patterns (e.g. occupied or unoccupied) and for different times of the day (e.g. morning and afternoon) [86].

In buildings where people are the main pollution sources, VRs (l/s.p) are derived by using CO2 measurements [68]. VR for a known volume depends on CO2 concentration entering the room, CO2 concentration leaving the room and internal generation rate of CO2 added to the room by occupants and their physical activities [15,87]. The time derivative of the monitored concentration is given in Equation (1):

$$\frac{dC}{dt} = G + Q_{in} - Q_{out}$$

(1)

Solving (1) by integration leads to:

$$C(t) = C_{in}e^{-\frac{G}{Q}} + \frac{G}{Q}(C_{ex} - C_{in})e^{-\frac{G}{Q}t}$$

(2)

where.

- \(C_{in}\) (kg/m³) is internal concentration of tracer gas
- \(C_{ex}\) (kg/m³) is external concentration of tracer gas
- \(G\) (kg/s) is generation rate of tracer gas emitted from an indoor source
- \(Q\) (m³/s) is internal-external exchange rate
- \(C_{in}\) (kg/m³) is initial concentration of tracer gas
- \(V\) (m³) is room volume
- \(Q/V\) (ac/s) is air change rate and
- \(t\) is time [15,87].

Equation (2) assumes that \(G\), \(Q\), and \(C_{ex}\) are constant.

Equipment generally records CO2 levels in ppm, therefore, to convert (ppm) to (kg/m³) equation (3) in Ref. [89,90] is applied. However, to avoid small numbers, (kg/m³) is shown in (ppm) and (kg/s) is shown in (cm³/s) in this study.

$$W = \frac{10^{-6} (ppm)(12.187)(MW)}{(273.15 + T)C}$$

(3)

Where.

- \(W\) (kg/m³) is density of CO2 levels
- ppm (parts per million by volume) is concentration of CO2 levels
- 12.187 is a constant of proportionality representing the atmospheric pressure
- \(MW\) (Kg) is gas molecular weight that is simply the sum of the atomic masses (44.01 g) and (273.15 + °C) is the temperature expressed in Kelvin.

ACRs (l/h) were estimated during school’s occupied period by using time-averaged values of G. Outdoor concentration of CO2 is fairly constant but varies depending on the location and the time of the day [33]. Typical outdoor air concentrations are 350–450 ppm (ppm) [33]. In this study, the external CO2 concentration is considered at 400 ppm as suggested in Refs. [91,92]. Based on the number of studied children, their age, metabolic rate, body surface and room temperature, CO2 generation per child is
calculated from 3.34 to 5.89 cm$^3$/s with a median of 3.41 cm$^3$/s and mean of 3.64 cm$^3$/s in this study. An earlier study by authors has provided detailed information on children’s CO$_2$ generation rates and their occupancy patterns [81]. Several other studies have reported similar CO$_2$ generation rates per child; 4.4–5.15 cm$^3$/s in Ref. [1], 3.8–4 cm$^3$/s in Ref. [15], 3.75–4.57 in Ref. [86] and 4.4 cm$^3$/s in Ref. [19].

To calculate VRs (l/s.p), ACRs (1/h) were multiplied by the volume of the classroom and divided by the number of the occupants. As the study is based on hourly ACRs and VRs in classrooms, scatter plots in this study represent hourly ACRs and VRs with their corresponding average CO$_2$ levels. In this study, estimated rates are based on outdoor air supply as the internal doors to the classrooms were generally closed during teaching period.

2.4. IAQ standards

The European standard of EN 13779 [68] recommends IAQ values (CO$_2$ levels and VRs) in four different building categories, Table 3. I) high level of expectation for spaces occupied by sensitive people with special requirements, II) normal level expectation for new buildings and renovations, III) moderate level of expectation for existing buildings and IV) low level of expectation only acceptable for a short period.

The American Society of Heating, Refrigerating and Air-conditioning Engineers (ASHRAE) standard 62 recommends CO$_2$ level of 1000 ppm and a minimum of 5 L/s per person plus 0.6–0.9 L/s per m$^2$ floor area (a total of approximately 8 L/s.p) for classrooms [23]. This amount of VR results in 3–5 ACH per classroom depending on classrooms’ size and volume [1,93,94].

2.5. Overview of the recorded data

Environmental variables for the total occupied period (9:00–15:30) are described statistically in Table 4 for non-heating and heating seasons. Mean $T_{op}$ and humidity are 23.8 (°C) and 49.7 (%) during non-heating seasons and 21.8 (°C) and 38.2% during heating seasons. The total of CO$_2$ measurements in 29 classrooms show that mean and median CO$_2$ concentrations are 1050 and 953 ppm during non-heating seasons, and 1208 and 1084 ppm during heating seasons.

Fig. 3 shows the variability of CO$_2$ measurements between classrooms, from a minimum of 475 ppm in classroom 1.01 to a maximum of 3430 ppm in classroom 8.31. Variability of CO$_2$ measurements within individual classrooms shows that classroom 4.14 has the lowest Standard Deviation (SD = 50 ppm) and classroom 8.31 has the highest Standard Deviation (SD = 904 ppm). The overview shows that 55% of all the CO$_2$ measurements in this study are above 1000 ppm.

