Indoor air quality (IAQ) in naturally-ventilated primary schools in the UK: Occupant-related factors

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ABSTRACT

Indoor Air Quality (IAQ) is affected by Context, Occupant and Building (COB) related factors. This paper evaluates IAQ as a function of occupant-related factors including occupants’ Adaptive Behaviours (ABs), occupancy patterns, occupant’s CO₂ generation rates and occupancy density. This study observed occupant-related factors of 805 children in 29 naturally-ventilated (NV) classrooms in UK primary schools during Non-Heating and Heating seasons.

Occupant-related factors affecting IAQ include occupants’ adaptive behaviours, occupancy patterns, occupants’ CO₂ generation rate and occupancy densities. Results of this study suggest that a classroom with high potentials for natural ventilation does not necessarily provide adequate IAQ, however, occupants’ good practice of ABs is also required. Average occupancy densities to have CO₂ levels of 1000 ± 50 ppm are suggested to be 2.3 ± 0.05 m³/p and 7.6 ± 0.25 m³/p. These values correspond to the classroom area of 62.1 ± 1.35 m² and volume of 205.2 ± 6.75 m³ with a height of 3.3 m. Mean CO₂ level is maintained below 900 ppm when all occupant-related factors are in the favour of IAQ, however, it exceeds 1300 ppm when none of the occupant-related factors are in favour of IAQ.

It is shown that 17% of CO₂ variations are explained by open area (m²), 14% by occupants’ generation rates (cm³/s) and 11% by occupancy density (m²/p). IAQ is mostly affected by occupants’ adaptive behaviours than other occupant-related factors in naturally-ventilated classrooms.

1. Introduction

Children spend almost 12% of their life inside classrooms, that is more time than in any other building except their home [1,2]. School and government authorities should ensure that appropriate indoor air quality (IAQ) is maintained for children [3]. IAQ in schools is recognized as one of the most important factors affecting students’ health [4–9] and academic performance [10–13]. IAQ in classrooms is mainly assessed by CO₂ levels [14–18], especially in buildings where people, exhaled air or bio-effluents are the main pollution sources [19]. Authors have previously suggested [20] that the main factors influencing IAQ in buildings fall into three categories of Context, Occupant and Building (COB). 1) Contextual factors on the macro level such as climatic conditions [21] and season [22–24], or the micro level such as regional temperature [25] and draughts from windows [26], 2) Building-related factors such as airtightness [27,28], schools’ location, classrooms and windows’ design [21], type of ventilation, ventilation rate [27], CO₂ exhalation rate and room volume [29], 3) Occupant-related factors such as occupants’ behaviour [26,27], maintenance and operation of systems, operating schedule [27], number of occupants [28,30], activity levels, amount of time spent in the room, previous room’s occupancy [23], occupants’ age and diet [9,25], and individual’s thermal comfort [5].

It is important to focus on occupant-related factors affecting IAQ in primary schools for four main reasons; 1) Children have physical and physiological differences with adults [31–35], which makes them more vulnerable and less resistant than adults to health risks from environmental hazards [36–41]. Physically, children have a smaller body surface area [42], have narrower airways [43,44], their organs, tissues and immune system are not fully developed [45] and their body’s defence against infection is limited [44]. Children breathe in more air (approximately 50% more) into their developing lungs relatively to their body weight [46,47]. Physiologically, children have higher metabolic and respiration rates [48] which results in children producing heat at a rate of 85% of that for adults [49,50]. 2) Due to above-mentioned differences...
and also teachers’ role in controlling classrooms [51,52], children’s environmental adaptive behaviours are more limited than that for adults [53–55]. The impact of poor IAQ on children is exacerbated because they usually do not complain about it [55,56]. 3) Classrooms are more crowded than other workplaces [45,57] and occupancy density of classrooms is about four times higher than that of office buildings [58]. Therefore, CO₂ exhalation rate can be higher in schools. 4) Children’s perception of IAQ can negatively be affected by external factors, such as type of their work [45,55] and their stress level [59]. Children’s work in schools is almost always new to them, while adults frequently perform routine tasks [55]. Thus, the effect of environmental conditions on schoolwork performance by children is larger than that on office-work performance by adults [60].

Healthy IAQ is vital for the health of children as they are more sensitive towards indoor air pollutants. Hence, the effect of occupant-related factors on IAQ is remarkable in the context of primary school buildings, especially considering potential unpredictability of occupant-related factors. This paper aims to provide a detailed analysis of IAQ as a function of occupant-related factors during heating and non-heating seasons to deliver healthier classrooms for the next generation of children.

2. Methodology

The main steps carried out in this methodology are 1. Sampling climate, building, windows’ design and occupants, 2. Acquiring data on adaptive behaviours, occupancy patterns, and environmental measurements, 3. Calculating occupants’ CO₂ emission rate 4. Reviewing Standards, 5. Overviewing recorded data.

2.1. Sample selection

In this study, samples were selected with specific attention to the climate in which buildings were located, buildings and their neighbourhood, windows within the buildings and buildings’ occupants.

2.1.1. Climate

The study was carried out in Coventry, West Midland, with a mild climate according to Koppen classification [61] from mid-July 2017 until the end of May 2018 to represent all climatic conditions. Schools were selected in the mild climate of the UK because mild or temperate climates can provide opportunities for buildings’ natural ventilation [62–65] and can reduce the biased impact of extreme climates on window operation in NV buildings.

2.1.2. Buildings

To study the effect of occupant-related factors, especially adaptive behaviours on IAQ, selected schools met five criteria. 1) Selected schools in this study are naturally ventilated since the main source of ventilation in most UK schools is windows. Furthermore, variations in temperature, humidity and pollutants from mechanical ventilation and air-conditioning systems [66] can limit our understanding about IAQ in buildings and its relation with occupants. 2) Buildings were selected in quiet areas to not restrict window operation due to high background noise level, as supported in Ref. [67,68]. 3) Buildings were selected in low-polluted areas to not restrict window operation due to high pollution level, as supported in Ref. [15,16,68]. 4) Buildings were selected with different architectural features as different buildings provide different potentials for practising adaptive behaviours (ABs), Table 1.5) Schools were selected among both renovated and existing buildings

