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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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ABSTRACT

Indoor Air Quality (IAQ) in classrooms is assessed by CO_2 levels and Ventilation Rates (VRs). Factors affecting VRs fall into **C**ontextual, **O**ccupant and **B**uilding **(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. **B**uilding-related factors classify classrooms with high or low potentials for natural ventilation, with 45% of classrooms having high potentials. **C**ontextual factors including season, operative temperature (T_{op}), outdoor temperature (T_{out}), 'T_{op}-T_{out}' and air density can limit or increase VRs. **O**ccupant-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 m^2 and 2 m^2 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 CO_2 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 CO_2 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 CO_2 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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Nomenclature

Symbols

T_{op}	Operative Temperature (°C)
T_{out}	Outdoor temperature (°C)
V	Air Speed (m/s)
RH	Relative Humidity (%)
G	CO_2 generation (kg/s)
Q_v	Volume flow rate (m3/s)
$C_{(t)}$	Internal concentration of tracer gas (kg/m^3)
C_{ex}	External concentration of tracer gas (kg/m^3)
Q/V	Air change rate (ac/s)
t	Time (s)
W	Density of CO_2 levels (kg/m^3)
M_W	Gas molecular weight (Kg)
C_D	Discharge coefficient (0.6 for sharp edges)
A	area of the opening (m^2)
T_i	Internal temperature (K)
T_e	External temperature (K)
$\overline{T}$	Average temperature (K)
g	Gravitational acceleration = 9.81 m^2/s
H_t	Height, top of the opening (m)
H_b	Height, bottom of the opening (m)
P-value	Significance of correlation Coefficient
m	Slope
Sm	S.E. of the slope

Acronyms

IAQ	Indoor Air Quality
ACR(s)	Air Change Rate(s)
VR(s)	Ventilation Rate(s)
Ppm	Parts Per Million
NV	Naturally Ventilated
COB	Context, Occupant and Building
AB(s)	Adaptive Behaviour(s)
S.D.	Standard Deviation
S.E.	Standard Error
CI	Confidence Interval
WA	Window Area
NW	Number of Windows
MHW	Minimum Height of Windowsill
OA	Open Area (m^2)

Abbreviations

Vo	Volume
H	Heating
NH	Non-heating
No	Number
D/H	Depth to Height Ratio
W/C	Window to Classroom area (%)
O/C	Operable area to classroom area (%)
ED	Exterior Door
DI	Direction of Wind

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, speed and accuracy of standardized tests increase by up to 15% [41,47]. When VRs increase from 3 to 8.6 l/s.p speed for different tests increase by 5–35% [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 Midland, 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, 73% and 3.0 m^2/s during non-heating seasons and are 7.1 °C, 80.5% and 2.8 m^2/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

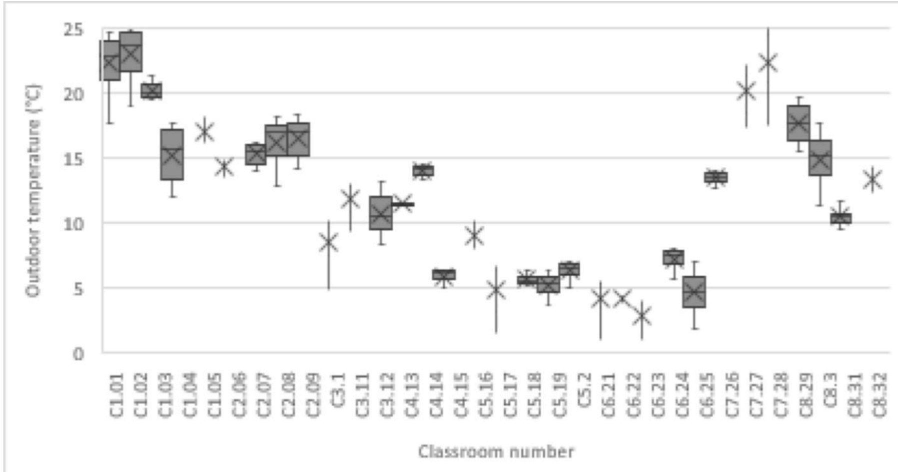

Fig. 1. Outdoor temperature for each classroom during school's occupancy.