3. Results and analysis

3.1. ACRs and VRs

Descriptive statistics of ACRs and VRs during teaching period were calculated and presented in Table 5. ACRs in 29 classrooms change from 0.3 to 10.99 (1/h) with a mean of 3.41 (1/h) and median of 2.58 (1/h), Table 5. Mean and median ACRs are 3.84 (1/h) and 3.15 (1/h) during non-heating seasons and are 3.02 (1/h) and 2.52 (1/h) during heating seasons.

### Table 4

<table>
<thead>
<tr>
<th>Variable</th>
<th>Minimum</th>
<th>Maximum</th>
<th>Mean</th>
<th>Median</th>
<th>S.D.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-heating</td>
<td>$T_{op}$ (°C)</td>
<td>17.9</td>
<td>28.1</td>
<td>23.8</td>
<td>23.8</td>
</tr>
<tr>
<td>RH (%)</td>
<td>35.8</td>
<td>66.6</td>
<td>49.7</td>
<td>48.1</td>
<td>7.7</td>
</tr>
<tr>
<td>CO$_2$ (ppm)</td>
<td>475</td>
<td>3430</td>
<td>1050</td>
<td>953</td>
<td>444</td>
</tr>
<tr>
<td>Heating</td>
<td>$T_{op}$ (°C)</td>
<td>16.2</td>
<td>27.4</td>
<td>21.8</td>
<td>21.9</td>
</tr>
<tr>
<td>RH (%)</td>
<td>24.6</td>
<td>54.9</td>
<td>38.2</td>
<td>36.6</td>
<td>7.6</td>
</tr>
<tr>
<td>CO$_2$ (ppm)</td>
<td>555</td>
<td>2659</td>
<td>1208</td>
<td>1084</td>
<td>427</td>
</tr>
</tbody>
</table>

Cumulative frequency (%) of ACRs (1/h) for teaching and total occupied period are depicted in Fig. 4. Median ACRs (1/h) for total occupied period (9:00 a.m.-3:30 p.m.) are 2.5 (1/h) during non-heating seasons and 2.1 (1/h) during heating seasons, Fig. 4.

Mean ACR in this study (3.41 1/h) is lower than ACR of 4.16 (1/h) in Ref. [13] where almost all classrooms had at least some open windows. It is also higher than mean ACR of 2.0 ± 1.3 (1/h) in Ref. [19] where HVAC systems were sometimes shut off in mechanically-ventilated classrooms. Higher ACRs in another study [29], from 1 to 22 1/h with average values from 0.7 to 8 1/h, are due to open windows and favourable wind’s direction [29].

VRs in this study range from 0.78 to 17.36 (l/s.p) with mean and median of 6.21 (l/s.p) and 5.37 (l/s.p), Table 5. Mean and median VRs during non-heating seasons (7.06 and 6.11 l/s.p) are higher than their corresponding values during heating seasons (5.45 and 4.75 l/s.p), Table 5. Cumulative frequency (%) of VRs (l/s.p) for teaching and total occupied period are shown in Figs. 5 and 6. Median VRs for total occupied periods are 8.1 (l/s.p) and 6.3 (l/s.p) during non-heating and heating seasons, Figs. 5 and 6.

Mean VR in this study (6.21 l/s.p) is higher than that (2.4 l/s.p) in NV Portuguese classrooms [16] because windows were not operated often during winter. It is also lower than average of 13 l/s.p in Finnish primary schools [16] because mechanically-ventilated classrooms could provide adequate IAQ even in winter [16].

3.2. Factors affecting ACRs and VRs

To improve IAQ and reduce CO$_2$ levels in school buildings, Contextual, Building and Occupant-related factors (COB) affecting ACRs and VRs are investigated, Fig. 7.

3.2.1. Building-related factors

Studies suggest that windows design as one of the building-related factors has a significant impact on natural ventilation and consequently IAQ [13,18,22,24,95]. Based on a comprehensive literature review, aspects of window design that affect natural ventilation are classified into six main groups; I) windows’ area and location [21,59,83,96–98], II) window/room ratio [59], III) windows’ arrangement [21,50,59,96,99], IV) windows’ orientation [50,99], V) windows’ operation method [83,96,97,100–103] and VI) windows’ supplements [21,104,105]. The review helps to classify classrooms with high or low potentials for natural ventilation.