| General | Classroom | Window Design | W Operation | NO³ | Density⁶ | AB ⁷ |
|---------|-----------|---------------|-------------|-----|---------|------|
| Mode    | Area      | No. | WA² | NW³ | W Type | Ventilation | MW⁴ | M²/ | M²/ | P  | P  |
| Non-heating 1.1 | 60 | 192 | 8 | 8 | Top-hung outward | Single-sided windows at 2 level | 1 | Manually | 25 | 2.4 | 7.7 | H |
| 1.2 | 60 | 8 | 8 | 8 | openings at 2 levels | + louvre opening | 1 | Manually | 25 | 2.4 | 7.7 | H |
| 1.3 | 60 | 8 | 8 | 8 | 1 | Manually | 25 | 2.4 | 7.7 | H |
| 1.4 | 60 | 8 | 8 | 8 | 1 | Manually | 28 | 2.1 | 6.9 | H |
| 2.6 | 60 | 192 | 8 | 8 | Top-hung outward | Single-sided windows at 2 level | 1 | Manually | 29 | 2.1 | 6.6 | H |
| 2.7 | 60 | 8 | 8 | 8 | openings at 2 levels | + louvre openings | 1 | Manually | 26 | 2.3 | 7.4 | H |
| 2.8 | 60 | 8 | 8 | 8 | 1 | Manually | 30 | 2.0 | 6.9 | H |
| 2.8 | 60 | 8 | 8 | 8 | 1 | Manually | 28 | 2.1 | 6.9 | H |
| Heating 3.10 | 65 | 227 | 2 | 5 | Top-hung outward | Single-sided | 1.7 | Manually | 25 | 2.6 | 9.1 | L |
| 3.11 | 70 | 245 | 2.2 | 6 | | Double-sided | 1.6 | Manually | 28 | 2.5 | 8.8 | L |
| 3.12 | 60 | 192 | 2.5 | 5 | | Single-sided | 2.6 | With handle | 25 | 2.4 | 7.7 | L |
| 4.13 | 50 | 130 | 0.5 | 2 | Top-hung outward | Single-sided | 1.8 | Manually | 27 | 1.9 | 4.8 | L |
| 4.14 | 60 | 156 | 0.5 | 2 | | Double-sided | 1.8 | Manually | 26 | 2.3 | 6.0 | L |
| 4.15 | 50 | 175 | 0 | 0 | No opening | – | No window | 29 | 1.7 | 6.0 | L |
| 5.16 | 55 | 137 | 5.7 | 8 | Top-hung openings at 2 levels | Single-sided at two levels | 0.5 | Manually | 30 | 1.8 | 4.6 | H |
| 5.18 | 55 | 5.7 | 8 | 8 | 0.5 | Manually | 27 | 2.0 | 5.1 | H |
| 5.20 | 55 | 5.7 | 8 | 8 | 0.5 | Manually | 32 | 1.7 | 4.3 | H |
| 6.21 | 60 | 168 | 1.8 | 4 | Top-hung outward | Single-sided windows + Louvre openings | 2.3 | Remote control | 29 | 2.1 | 5.8 | L |
| 6.22 | 60 | 1.8 | 4 | opening | 2.3 | Manually | 28 | 2.1 | 6.0 | L |
| 6.23 | 60 | 1.8 | 4 | 2.3 | Manually | 30 | 2.0 | 5.6 | L |
| 6.24 | 60 | 1.8 | 4 | 2.3 | Manually | 29 | 2.1 | 5.8 | L |
| 6.25 | 60 | 1.8 | 4 | 2.3 | Manually | 30 | 2.0 | 5.6 | L |
| Non-heating 7.26 | 70 | 252 | 3.9 | 6 | Top-hung outward | Double-sided | 2.7 | With handle | 29 | 2.4 | 8.7 | L |
| 7.27 | 55 | 137 | 3.3 | 3 | opening | Single-sided | 1.65 | Manually | 27 | 2.0 | 5.1 | H |
| 7.28 | 55 | 137 | 5.4 | 6 | | Double-sided | 1.6 | Manually | 30 | 1.8 | 4.6 | H |
| 8.29 | 60 | 150 | 2.2 | 4 | Top-hung outward | Single-sided | 1.4 | Manually | 28 | 2.1 | 5.4 | L |
| 8.30 | 60 | 150 | 2.2 | 4 | opening | 1.4 | Manually | 29 | 2.1 | 5.2 | L |
| 8.31 | 55 | 137 | 2.2 | 4 | | Double-sided | 1.4 | Manually | 24 | 2.3 | 5.7 | L |
| 8.32 | 55 | 137 | 2.2 | 4 | | Double-sided | 1.4 | Manually | 26 | 2.1 | 5.3 | L |

1 = Volume(m³); 2 = Window Area (m²); 3 = Number of Windows- 4 = Minimum Height of window sill (m); 5 = Number of Occupants- 6 = Occupant Density (m²/ number of students and m²/number of students)- 7 = Potentials for practice of AB.
because they should comply with different IAQ standard. Schools 1, 2 and 6 (13 classrooms) are among renovated schools and the rest (16 classrooms) are among existing buildings. In total, 29 naturally ventilated classrooms in eight primary schools were selected and studied during non-heating (NH) and heating (H) seasons, Table 1. Further details on the selection of the school buildings can be found in an earlier study by authors [52].

2.1.3. Windows
 To study how window design affects occupants’ Adaptive Behaviour (AB), classrooms are classified into two groups that provide high or low potentials for the practice of ABs based on a comprehensive literature review on window design.

Windows’ design: High and low-level openings by reducing draughts in the occupied zone and directing the airflow above the occupied head height zone can reduce CO₂ concentrations without discomforting occupants [15]. It is shown that large openings can be used for still summer days and small high-level openings can be used for winter days to avoid overheating [50,69]. Windows at different levels (high and low-level openings) and sizes (small and large) can provide IAQ [15,20,50,69–71] during both heating and non-heating seasons. Therefore, classrooms with windows at different levels and sizes can potentially increase occupants’ practice of ABs. Columns 5–9 in Table 1 (under window design section) show windows’ area, number of windows, windows’ type, ventilation type and a minimum height of operable windows, respectively.

Windows’ operation: Windows’ operation method affects occupants’ practice of ABs; it is shown that manual operation of windows helps to improve IAQ significantly [20,30,40,72,73] and makes people feel more comfortable in manually-controlled buildings [20]. Based on children’s physiology, safe windows designed at lower heights are more accessible for children’s window operation [20,52]. Therefore, classrooms that provide windows at accessible heights with manual and easy operation for children can potentially increase occupants’ practice of ABs. Windows operated with a remote control or a handle suggest lower operation potentials for practice of ABs. Column 10 in Table 1 shows windows’ type of operation. Classrooms that provide both of above criteria are classified as classrooms with high potentials for practice of ABs. The last column in Table 1 shows that 13 classrooms provide high potentials for practice of ABs and 16 classrooms provide low potentials for practice of ABs.

Fig. 1 shows a classroom with single-sided double openings at two different sizes and levels that are operated manually alongside the length of the classrooms (school 5). Fig. 2 shows a classroom with 2 small windows at the height of 1.8 m located at the end of the classroom (school 4).