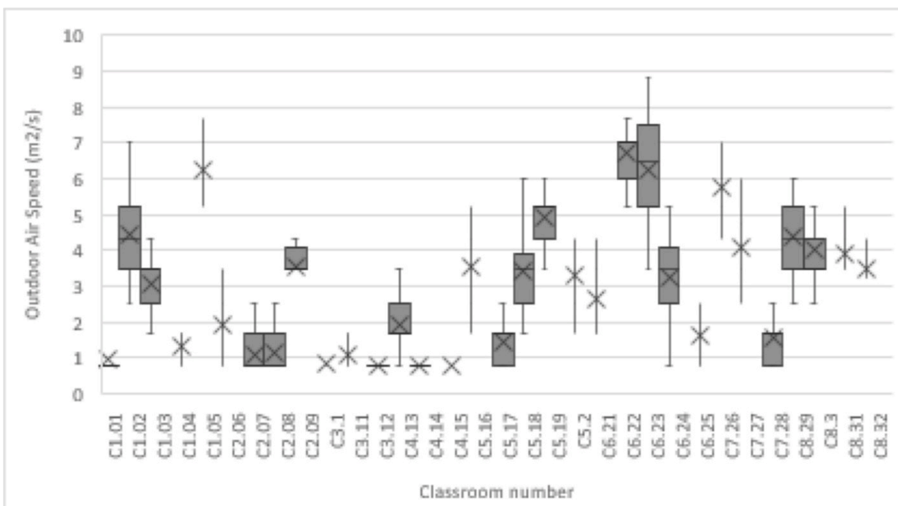

Fig. 2. Outdoor airspeed for each classroom during school's occupancy.

Table 1
Descriptive statistics of outdoor variables.

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

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 m^2), volume (130–252 m^3), 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 2
Questions on architectural features, occupancy patterns and control's operation taken from questionnaire and observation forms developed by authors [80]

Variables		Questions and Responses	
Observation at 10-min interval	**Occupancy 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 PE, ☐left for lunch, ☐left for assembly, ☐left for home	
	Windows operation	Total open area (m^2)? …	Total number of window adjustments? …
Classrooms' architectural features	Classroom area (m^2)? …	Total area of operable windows (m^2)? …	
	Type of window operation? … (☐manual, ☐manual with a handle, ☐automatic, ☐remotely controlled)		
	Type of window opening? … (☐Top hung, ☐side hung, ☐horizontal slider, ☐hopper, ☐awning, ☐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)		

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 CO_2 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 CO_2 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 CO_2 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, VR_S (l/s.p) are derived by using CO_2 measurements [68]. VR for a known volume depends on CO_2 concentration entering the room, CO_2 concentration leaving the room and internal generation rate of CO_2 added to the room by occupants and their physical activities [15,87]. The time derivative of the monitored concentration is given in Equation (1):

$$V\frac{dc}{dt} = G + QCex - QC(t) \tag{1}$$

Solving (1) by integration leads to:

$$C(t) = Cex + \frac{G}{Q} + \left(Cin - Cex - \frac{G}{Q}\right)e^{-\frac{Q}{V}t} \tag{2}$$

where.

$C_{(t)}$ (kg/m^3) is internal concentration of tracer gas
C_{ex} (kg/m^3) is external concentration of tracer gas
G (kg/s) is generation rate of tracer gas emitted from an indoor source
Q (m^3/s) is internal-external exchange rate
C_{in} (kg/m^3) is initial concentration of tracer gas
V(m^3) is room volume
Q/V (ac/s) is air change rate and
t (s) is time [15,87].

Equation (2) assumes that *G, Q*, and *Cex* are constant.

Equipment generally records CO_2 levels in ppm, therefore, to convert (ppm) to (kg/m^3) equation (3) in Ref. [89,90] is applied. However, to avoid small numbers, (kg/m^3) is shown in (ppm) and (kg/s) is shown in (cm^3/s) in this study.

$$W = \frac{10^{-6}(ppm)(12.187)(MW)}{(273.15 + T^\circ C)} \tag{3}$$

Where.

W (kg/m^3) is density of CO_2 levels
ppm (parts per million by volume) is concentration of CO_2 levels
12.187 is a constant of proportionality representing the atmospheric pressure
M_W (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 (1/h) were estimated during school's occupied period by using time-averaged values of G. Outdoor concentration of CO_2 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 CO_2 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, CO_2 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
Descriptive Statistics of environmental variables for total period during seasons.

Seasons	Variable	Minimum	Maximum	Mean	Median	S.D.
Non-heating	T_{op}(°C)	17.9	28.1	23.8	23.8	1.9
	RH (%)	35.8	66.6	49.7	48.1	7.7
	CO_2 (ppm)	475	3430	1050	953	444
Heating	T_{op}(°C)	16.2	27.4	21.8	21.9	1.9
	RH (%)	24.6	54.9	38.2	36.6	7.6
	CO_2 (ppm)	555	2659	1208	1084	427

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 [13]. 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 [19]. 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 [16]. 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
Recommended values for CO_2 levels and VRs by EN 13779 [68].