I) Windows’ Design: The amount of air going through the window opening depends on size, type and location of the opening [51,98]. Windows at different levels (high/low-level openings) and

### Table 3

<table>
<thead>
<tr>
<th>Categories</th>
<th>IAQ standard</th>
<th>Range of CO$_2$ levels</th>
<th>Total CO$_2$ values Based on outdoor CO$_2$ of 400 ppm</th>
<th>VRs (l/s.p)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Category I</td>
<td>High</td>
<td>&lt;400</td>
<td>&lt;800</td>
<td>&gt;10</td>
</tr>
<tr>
<td>Category II</td>
<td>Medium</td>
<td>400–600</td>
<td>800–1000</td>
<td>7–10</td>
</tr>
<tr>
<td>Category III</td>
<td>Moderate</td>
<td>600–1000</td>
<td>1000–1400</td>
<td>4–7</td>
</tr>
<tr>
<td>Category IV</td>
<td>Low</td>
<td>&gt;1000</td>
<td>&gt;1400</td>
<td>&lt;4</td>
</tr>
</tbody>
</table>
sizes (small/large) can provide sufficient ventilation [21, 59, 83, 96–98] to maintain thermal comfort and IAQ during heating and non-heating seasons. High-level openings provide cross-ventilation if windows are located at two different sides. Well-distributed high-level openings direct the airflow above the occupied zone and prevent cold draughts from dumping onto the occupants before mixing with the room air [21]. Therefore, these openings ventilate the space efficiently and cool the thermal mass [21] without discomforting occupants, especially during heating seasons. Low-level openings can provide local ventilation [96]. It is also found that ACR is increased with window’s height [21, 106]. Large openings can be used for still summer days [59, 96] and small openings can be used for winter days to avoid overheating [59, 96]. Therefore, windows at different heights and sizes provide higher potentials for natural ventilation. Columns 10–14 in Table 6 (under windows’ configuration) present features related to windows’ design.

II) Window/room ratio: Window area in proportion to classroom area should have the potential to provide enough natural ventilation. BREEAM, as an international rating scheme on buildings’ environmental performance, sets criteria that minimum proportion of window area to room area should be 5% to provide natural

Table 5

Descriptive statistics of ACRs and VRs during teaching period.

<table>
<thead>
<tr>
<th>Seasons</th>
<th>Parameters</th>
<th>Minimum</th>
<th>Maximum</th>
<th>Range (Max-Min)</th>
<th>Mean</th>
<th>Median</th>
<th>S.D.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-heating (NH)</td>
<td>ACR (1/h)</td>
<td>0.49</td>
<td>10.99</td>
<td>10.5</td>
<td>3.84</td>
<td>3.15</td>
<td>2.65</td>
</tr>
<tr>
<td></td>
<td>VR (l/s.p)</td>
<td>0.78</td>
<td>17.36</td>
<td>16.58</td>
<td>7.06</td>
<td>6.11</td>
<td>4.28</td>
</tr>
<tr>
<td>Heating (H)</td>
<td>ACR (1/h)</td>
<td>0.30</td>
<td>9.09</td>
<td>8.79</td>
<td>3.02</td>
<td>2.52</td>
<td>1.92</td>
</tr>
<tr>
<td></td>
<td>VR (l/s.p)</td>
<td>0.85</td>
<td>15.56</td>
<td>14.71</td>
<td>5.45</td>
<td>4.75</td>
<td>3.24</td>
</tr>
<tr>
<td>Whole Year (WY)</td>
<td>ACR (1/h)</td>
<td>0.3</td>
<td>10.99</td>
<td>10.69</td>
<td>3.41</td>
<td>2.58</td>
<td>2.31</td>
</tr>
<tr>
<td></td>
<td>VR (l/s.p)</td>
<td>0.78</td>
<td>17.36</td>
<td>16.58</td>
<td>6.21</td>
<td>5.37</td>
<td>3.83</td>
</tr>
</tbody>
</table>

Fig. 3. CO₂ changes in each classroom during occupied period.

Fig. 4. Cumulative frequency (%) of ACRs (1/h) for teaching and total occupied period.
Cumulative frequency (%) of VRs (l/s.p) for total occupancy period.

Fig. 5. Cumulative frequency (%) of VRs (l/s.p) for teaching period.

Cumulative frequency (%) of VRs (l/s.p) for total occupied period.

Fig. 6. Cumulative frequency (%) of VRs (l/s.p) for total occupancy period.

ventilation [59]. Columns 7–9 in Table 6 (under classroom’s characteristics) shows classrooms’ window/room ratio.

III) Windows’ Arrangement: ‘Natural ventilation is the flow of air through doors, windows, vents, and other openings caused by wind pressure or stack effect’ [107]. There are two main types of windows’ arrangement for natural ventilation: 1) single-sided that mostly relies on temperature gradients (room-scale stack ventilation) and 2) double-sided (cross-ventilation) that mostly relies on wind turbulence [51,96,99,108]. Single-sided natural ventilation is possible through two different designs; 1) same opening on one side of the room, 2) different openings when inlet and exit openings are at different levels on one side of the room [99]. When the same opening provides for both supply and extract in single-sided configurations, wind-driven ventilation is restricted [59]. Therefore, by vertical separation of windows in single-sided ventilation, the room-scale stack flow is increased [50,51], because it lets in cold outdoor air into a building via low-level vents and lets out warmer indoor air via high-level openings, especially when temperature difference between inside and outside is higher [51]. To ensure that the full depth of a single-sided space is adequately ventilated, the depth of the room should be limited to 5.5 m or 2 times the room’s height [51,59,109]. However, separating the openings vertically increases the effective depth to 2.5 times the room’s height [21,51]. Cross-ventilation is usually driven by wind-generated pressure differences [51]. To ensure cross-ventilation, openings should be at different heights on opposite facades [21,50,51]. When adequate cross-ventilation is provided, depth of the room can exceed to 7–15 m or 5 times the room height [21,51]. Therefore, classrooms’ depth-to-height ratios should be met to provide adequate potentials for natural ventilation. Columns 7–14 in Table 6 present classrooms and windows’ arrangement.