2.1.4. Occupants
 Among primary school students, children in their late middle childhood (9–11 YO) compared to their peers in early middle childhood (6–9 YO) were selected as the main respondents of this study. Children in late middle childhood compared to their peers have a better understanding of their environment [52] and have higher heights according to UK-World Health Organisation growth charts [42] which let them be more engaged in environmental adaptive behaviours. Furthermore, older children are allowed to move around during classroom breaks and operate controls, whereas younger children are kept under stricter supervision inside the classrooms [74].

2.2. Data acquisition
 The overview of behavioural studies shows that they mostly use transverse method to collect data [75–83], therefore, the study applies the transverse method. Hence, data acquisition and observations were carried out in 29 different classrooms on 29 distinct days throughout one year. To increase the validity of the study and reduce bias, the number of studied classrooms is similar during both seasons, 15 classrooms during non-heating and 14 classrooms during heating seasons. Table 1 shows the number of studied classrooms, the season at which each classroom was studied and the number of observed children in each classroom.

An observation form that was developed and validated in an earlier study by authors [84] is used to obtain information on architectural features, occupancy patterns and controls’ operation, Table 2. Observations were conducted to have an in-depth understanding of factors affecting IAQ, as applied in another study [85]. Occupancy patterns and window operations are observed at 10-min intervals.

Schools’ occupied period is divided into three categories, teaching, non-teaching and total period. In this study, teaching period accounts for 75.4% of the times and non-teaching period, consisting of lunch supervision inside the classrooms [74].

2.2.1. Environmental measurements
 Environmental variables affecting occupants and their adaptive behaviours 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) at a height of 1.1 m as recommended by ISO 7726 [86]. Specifications of the measuring equipment are shown in Table 3.

The instruments were usually set up in the classrooms before children’s arrival in the morning and continued recording until the end of the school day (08:50–15:30). Time-lapse cameras were installed inside the classrooms to record occupants’ adaptive behaviours on blinds and doors at 5-min intervals.

2.3. Carbon dioxide (CO₂) generation (G)

CO₂ generation (G) is calculated based on children’s age, metabolic
rate, body surface area and room temperature. CO₂ generation for an average child is given in Equation (1) [26]:

\[ G = \frac{-0.94(A - 5) + 52.3}{40} \]

(1)

Where

\[ k = \frac{0.148am + 273}{273} \]

(2)

\( G \) (kg/s) is CO₂ generation

\( A \) (years) is children’s age

\( m \) (W/m²) is the metabolic rate

\( a \) (m²) is body surface area

\( t_r(°C) \) is room temperature

Body surface area is calculated from Dubois equation (3) [26] when

\[ a = 0.202w^{0.425}h^{0.725} \]

(3)

Children’s height and weight were derived from UK-World Health Organisation growth charts (average weight = 32 Kg and average height = 1.38 m) [42]. Average body surface area of 9–11 years old children was found 1.1 m² [42].

Metabolic Equivalent of Task (MET) is the ratio of the working metabolic rate to the metabolic rate at resting condition [41]. MET equals the energy produced per unit surface area of an average person (1.8 m²) seated at rest [58], where 1 MET = 58.2 W m⁻² for seated relaxed activities [58,86]. MET expresses physical activity of humans and varies with type of activity [86]. Metabolic rate of children can be modified by considering 0.85 value to metabolic rate of adults [87,88] because children produce heat at a rate of 85% of that for adults [15,49,50]. Metabolic rate of 1.2 corresponds to CO₂ concentration of approximately 900 ppm, assuming outdoor CO₂ concentration of 400 ppm [89]. The study by Havenith (2007) has estimated metabolic rate (W·m⁻²) of 9–11 years old primary school children for different school activities (language = 52, writing = 53, art = 59, drawing = 62 and calculus = 64 W·m⁻²) [32]. Metabolic rate of children [32] and adults [87] for different activities is shown in Table 4.

Calculated CO₂ generation rate per child according to equation (1) ranges from 3.34 to 5.89 cm³/s with a median of 3.41 cm³/s and mean of 3.64 cm³/s. Several other studies have reported similar CO₂ generations per child; 4.4–5.15 cm³/s in Ref. [28,29], 3.8–4 cm³/s in Refs. [26], 3.75–4.57 in Ref. [90], and 4.4 cm³/s in Ref. [27].

### 2.4. IAQ standards

The European standard of EN 13779:2007 [91] recommends IAQ values in four different building categories in Table 5. I) high level of expectation for spaces occupied by sensitive people, II) normal level of 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 CO₂ level of 1000 ppm [92].

### 2.5. Statistical analysis

To decide on the most appropriate statistical test, the dependent variable and its type should be identified. To check the normality of CO₂ values in this study, the histogram is used, as supported in Ref. [93]. Fig. 3 shows that CO₂ measurements are not normally distributed, therefore, none-parametric tests are used, as supported in Refs. [94,95].

Statistical analysis in this study is categorized into four main groups: 1) Descriptive, 2) Correlational, 3) predictive and 4) Group differences (cause and effect). Table 6 shows a summary of tests done in

| Table 2 |
| --- |
| Questions on architectural features, occupancy patterns and adaptive behaviours taken from questionnaires developed by authors [84]. |

| Variables | Questions and Responses |
| --- | --- |
| Occupation Patterns | No. Students in the classroom? Type of subject? (Math, English, Art, ...) |
| Type of activity? (Seated, Reading and writing, Standing and tidying, singing, dancing or performing) |
| Occupancy pattern in the classroom? (Occupied, Not occupied, Left for break, Left for Lunch, Left for assembly, Left for home) |
| Windows operation | Total open area (m²)? ... Total number of window adjustments? ... |
| Classrooms' architectural features | Classroom area (m²)? ... Total area of operable windows (m²)? ... |
| Type of window operation? (Window opens and shuts automatically, handles to control) |
| Type of window opening? (Top hung, Slide hung, Horizontal slider, Chopper, Sliding, Casement) |
| Depth to Height Ratio? ... Openings area to classroom area? ... Min Height of operable windows? ... |
| Type and number of doors? (Connecting door between classes, internal door, external door) |

| Table 3 |
| --- |
| Specifications of the measuring equipment shown in an earlier study by authors [84]. |

| Probe | Variables | Meas. Range | Resolution |
| --- | --- | --- | --- |
| SWEMA | Humidity and air temperature | 0 to 100 %RH | 0.1% RH |
| | Air velocity and, | 0 to +60 °C | 0.1 °C |
| | Air temperature | 0.05–3.0 m/s | 1 m/s |
| | | 15–30 °C | 0.1 °C |
| | Radiant temperature (Ø globe: approx.150 mm) | 0 to +50 °C | 0.1 °C |
| Data | Temperature | –35 to +80 °C | 0.1 °C |
| Logger | Humidity | 0 to 100 %RH | 0.5% RH |
| TGE-0011 | CO₂ | 0–5000 ppm | 1 ppm |

### Table 4

| Children [32] | Adult [87] |
| --- | --- |
| Type of activities for children | W/ m² | MET | Type of activities for adults | W/ m² | MET |
| Seated activities | 58 | 1 | Seated activities (Office, dwelling, school, laboratory) | 70 | 1.2 |
| (working individually, listening, writing and following) | | | Standing (shopping, laboratory, light industry) | 93 | 1.6 |
| Standing (walking through classroom to get material and light manual work) | 79 | 1.3 | | |
| Standing, medium activity (signing and adjusting clothing for PE) | 99 | 1.7 | Standing, medium activity (shop assistant, domestic and machine work) | 116 | 2 |
Summary of all tests in this study.