Categories	IAQ standard	Range of CO_2 levels	Total CO_2 values Based on outdoor CO_2 of 400 ppm	VRs (l/s.p)
Category I	High	<400	<800	>10
Category II	Medium	400–600	800–1000	7–10
Category III	Moderate	600–1000	1000–1400	4–7
Category IV	Low	>1000	>1400	<4

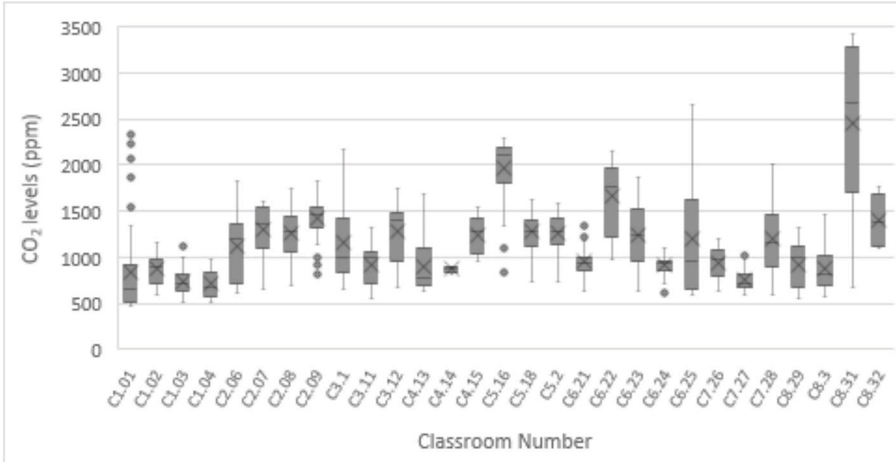

Fig. 3. CO_2 changes in each classroom during occupied period.

Table 5
Descriptive statistics of ACRs and VRs during *teaching* period.

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

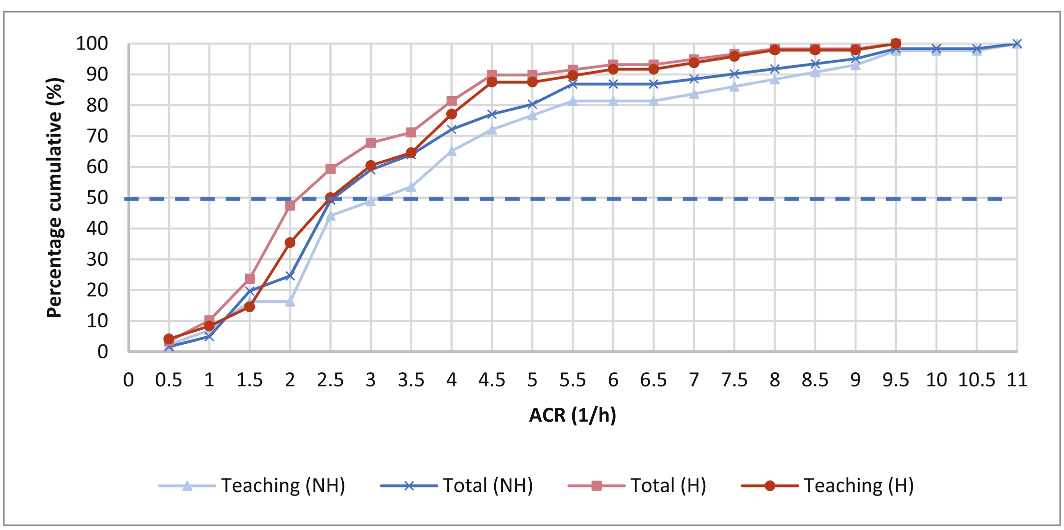

Fig. 4. Cumulative frequency (%) of ACRs (1/h) for teaching and total occupied period.

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

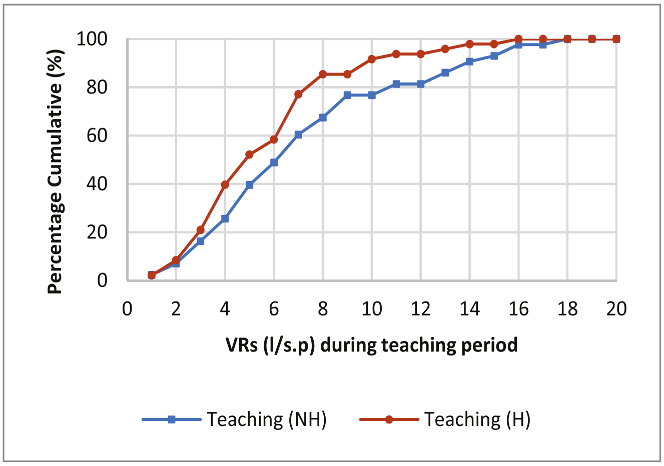

Fig. 5. Cumulative frequency (%) of VRs (l/s.p) for teaching period.