IV) Windows’ Orientation: Window orientation influences VRs regarding prevailing wind speed and direction [50,51]. When the building is not protected from wind, windows are not parallel to wind direction and wind speed is not null, double-sided/cross ventilation is set-up, otherwise, single-sided ventilation is set-up [50,99]. It is shown that in double-sided classrooms the effect of wind is dominant, however, in single-sided buildings, stack flow through temperature difference is more dominant [51,99]. Therefore, windows that are oriented towards the prevailing wind direction can provide higher levels of wind-induced ventilation, especially in double-sided classrooms (Table 6: column 4).

V) Windows’ Operation: Previous studies have shown that manual operation of windows improve IAQ significantly [2,8,29,83,95], especially during heating seasons [7,13,18,29,24,95]. Windows’ ease of use [83,100,110] and access and proximity to windows [50,83,101–103] are among other factors affecting window operation and potentials for natural ventilation. Based on children’s physique, windows designed at lower heights are more accessible for children’s window operation [83]. Windows’ operation method and windows’ minimum accessible-height are shown in Table 6, columns 12 and 15.

VI) Windows’ supplements: Windows that are supplemented with ventilation grills can provide extra ventilation and increase potentials for natural ventilation [21,51,104,105]. Fig. 10 (school 1) and Fig. 11 (school 6) show louvres with fixed horizontal slats that are angled to let air in. In 45% of studied classrooms (schools 1, 2 & 6) louvre openings are designed alongside windows (Table 6: column 14).

In this study, 90% of classrooms are single-sided and 10% are double-sided, Table 6. Around 42% of single-sided classrooms have openings that are designed at two different levels (classrooms in schools no. 1, 2 and 5). Figs. 8 and 9 show classrooms with single-sided openings at two different sizes and one size.

Table 6 presents Building-related (B) characteristics of classrooms based on overviewed literature. Classrooms that provide at least four out of six above criteria are considered as classrooms with high potentials for natural ventilation. The last column in Table 6 shows classrooms’ potentials for natural ventilation (High or Low). In this study, 13 classrooms out of 29 (45%) have high potentials for natural ventilation, Table 6.

A subset of classrooms (25%) has exterior doors to the playground that are usually operated according to occupancy patterns (Table 6: column 16). Operation of exterior doors can increase classrooms’ VTs [18]. Due to blinds’ potential on resisting airflows [59,109], their impact on obstructing free open area is considered in the analysis.

3.2.2. Contextual factors

Concerns about global warming, energy consumption and maintaining a healthy indoor environment have resulted in a growing interest in NV buildings [50,51,111]. However, natural ventilation is affected by contextual factors [52]; it can only be applied to certain climates [50–52] and it might be limited due to high background noise level [21,49,51,58–62] or pollution [21,51,55,60,61] because ‘outdoor air’ into the building may not be ‘fresh air’ [26,27]. Therefore, this study, as explained in methodology, has selected schools in low-polluted and quiet areas. This study has focused on contextual factors that are more challenging to control including season, outdoor air speed, operative temperature (T_op), outdoor temperature (T_out) and the difference between indoor and outdoor temperature (T_op–T_out). Since outdoor climate
has an immediate impact on indoor conditions [28], $T_{op}$ is also considered as a contextual factor.

### 3.2.2.1. Seasons

There is evidence that seasonal variations affect VRs indirectly by changing occupants’ Adaptive Behaviours [6]. Results of Mann-Whitney test in this study show that median VRs are different during heating and non-heating seasons ($U = 1372, p = 0.025$). Fig. 12 shows that mean and median VRs are higher during non-heating seasons (7.06 and 6.1 l/s.p) that heating seasons (5.45 and 4.8 l/s.p). Part of this can be explained by seasonal factors because average open area during non-heating seasons (2.4 m$^2$) is higher than that during heating seasons (0.8 m$^2$) as seen in boxplots in Fig. 13. Other studies support that VRs can be lower during heating seasons due to closed windows [14,18], therefore, it is shown that winter VRs mostly do not meet the recommended values by standards [16,27].

Observations during field studies, shown in an earlier study by authors [112], suggest that lower open areas during heating seasons are due to low outdoor temperatures or draught, as supported in Refs. [16,18,27,113] and energy concerns, as supports in Ref. [114]. Results of this study show that open areas during non-heating seasons have a stronger correlation with $T_{op}$ (Spearman Correlation coefficient = 0.53, $P < 0.001$) than with CO$_2$ levels (Spearman Correlation coefficient = $-0.32$, $P < 0.001$). Cohen has proposed classifications for the strength of correlations using $r$ values; 0.10 to 0.30 is interpreted as a weak correlation, 0.30 to 0.50 as a moderate correlation and greater than 0.50 as a strong correlation [115]. It is assumed that higher absolute values and smaller $P$ values imply a stronger correlation [116]. According to Cohen classification, the correlation of open areas with $T_{op}$ is strong during non-heating seasons.