Table 6

| Variables | Independent | Dependent | Corresponding Test | Variables in this Study | Independent |
|-----------|-------------|-----------|--------------------|-------------------------|-------------|
| 1 interval IV | ordinal or interval (Skewed Data) | Spearman correlation test | CO₂ levels | Open area (m²), G (cm³/s), OD (m³/p, m³/p) |
| 1 IV with 2 levels | ordinal or interval (Skewed Data) | Mann-Whitney test | CO₂ levels | Two Seasons Occupied groups (teaching and break) |
| 1 IV with 2 or more groups | ordinal or interval (Skewed Data) | Non-parametric Kruskal-Wallis test | CO₂ levels | Categories for ABs (potential and practice), Categories of occupant-related factors |

Distribution of CO₂ levels: Frequency (%) of CO₂ measurements falling in four categories of EN 13779:2007 [91] is shown in Fig. 7. During non-heating seasons, 29.1% of CO₂ measurements fall in category I (CO₂ < 800 ppm), 20.1% in category II (800 < CO₂ < 1000 ppm), 27.5% in category III (1000 < CO₂ < 1400 ppm) and 23.2% in category IV (CO₂ > 1400 ppm), Fig. 7. During heating seasons, 13% of CO₂ measurements fall in category I, 27% in category II, 30.6% in category III and 29.4% in category IV, Fig. 7. Category I has the highest frequency (29.1%) of CO₂ measurements during non-heating seasons and category III has the highest frequency (30.6%) during heating seasons.

Overall, 45% of CO₂ measurements in this study are below 1000 ppm and 55% of all CO₂ measurements are above 1000 ppm. In a similar study, 53% of CO₂ measurements exceed concentration value of 1000 ppm due to classrooms’ insufficient ventilation. Results of another study show that 17% of the measurements exceeded ASHRAE’s upper limit of 1,000 ppm, and 34% exceeded CO₂ level of 850 ppm [59], because windows and doors were usually kept open during most of occupancy hours [59].
Mean and Median CO\textsubscript{2} levels: In this study, mean CO\textsubscript{2} concentrations during teaching periods (1087(NH), 1224(H) and 1155 (T)) are above 1000 ppm which is recommended by ASHRAE standard 62 [92] and several other studies [3]. Average CO\textsubscript{2} level in this study is higher than average of 1070 ppm in Ref. [25] due to frequent window openings [25] and it is lower than average of 1957 ppm in Refs. [26] due to not frequent window opening [26]. In this study, mean CO\textsubscript{2} concentration for total occupied period (T) is slightly lower than that for teaching period because total period includes non-teaching period with low occupancy density. This finding is supported in Ref. [30] with lower CO\textsubscript{2} levels during non-teaching period (1055 ppm) than teaching period (1482 ppm) [30]. In this study, daily mean concentrations exceed 1000 ppm in 55% of the classes, exceed 1500 ppm in 10% of the cases and exceed 2000 in 3% of cases. In a similar study [25], daily mean concentrations exceed 1000 ppm in 52% of NV classes, exceed 1500 ppm in 29% of cases and exceed 2000 ppm in 10% of classes [25]. In another study, median CO\textsubscript{2} level during school day exceeds 1000 ppm in only 28% of classrooms due to use of mechanical ventilation systems in Ref. [90].

### Table 7

Descriptive Statistics of CO\textsubscript{2} levels for teaching and total period.

| Mode           | Period       | N  | Minimum | Maximum | Mean  | Median | S.D. |
|----------------|--------------|----|---------|---------|-------|--------|------|
| Non-heating (NH)| Teaching     | 359| 475     | 3360    | 1087  | 1002   | 440  |
|                | Total        | 526| 475     | 3430    | 1050  | 953    | 444  |
| Heating (H)    | Teaching     | 358| 555     | 2269    | 1224  | 1125   | 422  |
|                | Total        | 443| 555     | 2659    | 1208  | 1084   | 427  |
| Whole Year (WY)| Teaching     | 717| 475     | 3360    | 1155  | 1063   | 436  |
|                | Total        | 969| 475     | 3430    | 1122  | 1021   | 443  |

Fig. 4. Cumulative frequency (%) of CO\textsubscript{2} measurements.

Fig. 5. Number of classrooms with high and low potentials for ABs in each category of IAQ.

Fig. 6. Number of renovated and existing classrooms in each category of IAQ.

### 3.2. CO\textsubscript{2} levels and occupant-related factors

Occupant-related factors that affect IAQ including occupants’ adaptive behaviours, occupancy patterns, occupants’ CO\textsubscript{2} generation rate and occupancy density are presented in Fig. 8.

#### 3.2.1. Occupants’ adaptive behaviours (ABs)

Due to the significant effect of adaptive behaviours on IAQ [26,59, 102,103], this study focuses on window operation as the main environmental practice.

**Window Operations; Potentials and Practices:** In this study, 45% of classrooms provide high potentials for practising ABs, however, it is also important to consider school occupant’s practice of environmental ABs. This study introduces two terms of ‘good practice’ and ‘poor practice’ for occupants’ environmental ABs. Good practice suggests occupants’ adequate operation of windows to erase accumulated CO\textsubscript{2} concentrations (average open area more than 50% in each classroom)
and poor practice suggests occupants’ inadequate window operation to provide IAQ (average open area less than 50% in each classroom).