Therefore, windows are operated more often during non-heating seasons to lower high temperatures, as supported in Ref. [85], which in turn lowers CO$_2$ levels. Previous studies support that window and doors are operated more when the temperature is high [85,117] rather than when IAQ is low [114] because poor IAQ is not perceived due to gradual sensory fatigue or adaptation [21,118].

### 3.2.2.2. Outdoor air-speed and direction

Several studies have shown that amount of air going through the window opening is affected by air-speed [21,29,31,50,51,55,61,98] and wind direction [50,51,98]. In this study, air-speed and wind direction are obtained from Met office Website [54] and presented in Table 8. Results of this study show that VRs are not correlated with outdoor air speed ($P = 0.57 > 0.05$). This can be attributed to four main reasons; first, in 41% of the classrooms (12 classrooms) outdoor air speed is less than 2 m/s. There is evidence that natural ventilation will be improved by air velocities frequently above 2 m/s [107]. Second, windows’ orientation in 55% of the classrooms (16 classrooms) is not faced towards wind direction, Table 8. Top-hung windows direct airflow towards occupants when perpendicular to the wind [51]. Third, 90% of the classrooms in this study are single-sided, therefore, wind-driven ventilation is more restricted in them, as suggested in CIBSE, Ventilation and ductwork [59]. Fourth, air-speed and wind direction obtained from a meteorological station are more valid in a limited perimeter around the instruments and they are changed by obstacles, especially at low speed. This study suggests that outdoor air speed increases VRs more significantly when windows are fully open, when air speed is adequate, when windows are oriented towards wind direction, and when openings for supplying and extracting air are not the same in single-sided openings. In this study, wind speed and direction are not favourable in around 50% of studied classrooms. Another study supports that wind fails to provide a stable ventilation rate since wind speed and direction change over wide ranges [107].

### 3.2.2.3. $T_{op}$ and $T_{out}$

Weather is the driving force for natural ventilation [50], therefore, VRs vary constantly by change in weather conditions [119]. Seasonal variations directly affect VRs by changing indoor and outdoor climatic variables [6]. In this study, $T_{op}$ is correlated with ACRs (Spearman Correlation coefficient = 0.20, $P < 0.05$) and VRs (Spearman Correlation coefficient = 0.29, $P < 0.001$). $T_{out}$ is also correlated with ACRs (Spearman Correlation coefficient = 0.27, $P < 0.01$) and VRs (Spearman Correlation coefficient = 0.31, $P < 0.01$). The correlation suggests that when $T_{op}$ and $T_{out}$ are higher, VRs and ACRs are also higher. This is because as $T_{op}$ and $T_{out}$ increase, there is a higher tendency to open windows which in turn increases VRs, as supported in Ref. [7,13]. Considering the correlation between $T_{op}$ and VRs, VRs...
### Table 6
An overview of Building-related features of schools and classrooms.

<table>
<thead>
<tr>
<th>Mode &amp; Date</th>
<th>No. Classrooms’ Characteristics</th>
<th>Windows’ Configurations</th>
<th>Window Operation</th>
<th>ED&lt;sup&gt;a&lt;/sup&gt;</th>
<th>PNV&lt;sup&gt;i&lt;/sup&gt;</th>
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<tbody>
<tr>
<td></td>
<td>Orientation</td>
<td>Area</td>
<td>Vo&lt;sup&gt;b&lt;/sup&gt;</td>
<td>D/&lt;br&gt;H&lt;sup&gt;c&lt;/sup&gt;</td>
<td>W/&lt;br&gt;C&lt;sup&gt;d&lt;/sup&gt;</td>
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<tr>
<td>Non-Heating</td>
<td>July 2017</td>
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<td>NE</td>
<td>60</td>
<td>192</td>
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<tr>
<td></td>
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<td>192</td>
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<td>1.4</td>
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<td></td>
</tr>
<tr>
<td></td>
<td>Sep 2017</td>
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<td>NW</td>
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<td>192</td>
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<td>SE</td>
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<td>2.9</td>
<td>NW</td>
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<td>192</td>
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<tr>
<td>Heating</td>
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<td>S&amp;W</td>
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<td>175</td>
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<tr>
<td>Non-Heating</td>
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<td>NE, NW</td>
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<td>55</td>
<td>137</td>
</tr>
<tr>
<td></td>
<td></td>
<td>8.32</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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*a* vol (m<sup>3</sup>)

*b* Depth to Height Ratio.

*c* Window area to classroom area (%).

*d* Operable area to classroom area (%).

*e* Window Area (m<sup>2</sup>).

*f* Number of Windows.

*g* Minimum Height of windowsill (m).

*h* Exterior Door.