The study has defined four groups of ABs based on potentials and practices; 1) High potentials and good practice, 2) High potentials and poor practice, 3) Low potentials and poor practice, 4) Low potentials and good practice. Results of the Kruskal-Wallis test show that there is a significant difference in median CO$_2$ levels ($X^2 (3) = 24.3, p = 0.001$) between these defined groups, Fig. 9. To test categorical independent (such as groups of ABs) with interval dependent (such as CO$_2$ levels), analysis of covariance is used. Mean CO$_2$ levels in defined categories are 896, 1459, 1380 and 1007 ppm, respectively. Mean CO$_2$ level is lowest in group 1 (high potentials and good practice) and then in group 4 (low potentials and good practice), Fig. 9. To test categorical independent (such as groups of ABs) with interval dependent (such as CO$_2$ levels), analysis of covariance is used. Mean CO$_2$ levels in defined categories are 896, 1459, 1380 and 1007 ppm, respectively. Mean CO$_2$ level is lowest in group 1 (high potentials and good practice) and then in group 4 (low potentials and good practice), Fig. 9. Classrooms with good practice (mean = 896 and 1007) compared to classrooms with poor practice (mean = 1459 and 1380) can provide lower CO$_2$ levels disrespectful of their potentials for ABs. Results show that to maintain mean and median CO$_2$ levels lower than 1000 ppm, classrooms with both high potentials and good practice are required, however, occupants’ practice is more important than classrooms’ potentials. This suggests that classrooms with high potentials do not necessarily lower CO$_2$ levels and good practice of ABs is also required.

It is shown that ‘high performance’ buildings do not determine CO$_2$ levels [27]; IAQ is mostly affected by maintenance, operation practices, operating schedule and teacher behaviour [27]. Another study indicates that classrooms should be designed capable of supplying enough fresh air, however, occupants should avail themselves of this capability [26]. This study suggests that good practice of ABs at the right time can prevent CO$_2$ build-up and increase IAQ, as supported in Refs. [15,26,27,59,102,103]. A review of published studies spanning 1983–2013 suggests that behavioural changes have the potential to reduce indoor air pollution by 20%–98% in laboratory settings and 31%–94% in field settings [104].

**Window Operation and Environmental Variables:** In studied classrooms, teachers are mainly in charge of window operations, as supported in previous studies [40,105,106], and only 16% of operations are carried out by children. To discover how window openings are affected by environmental variables, CO$_2$ levels and operative temperatures ($T_{op}$) at which windows are opened and average CO$_2$ levels in corresponding classrooms are plotted in Fig. 10. Results of this study show that CO$_2$ levels at which windows are opened and average CO$_2$ levels in corresponding classrooms are strongly correlated (Spearman Correlation coefficient $= 0.60, P < 0.001$). According to Cohen’s classification [98], high correlation coefficient and small $P$ values suggest a strong correlation.

Results show that 52% and 16% of window openings occur when CO$_2$ levels are higher than 1000 and 1500 ppm, respectively. Around half (52%) of window openings in this study occur when CO$_2$ levels $>1000$ ppm which can be attributed to following reasons: 1. Window
Building and Environment 180 (2020) 106992

8

operation can be affected by inappropriate design of windows and controls, as supported in Refs. [20,52]. Furthermore, some openings are not designed based on children’s ergonomics [51,52]. In this study, 55% of classrooms provide low potentials for practice of ABs. 2. Window operation is more limited and less frequent among children than their teachers as they are mainly in charge of controlling classroom condition [40,52,56,105]. Authors highlight that only 16% of environmental ABs are done by children in this study due to the above reasons. 3. Window operation can also be affected by operative temperature. Teachers who are mainly in charge of the classrooms have higher comfort temperature than children [52,105,107]. According to an earlier study by authors [52], the upper limit of thermal comfort band for studied children is around 23 °C in this study, while for their teacher the upper limit is higher. Fig. 10 shows that among cases that window opening occurs at CO₂ levels higher than 1000 ppm, 20% of them have T_{op}<23 °C. This suggests that despite high concentrations (CO₂ > 1000 ppm), windows were kept closed by teachers to avoid their thermal discomfort in 20% of the cases.

Windows’ Open Area and IAQ: Occupants’ environmental adaptive behaviours by changing total open areas (open windows and external doors) affect IAQ. Results show that CO₂ levels and total open areas are significantly correlated during non-heating (Spearman Correlation coefficient = −0.32, P < 0.001) and heating seasons (Spearman Correlation coefficient = −0.45, P < 0.001). Results suggest negative moderate correlations between CO₂ levels and total open areas for non-heating (−0.32) and heating seasons (−0.45). To investigate how changes in CO₂ levels are explained by total open areas (m²), open areas and CO₂ measurements at 10-min intervals are plotted in Fig. 11. R² values in Fig. 11 suggest that 13% and 31% of CO₂ variations are explained by open areas during non-heating and heating seasons, respectively. Combining data from heating and non-heating seasons suggest that 17% of CO₂ variations are explained by open areas.

Correlations and R² values between CO₂ levels and open areas are higher during heating seasons than non-heating seasons. It is mainly
because open areas during non-heating seasons are more correlated to $T_{op}$ (Correlation coefficient = 0.53, $P < 0.001$) than CO$_2$ levels (Correlation coefficient = -0.32, $P < 0.001$). However, open area during heating seasons is more related to CO$_2$ levels (Correlation coefficient = 0.45, $P < 0.001$) than $T_{op}$ (Correlation coefficient = 0.29, $P < 0.001$).

Previous studies suggest that windows and doors are operated more when temperature is high [108, 109] rather than when IAQ is poor [110], mainly because poor IAQ is not perceived due to gradual sensory fatigue or adaptation [15, 111].

**Window operation and Seasonal Changes:** There is evidence that seasonal variations affect CO$_2$ concentrations indirectly by changing occupants’ ABs [112]. Figs. 12 and 13 show changes in CO$_2$ levels and open areas during non-heating and heating seasons. Results of Mann-Whitney test in this study confirm that median CO$_2$ levels are significantly different during heating and non-heating seasons ($U = 88399$, $p = 0.000$). These Figures show that mean and median CO$_2$ levels are 137 ppm and 123 ppm higher during heating seasons than non-heating seasons due to lower average open areas during heating seasons (0.8 m$^2$) than non-heating seasons (2.4 m$^2$). Window operation is less frequent during heating seasons due to cold or draught [22, 24, 74, 113] and energy consumption [110], which results in lower average open areas. It is shown that meeting IAQ requirements without compromising thermal comfort is difficult during heating season [113].

Results of a similar study show that median CO$_2$ values during heating seasons (1400 $< \text{Median CO}_2 < 3000$ ppm) are higher than those during non-heating seasons (Median$\text{CO}_2 < 1000$ ppm), which is due to higher open windows during non-heating seasons [5]. Average CO$_2$ concentrations are 1.2–3.5 times higher during heating seasons compared to non-heating seasons due to open windows during non-heating seasons [5]. Another study shows that average CO$_2$ concentration reaches to almost 2500 ppm in one of the schools due to limitations in window opening during the winter [38]. In another study, mean CO$_2$ concentrations remain below 1000 ppm in all schools during the summer [38].