*i* Potentials for natural ventilation.
should be adequate to remove significant amounts of thermal gains that may lead to overheating, as supported in Ref. [21,50,109].

### 3.2.3. Occupant-related factors

Table 6 highlights that 45% of studied classrooms provide high potentials for natural ventilation, however, the study introduces two terms for occupants’ environmental ABs: ‘good practice’ and ‘poor practice’. ‘Good practice’ refers to when occupants operate available controls efficiently (average open area more than 50% in each classroom) to maintain adequate VRs and ‘Poor practice’ refers to when occupants do not operate available controls efficiently (average open area less than 50% in each classroom) to provide VRs. Open areas in Table 8 (Column 8) for each classroom can be compared with their corresponding available window area in Table 6 (Column 10) to classify occupants’ practice of adaptive behaviours in Table 8 (Column 9).

Four groups based on potentials and practices for natural ventilation are defined in Fig. 14; 1) High potentials and good practice for natural ventilation, 2) High potentials/poor practice, 3) Low potentials/poor practice, 4) Low potentials/good practice.

Results of the Kruskal-Wallis test show that there is a significant difference in median VRs $X^2(3) = 59.9, p = 0.000$ between these defined groups, Fig. 14. Fig. 14 shows median VRs in defined groups are 8.9, 3.7 and 6.9 l/s.p and mean VRs are 10.3, 3.5, 3.6 and 8.1 l/s.p, respectively. Mean and median values are the highest in the first group (high potentials/good practice). The second favourable group in terms of VRs (category 4) provides low potentials/good practice for natural ventilation, Fig. 14. This study suggests that operation on controls is as important as the design of classrooms and controls.

### 3.3. Reflection of COB factors on windows’ open areas

Window operation as one of the most important adaptive behaviours in this study, is the reflection of all Contextual (weather conditions),
Occupant-related (occupant’s operation) and Building-related (windows’ design) factors (COB). Results show that open areas are correlated with VRs during non-heating (Spearman Correlation coefficient = 0.42, P < 0.01) and heating seasons (Spearman Correlation coefficient = 0.62, P < 0.001). Figs. 15 and 16 show measured open areas with their corresponding hourly VRs. Regressions in Figs. 15 and 16 suggest that 12% and 19% of variations in VRs are explained by open areas during non-heating and heating seasons, respectively. Regressions suggest that by the increase in open areas, VRs increase and CO\textsubscript{2} levels decrease, as supported in Ref. [8,13]. In a similar study, the effect of open area on VRs is investigated in 62 classrooms in 27 NV schools of Athens under three different situations: 1) VR of 1.5 l/s.p when windows are closed, 2) VR of 4.5 l/s.p when some windows are open and 3) VR of 7 l/s.p when most of the windows are open [13]. Another study shows that when all windows and doors are closed, VRs in NV classrooms are less than 1 l/s.p [8].

To find out how data defines the linear regression and to interpret the best-fit values, it is important to know how precise they are, therefore, confidence intervals for linear models are shown in Figs. 15 and 16. The width of the confidence intervals is determined by the number of data points, their distances from the line, and the spacing of the X values [120]. Equations (4)–(6) show 95% confidence intervals on the slope, intercept and dependent variables [121,122].

95% CI on the slope = $\hat{m} \pm t_{0.05,\,2}S_m$ \hspace{1cm} (4)

95% CI on intercept = $\hat{b} \pm t_{0.05,\,2}S_b$ \hspace{1cm} (5)

An Approximation of the 95% confidence interval on $Y = \hat{y}$

\[\pm \left[ t_{0.025,\,2}S_y \right] / \sqrt{n} \] \hspace{1cm} (6)

Table 7 shows the calculation of confidence intervals for the linear relationships between open area and VRs in Figs. 15 and 16. Results in Table 7 show that 95% confidence intervals on slopes (Row 11) exclude 0 (m\textsubscript{NH} = 0.76 ± 0.67 and m\textsubscript{H} = 2.11 ± 1.28), therefore, we can conclude that there is a significant linear relationship between open area and VRs. According to Table 7, there is a 95% chance that the intervals calculated for non-heating (±1.28) and heating seasons (±1.07) contain

Fig. 11. A classroom in school 6 providing louvre openings alongside windows.

Fig. 12. VRs during heating and non-heating seasons.

Fig. 13. Open areas (m\textsuperscript{2}) during heating and non-heating seasons.
the true value of VRs.

Confidence intervals on ventilation rates are narrower during heating (1.07) than non-heating (1.28) seasons, therefore, it can be suggested that data defines the linear fit more precisely during heating seasons. Results of this study in Figs. 15 and 16 show that to have VR of 8 ± 1.28 l/s.p during non-heating seasons and VR of 8 ± 1.07 l/s.p during heating seasons, average open areas of 3.8 m² and 2 m² are required, respectively. These average open areas are suggested over 29 classrooms in this study and they may not apply without caution to other buildings and climates.