Due to the effect of occupant behaviour on IAQ [103, 104], motivating and training school occupants for appropriate adaptive behaviours help to improve IAQ [21]. Several studies have shown that CO$_2$ warning devices by reminding occupants of the time at which windows should be operated can decrease CO$_2$ levels [55, 63, 103, 114, 115].

**3.2.2. Occupancy patterns:**

There is evidence that occupancy patterns affect CO$_2$ levels generated in indoor environment [23, 25, 28, 41, 74, 85, 102, 116, 117]. An overview of the results in this study shows that occupancy patterns and CO$_2$ levels in studied schools are dynamic and varied, as suggested in similar studies [112]. Fig. 14 shows mean and median CO$_2$ values from all 29 classrooms against time of day. As can be seen in Fig. 14, mean and
Building and Environment 180 (2020) 106992

median lines are similar which suggests data’s symmetrical distribution. Similar studies support that small difference between mean and median shows symmetrical distribution [96].

The observation and trend suggest that teachers usually arrive before children at 8:00 and they possibly operate windows based on the classroom’s temperature and IAQ. Children get into the classroom around 8:40–08:50 to start teaching session at around 9:00. Children often remain in the classroom for 2 h before they leave for a short break (10:50–11:10 a.m.). According to Fig. 14, mean CO₂ concentration goes up to 1350 ppm until the first break and reduces to 1190 ppm during the first break (12% reduction). Breaks are not long enough to decrease CO₂ levels significantly, however, longer breaks for assembly or Physical Education (PE) can decrease CO₂ levels more noticeably. After the first break, children remain in the classroom until lunch break (12:10–13:10). Longer lunch breaks can lower mean CO₂ levels from 1250 ppm to around 800 ppm (36% reduction). After lunch break, mean and median CO₂ levels usually increase until the end of afternoon session (15:20). It is shown that periodical absence of students during recess times is one of the main reasons behind periodical drop and rise of CO₂ concentrations in classrooms [41]. This trend for rising and fall of CO₂ levels in studied schools is suggested in several other studies [90, 102].

Fig. 14 shows that mean and median CO₂ levels are higher at the end of morning sessions (approximately 12:20 pm) compared to afternoon sessions (approximately 3:30 pm) due to longer morning sessions and accordingly more CO₂ built-up. Furthermore, longer lunch breaks (causing 36% reduction in CO₂ levels) compared to short breaks (causing 12% reduction in CO₂ levels) can clear accumulated CO₂ levels more significantly, as supported in Ref. [59]. Results of another study show the effect of scheduled breaks on maintaining CO₂ levels in different building types; 35% reduction for renovated schools, 25% reduction for new schools and 5% reduction for old schools [74]. The reduction of 160 ppm during the first break which is usually around 20 min shows a decrease of 8 ppm/min among studied classrooms. Similarly, reduction of 450 ppm during lunch break which is usually around 50 min shows a decrease of 9 ppm/min. Speed of clearance (ppm/min) is slightly higher during lunchtime than that during break which can be explained by larger open areas (2.3 m² v.s. 1.6 m²) during lunchtime. Another study by taking into account all school breaks from different buildings expects a reduction of 19.4 ppm/min [74], which gives a reduction of 250 ppm for a 13-min break [74]. Results of this study, as already supported in Ref. [74], suggest that although the effect of school breaks on decreasing pollutant concentration is significant, it is still insufficient to lower accumulated CO₂ levels within standards.

3.2.3. Occupants’ CO₂ generation (G) rates

Total CO₂ generation rate (G) from building occupants considers number of children, their age, metabolic rate, activity level, body surface area and room temperature [26]. In this study, children’s generation rates are calculated at 10-min intervals due to varied occupancy patterns. Generation rates per child (3.34–5.89 cm³/s) are multiplied by the number of children for calculating children’s generation rates at 10-min intervals. Generation rate of teachers (11 cm³/s) is added to this amount for total G. Fig. 17 shows box plots of total G for sedentary and non-sedentary activities. Mean G for sedentary activities (Reading and writing) equals to 97 cm³/s and for non-sedentary activities (Standing

Fig. 14. That is where the effect of adaptive behaviours consistent with occupancy patterns becomes more important.

Figs. 15 and 16 show changes in CO₂ levels and open area in box plots. Results of Mann-Whitney test in this study confirm that median CO₂ levels are significantly different during teaching and break period (U = 71293, p = 0.000). These figures show that higher CO₂ levels during teaching period (1156 ppm) compared to breaks (1032 ppm) which can be explained by higher mean open area during breaks (2.1 m²) compared to teaching period (1.8 m²). It is suggested that windows are closed during teaching period due to low exterior temperatures [74] or outdoor noise [103]. Therefore, this study recommends that by leaving windows open during breaks, accumulated CO₂ levels can be cleared without comprising children’s overall comfort, as supported in Refs. [41,74,103]. It is shown that IAQ during breaks can be 1–4 times higher than that during teaching period [25].

Fig. 15. Changes in CO₂ levels during occupied period.

Fig. 14. The trend for rising and fall of CO₂ levels during school occupancy based on 29 classrooms.
and walking) equals to 132 cm$^3$/s, Fig. 17. Similar studies support that students’ activity intensity contribute to classrooms’ CO$_2$ concentrations [85,116]. Effect of ‘activity type’ on CO$_2$ levels is more noticeable when two classrooms join for some activities or when children get back from play and bring a different heat load to classrooms [28].

Mean generation rates for sedentary activities in each classroom are plotted against mean CO$_2$ levels in Fig. 18. Results show that mean CO$_2$ levels and total generation rates are correlated (Spearman Correlation coefficient = 0.17, $P < 0.001$). $R^2$ value suggests that 14% of CO$_2$ variations are explained by average $G$, Fig. 18.

Considering average number of students in this study (25) and one standing teacher, total generation rate for sedentary activities is estimated at around 102 cm$^3$/s. According to Fig. 18, corresponding average CO$_2$ level for $G$ value of 102 cm$^3$/s is 1360 ppm. Considering that IAQ decreases when CO$_2$ production rate is greater than its removal rate [118], it is important to remove high emission rates from the building by the good practice of ABs.