Average open area during non-heating seasons (3.8 m²) is almost twice than that during heating seasons (2 m²). This can be explained by air density differences and mostly by temperature differences between inside and outside during both seasons. First, air density is inversely related to temperature, therefore, cold winter air is denser than warm summer air. When outdoor temperature is high, the absorbed energy in the form of heat makes molecules in the air move and expand, which decreases air density [123]. This suggests that high temperatures take more volume compared to low temperatures. Therefore, more air and accordingly higher open areas are required during non-heating seasons compared to heating seasons to provide the same level of VRs and IAQ. In this study, mean outdoor temperature during heating seasons (7.1 °C) is around 10

Fig. 14. Mean VRs in each group for potentials and practices of natural ventilation.

Fig. 15. Influence of open areas (m²) on VRs (l/s.p) during non-heating seasons.
According to the Ideal Gas Law for dry air, air density decreases by about 1% for 3 °C increase in temperature [124]. The density variation of the outdoor air between the heating season (7.1 °C) and the non-heating season (17.6 °C) is only 3.5% which cannot explain the need for doubling the claimed opening area.

The difference can mostly be explained by the increase of the stack effect during heating seasons. ‘Stack effect’ is generated by vertical pressure difference, depending on the temperature difference between inside and outside [107]. The temperature difference between inside and outside is higher during heating seasons, Table 4, as also supported by Mumovic (2018) [51]. The study by Larsen and Heiselberg (2008) explains how to calculate the volume flow rates driven by thermal buoyancy through a single opening which can be found in Equation (7):

$$Q_v = \frac{1}{3} C_D A^\frac{1}{3} (T_i - T_e) g H (H_t - H_b) \sqrt{T}$$

Where,

- $Q_v$ is the volume flow rate (m$^3$/s),
- $C_D$ is the discharge coefficient depending on the type of opening (0.6 for sharp edges),
- $A$ is the area of the opening (m$^2$),
- $T_i$ is the internal temperature (K),
- $T_e$ is the external temperature (K),
- $T$ is the average temperature (K),
- $g$ is the gravitational acceleration (m/s$^2$), about 9.81 m/s$^2$,
- $H_t$ is the height, top of the opening (m) and
- $H_b$ is the height, bottom of the opening (m) [98].

It can be suggested from equation (7) that the airflow rate through an opening in absence of wind depends on the air density difference, hence to the absolute temperature difference between outside and inside environments. The equation shows that the airflow rate increases with the square root of the temperature difference. Using Equation (7) for the results of this study show that an opening with an area of 1 m$^2$, with the $H_t$ of 2 m and $H_b$ of 1 m provides an airflow rate of 1150 m$^3$/h during non-heating seasons (Average of 23.8 °C inside and 17.6 °C outside) and 1852 m$^3$/h during heating seasons (Average of 21.8 °C inside and 7.1 °C outside). Therefore, the higher temperature difference between inside and outside during heating seasons helps to create a higher exchange rate through windows, as supported in several studies [50, 51, 61, 98, 99, 106]. The effect of temperature difference is specifically dominant in single-sided classrooms where cool outdoor air enters the room through the lower part of the opening and is exchanged with warm indoor air that escapes through the upper part [99].
3.4. Effect of VRs on IAQ

Several studies recognize CO$_2$ levels as an indicator of ventilation in an indoor environment [6,20,23,31,66]. In this study, hourly average CO$_2$ levels are strongly and negatively correlated with hourly VRs (Spearman Correlation coefficient = −0.81, P < 0.001). Fig. 17 shows the power trendline between hourly VRs and CO$_2$ levels during the teaching period. Fig. 17 shows that 63% of CO$_2$ changes are explained by VRs. The power trendline suggests that when VRs are high, CO$_2$ levels decrease and IAQ increases, as supported in other studies [1,6,29,86,125]. Similar studies highlight that CO$_2$ levels are strongly correlated with VRs ($R^2 = 0.59$ in Ref. [29]) and ($r = 0.88$ in Ref. [125]). Fig. 17 shows that to have CO$_2$ levels of 1000 ppm, an average VR of 8 l/s.p, as confirmed in similar studies [1,21,23,93,94].

4. Discussion

This study has shown correlation coefficients (Spearman Rank) for variables correlated to ACRs and VRs in Fig. 18. According to Cohen Classification, the correlation of ACRs and VRs with open areas and CO$_2$ levels is strong in Fig. 18. The strong correlation between open area and ‘ACRs and VRs’ supports that open area is the reflection of all COB factors.

Careful consideration should be given to windows’ design for both heating and non-heating seasons for two main reasons. First, heating of the inlet air during cold seasons can take lots of energy. There is evidence that heating of incoming ventilation air can represent 20%–50% of a building’s thermal load so it should be reduced as far as possible [21]. Therefore, only outdoor air required for maintaining IAQ is welcomed during heating seasons and anything more than that is considered energy penalty [21]. Second, cold air can be perceived draughty during heating seasons even if it is not moving [50] and it can cause discomfort if it dumps onto the occupants before mixing with room air [21]. Therefore, winter openings (windows or ventilation grills) should be designed differently in size and height than summer windows to provide adequate VRs without compromising thermal comfort and wasting energy. Besides design aspects, occupants should also be reminded and motivated to operate controls at the right time. Several studies have recommended using CO$_2$ warning devices which remind occupants of the time at which windows should be operated [49,51,60,126–128] to decrease CO$_2$ levels.