### 3.2.4. Occupancy density (OD)

Accumulation of CO$_2$ levels vary within area and volume of the classroom, therefore, occupancy density should be considered for evaluating IAQ. Occupancy density is defined as the area per number of occupants (m$^2$/p) [119] or volume per number of occupants (m$^3$/p). In this study, occupancy density in m$^2$/p ranges from 1.7 to 2.6 m$^2$/p, with a mean of 2.1 m$^2$/p. Another study suggests occupancy density of 1.8–2.4 m$^2$/p for school classrooms which is significantly higher than that in offices (10 m$^2$/person) [57]. Several studies suggest that occupancy density in schools is approximately four times higher than that in office buildings since school occupants are sitting very close [57,58,112]. Occupancy densities (m$^2$/p) in classrooms are plotted against corresponding mean CO$_2$ levels in Fig. 19. Results show that CO$_2$ levels and OD (m$^2$/p) are correlated (Spearman Correlation coefficient = –0.14, $P < 0.001$). $R^2$ value in Fig. 19 shows that 17% of CO$_2$ variations are explained by occupancy density (m$^2$/p).

Occupancy densities (m$^2$/p) range from 4.3 to 9.1 m$^2$/p, with a mean of 6.3 m$^2$/p. Occupancy densities (m$^2$/p) in each classroom are plotted against mean CO$_2$ levels in Fig. 20. Results show that CO$_2$ levels and occupancy density (m$^2$/p) are correlated (Spearman Correlation coefficient = –0.13, $P < 0.001$). $R^2$ value in Fig. 20 shows that 11% of the variations in average CO$_2$ levels are explained by occupancy density (m$^2$/p).

Figs. 19 and 20 display that high occupancy densities cause high CO$_2$ concentrations, as suggested in several other studies [5,55,57,85,102,103,118,120]. Results of this study show that to maintain the average CO$_2$ level of 1000 ppm, occupant density should be at least 2.3 m$^2$/p and 7.6 m$^3$/p, Figs. 19 and 20. The suggested OD in this study complies with occupancy density recommended by Eurostat (2011), which is from 2 to 3.1 m$^3$/person based on 20.8 + 2.0 students for the average size of primary classrooms in European and American countries [121].

In this study, there are averagely 27 occupants (25 students + teacher + teacher assistant) in each classroom. Results of this study in Figs. 19 and 20 show that average occupancy densities to have CO$_2$ levels of 1000 ± 50 ppm is 2.3 ± 0.05m$^2$/p and 7.6 ± 0.25 m$^3$/p. These values correspond to classroom area and volume of 62.1 ± 1.35 m$^3$ and 205.2 ± 6.75 m$^3$ with a height of 3.3 m. Building Bulletin 99 (Briefing Framework for Primary School Projects) also suggests that the ‘standard’ size of a primary classroom for 30 pupils is around 70 m$^2$ (2.3 m$^2$/person) [122]. Considering the shortage of space in the educational sector [123–125], if providing the recommended area is not possible for the designer, classrooms’ height can be increased to more than 3.3 m to maintain the required volume for maintaining IAQ. The focus of guidelines for recommended OD (m$^2$/p) is mainly on providing the required area for children’s physical activities. However, this study highlights the importance of all three dimensions in OD values (m$^3$/p) for maintaining IAQ. It is important to keep the number of children in proportion to the classroom’s area and volume, also supported in Ref. [90], because overcrowded classrooms cause high CO$_2$ concentrations and high emissions of body odor [30,57,85,103,112,118]. It is shown that high-density classrooms, with too many children or too little space, lead to pupils’ stress, reductions in desired privacy levels and loss of control [120].

### 4. Discussion

The study has investigated occupant-related factors that affect IAQ including occupants’ adaptive behaviours, occupancy patterns, occupants’ CO$_2$ generation rate and occupancy density. Table 8 shows correlations and $R^2$ values between IAQ and occupant-related factors. Correlations and $R^2$ values in Table 8 suggest that among all occupant-related factors, occupant’s adaptive behaviours have the strongest correlation (−0.40) with CO$_2$ levels and account for the highest CO$_2$ variation (17%).

Therefore, when children’s number and type of activity result in high concentrations, good practice of ABs can clear accumulated CO$_2$ levels in classrooms.

#### 4.1. Comparing classrooms’ IAQ with standards

To evaluate IAQ in each classroom, average CO$_2$ levels in each classroom are compared with values recommended by EN 13779:2007 [91] and ASHRAE [92]. The last column in Table 9 shows occupant-related factors that potentially lead to high CO$_2$ levels in classrooms with the following acronyms:

- **AB for Adaptive Behaviours** when the poor practice of ABs is a potential reason for high CO$_2$ levels.
- **G for Generation Rate** when $G$ higher than 102 cm$^3$/s based on 25 sedentary students is a potential reason for high CO$_2$ levels.
OD for Occupancy Density when OD lower than 2.3 $m^2/p$ is a potential reason for high CO$_2$ levels.

As can be seen in Table 9, the reasons for high concentrations are related to one factor or a mix of occupant-related factors. Fig. 21 shows changes in CO$_2$ levels by the change in occupant-related factors. Results of the Kruskal-Wallis test show that there is a difference in median CO$_2$ levels $[X^2 (2) = 6.6, p = 0.038]$ when the number of favourable occupant-related factors are different, Fig. 21. According to Fig. 21, when all occupant-related factors can potentially reduce CO$_2$ levels, mean concentration is 893 ppm with the maximum of 964 ppm, when one or two occupant-related factors can potentially reduce CO$_2$ levels, mean concentration is 1122 ppm with the maximum of 1404 ppm and when none of the occupant-related factors can potentially reduce CO$_2$ levels, mean concentration is 1317 ppm with the maximum of 1979 ppm. This suggests that when all occupant-related factors are favourable, CO$_2$ levels below 1000 ppm can be maintained. However, when occupant-related factors are not favourable, it is less likely to maintain adequate CO$_2$ levels.

There is evidence that renovated schools provide more suitable conditions compared to non-renovated schools [21, 38]. In this study, 54% of renovated classrooms have CO$_2$ (mean) > 1000 ppm, among which 73% with the poor practice of ABs. Furthermore, 73% of classrooms with high potentials for ABs have CO$_2$ (mean) > 1000 ppm, among which 69% with the poor practice of ABs. This suggests that to maintain IAQ in existing and renovated school buildings, more focus should be directed at school occupants, their occupancy patterns and adaptive behaviours.