4.1. Evaluating classrooms’ IAQ against standards

To evaluate IAQ, average CO$_2$ levels and VRs in each classroom are compared with values recommended by EN 13779:2004 (category II for renovated and III for existing buildings) [68] and ASHRAE [23]. The last column in Table 8 shows COB factors that potentially lead to low VRs in classrooms with the following acronyms:

- **C** for Contextual factors when unfavourable wind speed or direction are potential reasons for low VRs.
- **O** for Occupant-related factors when occupants have a poor practice of ABs.
• **B for Building-related factors** when classrooms have low potentials for natural ventilation.

As can be seen in Table 8, the reasons for inadequate VRs (the last column) can be related to one factor or a mix of factors. Results of the Kruskal-Wallis test show that there is a significant difference in median VRs levels \(X^2(3) = 12.6, p = 0.006\), when number of favourable COB factors are different, Fig. 19. According to Fig. 19, classrooms in which all COB factors are met provide average VR of 11 l/s.p, classrooms in which two COB factors are met provide average VR of 7.4 l/s.p, classrooms in which one COB factor is met provide average VR of 5.8 l/s.p and classrooms in which none is met provide average VR of 3.1 l/s.p. This suggests that meeting all COB factors provides adequate VRs while meeting none results in significantly low VRs.

Table 8 highlights that 59% of the classrooms meet IAQ criteria.
recommended by EN 13779 [68], with the average of 9.36 l/s.p for
recommended by EN 13779 [68], with the average of 9.36 l/s.p for
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5. Conclusion
This study acknowledges contextual, occupant and building-related
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References

[1] M.B. Luther, P. Horan, O. Tokede, Investigating CO2 concentration and
occupancy in school classrooms at different stages in their life cycle, Archit, Sci.

[2] V. De Giuli, O. Da Pos, M. De Carli, Indoor environmental quality and pupil
perception in Italian primary schools, Build. Environ. 56 (2012) 335–345,


quality in classrooms? Part 2: health outcomes and perceived indoor air quality
in relation to classroom exposure and building characteristics, Build. Serv. Eng.

the health effects and risks associated with children’s inhalation exposures—asthma


[7] R.M.F. Almeida, V.P. Freitas, V.P. De Freitas, Indoor environmental
quality of classrooms in Southern European climate, Energy Build. 81 (2014)

[8] Y. Hou, J. Liu, J. Li, Investigation of indoor air quality in primary school
proeng.2015.09.037.

T. Woodruff, Potential new approaches for children’s inhalation risk assessment,


G. Bartzis, Indoor air quality investigation of the school environment and
estimated health risks : two-season measurements in primary schools in Koszani ,
aprev.2016.07.092.

dioxide concentration, temperature, and energy use during the heating season in
classrooms with different ventilation retrofit—ASHRAE RI1624, Sci. Technol.
Built Environ. 4731 (2018) 1–12, https://doi.org/10.1080/2
2374743.2018.1432928.

M. Papaglastra, N. Gaitani, D. Kolokosta, V. Assimakopoulos, Experimental
investigation of the air flow and indoor carbon dioxide concentration in
classrooms with intermittent natural ventilation, Energy Build. 40 (2008)

ventilation strategy on indoor air quality in schools, Sci. Total Environ. 595

[15] D.A. Coley, A. Beisterine, Carbon dioxide levels and ventilation rates in schools,
1735355.2012.1163621.

rates at primary schools : comparison between Portugal and Finland, J. Toxicol.
Environ. Health Part A. 76 (6) (2013) 400–408, https://doi.org/10.1080/1
5287394.2013.763572.

CO2measurements in Serbian schools and ventilation rate calculation, Energy

[18] J. Pan, P. Warzocki, X. Wang, Y. Wang, Ventilation system type, classroom environmental
quality and pupils’ perceptions and symptoms, Build. Environ. 75 (2014) 46–57,
https://doi.org/10.1016/j.buildenv.2014.01.015.

in recently constructed US school classrooms, Indoor Air 27 (5) (2017) 880–890,
https://doi.org/10.1111/ina.12384.

concentrations with health andother responses in commercial and institutional


between classroom CO2 concentrations and student attendance in Vermont
0688.2004.00251.x.

[23] American Society of Heating Refrigerating and Air Conditioning Engineers
(ASHRAE), Ventilation for Acceptable Indoor Air Quality, ANSI/ASHRAE Std.

Association between classroom ventilation mode and learning outcome in Danish
buildenv.2015.05.017.

[25] Z. Bakó-Biro, D.J. Clements-Croome, N. Kochhar, H.B. Awbi, M.J. Williams,
Ventilation rates in schools and pupils’ performance, Build. Environ. 48 (2012)

016/j.buildenv.2008.08.008.

[27] A.B. Legg, W.J. Batty, Air quality and ventilation rates in school classrooms I: air