5. Conclusion

This paper was focused on occupants’ role for maintaining IAQ in naturally-ventilated primary schools during heating and non-heating seasons. The study highlights that IAQ is closely related to occupants’ adaptive behaviour, occupancy patterns, CO$_2$ generation rates and occupant density, however, the impact of occupants’ adaptive behaviours is more significant. Although classrooms’ potentials for facilitating adaptive behaviours is fundamental in maintaining IAQ, this study suggests that occupants’ interaction with the building (i.e. Good Practice of ABs) is more significant. Therefore, there is a need to encourage and train school occupants (i.e. teachers and children) for Good Practice of Adaptive Behaviours. Furthermore, teachers will have more effective ABs if they are trained about the impact of occupancy patterns and generation rates on CO$_2$ built-up. For example, when windows are left open during breaks or lunchtime, accumulated CO$_2$ levels are cleared without comprising children’s thermal comfort. Therefore, good practice of ABs is not only limited to occupants’ interaction with controls but also related to the correct time for interaction to maintain other elements of comfort (i.e. thermal comfort). Available guidelines mainly focus on OD ($m^2/p$) in two dimensions to provide the required area for children’s physical activities in classrooms; however, this study...
Table 8
Correlation and $R^2$ values between CO$_2$ levels and occupant-related factors.

| Occupant-related factors affecting IAQ | Correlation | P-value | Correlation by Cohen’s Classification | $R^2$ Value | Interpretation |
|----------------------------------------|-------------|---------|---------------------------------------|------------|----------------|
| Occupants’ adaptive behaviours: Open Area | $-0.40$ | $P < 0.001$ | Negative Moderate | 0.17 | 17% of CO$_2$ variations are explained by open area ($m^2$) |
| Occupants’ generation rates (cm$^3$/s) | 0.17 | $P < 0.001$ | Positive weak | 0.14 | 14% of CO$_2$ variations are explained by occupants’ generation rates (cm$^3$/s) |
| Occupancy density (m$^2$/p) | 0.14 | $P < 0.001$ | Positive weak | 0.17 | 17% of CO$_2$ variations are explained by occupancy density (m$^2$/p) |
| Occupancy density (m$^3$/p) | 0.13 | $P < 0.001$ | Positive weak | 0.11 | 11% of CO$_2$ variations are explained by occupancy density (m$^3$/p) |

Table 9
Comparing mean CO$_2$ levels in classrooms with Standards.

| Type | No. | Potentials for ABs | Occupant-related factors | CO$_2$ level | EN 13779 [91] | ASHRAE [92] | Factor |
|------|-----|-------------------|--------------------------|--------------|---------------|--------------|--------|
| Renovated | 1.1 | H | Open Area | 5.8 | H | 164 | 2.1 | 6.6 | 1058 | $\times$ | $\times$ | G, OD |
| 1.2 | H | 4.9 | H | 101 | 2.4 | 7.7 | 961 | ✔ | ✔ | – |
| 1.3 | H | 5.3 | H | 101 | 2.4 | 7.7 | 772 | ✔ | ✔ | – |
| 1.4 | H | 2.2 | L | 107 | 2.1 | 6.9 | 781 | ✔ | ✔ | AB, G, OD |
| 2.6 | H | 1.1 | L | 115 | 2.2 | 7.0 | 1119 | $\times$ | $\times$ | AB, G, OD |
| 2.7 | H | 1.2 | L | 77 | 3.5 | 11.2 | 1352 | $\times$ | $\times$ | AB |
| 2.8 | H | 1.2 | L | 79 | 4.4 | 14.0 | 1228 | $\times$ | $\times$ | AB |
| 2.9 | H | 2.5 | L | 114 | 2.1 | 6.9 | 1434 | $\times$ | $\times$ | AB, G, OD |
| Existing | 3.10 | L | 0.9 | H | 89 | 3.1 | 10.9 | 1202 | $\times$ | $\times$ | AB |
| 3.11 | L | 2.0 | H | 112 | 2.6 | 9.0 | 993 | $\times$ | $\times$ | G |
| 3.12 | L | 0.6 | L | 62 | 4.2 | 13.5 | 1369 | $\times$ | $\times$ | AB |
| 4.13 | L | 1.6 | H | 90 | 2.5 | 6.4 | 890 | ✔ | ✔ | – |
| 4.14 | L | 1.8 | H | 77 | 3.7 | 9.6 | 881 | ✔ | ✔ | – |
| 4.15 | L | 0.0 | L | 103 | 2.2 | 7.7 | 1273 | $\times$ | $\times$ | AB, G, OD |
| 5.16 | H | 0.1 | L | 119 | 2.1 | 5.1 | 1979 | $\times$ | $\times$ | AB, G, OD |
| 5.18 | H | 1.3 | L | 95 | 2.6 | 6.4 | 1308 | $\times$ | $\times$ | AB, G |
| 5.20 | H | 1.0 | L | 105 | 2.5 | 6.2 | 1261 | $\times$ | $\times$ | AB, G |
| Renovated | 6.21 | L | 1.3 | H | 84 | 2.3 | 6.4 | 964 | $\times$ | $\times$ | – |
| 6.22 | L | 0.0 | L | 109 | 2.2 | 6.2 | 1740 | $\times$ | $\times$ | AB, G, OD |
| 6.23 | L | 0.0 | L | 110 | 2.2 | 6.2 | 1249 | $\times$ | $\times$ | AB, G, OD |
| 6.24 | L | 1.1 | H | 125 | 2.2 | 6.1 | 909 | $\times$ | $\times$ | G, OD |
| 6.25 | L | 0.0 | L | 113 | 2.0 | 5.6 | 980 | $\times$ | $\times$ | AB, G |
| Existing | 7.26 | L | 0.3 | L | 113 | 2.5 | 9.0 | 956 | $\times$ | $\times$ | AB, G, OD |
| 7.27 | H | 3.9 | H | 106 | 2.0 | 5.1 | 761 | $\times$ | $\times$ | G |
| 7.28 | H | 3.0 | L | 108 | 1.9 | 4.6 | 1218 | $\times$ | $\times$ | AB, G |
| 8.29 | L | 1.7 | H | 107 | 2.3 | 5.6 | 887 | $\times$ | $\times$ | G, OD |
| 8.30 | L | 1.6 | H | 111 | 2.1 | 5.4 | 899 | $\times$ | $\times$ | G |
| 8.31 | L | 0.0 | L | 100 | 2.3 | 5.7 | 2487 | $\times$ | $\times$ | AB, OD |
| 8.32 | L | 1.7 | H | 111 | 2.1 | 5.3 | 1404 | $\times$ | $\times$ | G |

Fig. 21. CO$_2$ level according to the numbers of favourable occupant-related factors.
underlines the importance of height as the third dimension in OD values (m²/p) to maintain IAQ. This study suggests minimum occupancy densities of 2.3 m²/p and 7.6 m²/p for maintaining CO₂ level<1000 ppm in primary school classrooms.

Declaration of competing interest

None.

Acknowledgements

The authors would like to thank Professor James Brusey for his comments and insight that improved the paper. We would like to acknowledge headteachers, teachers and children in studied primary schools in Coventry for their cooperation. We appreciate financial support of Coventry University to complete this research.

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S. S. Korsavi et al. Building and Environment 180 (2020) 106992
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