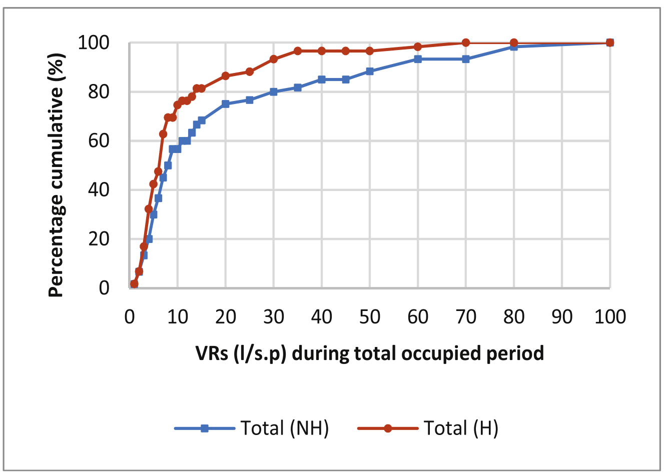

Fig. 6. Cumulative frequency (%) of VRs (l/s.p) for total occupancy period.

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 extracts 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 [2,8,29,82,83,95], especially during heating seasons [7,13,18,22,24,95]. 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' VRs [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

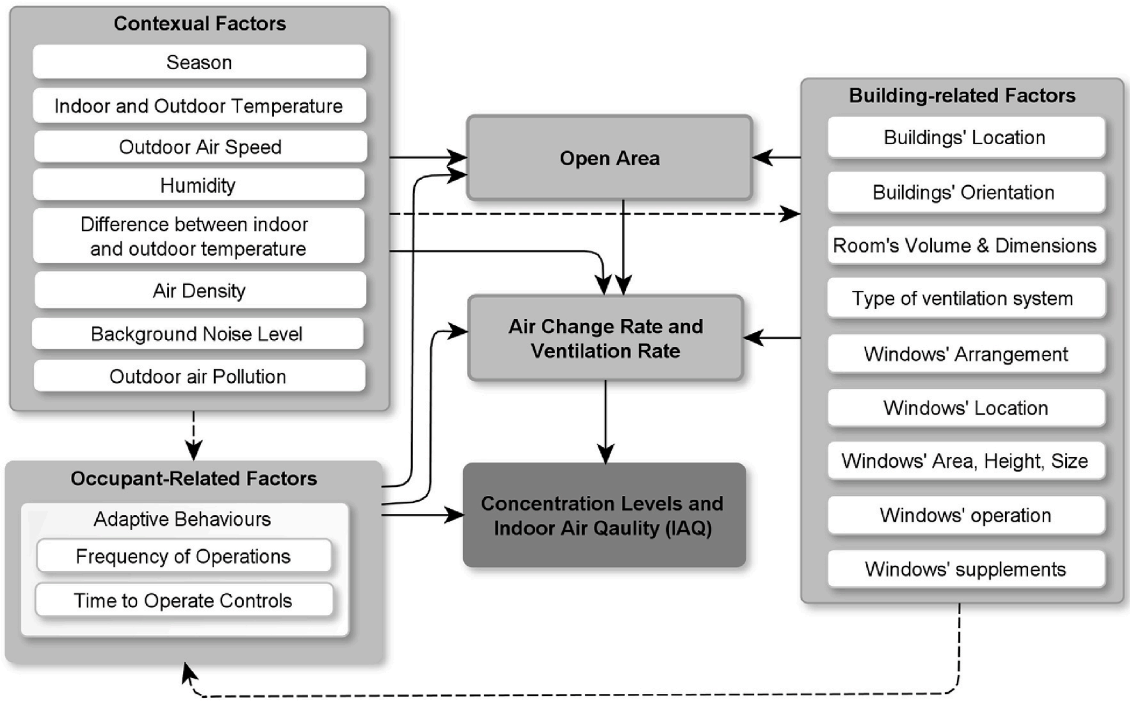

Fig. 7. Summary of factors affecting ACRs, VRs and CO_2 levels.

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.

Mode & Date		No.	Classrooms' Characteristics						Windows' Configurations					Window Operation	ED[h]	PNV[i]
			Orientation	Area	Vo[a]	D/H[b]	W/C[c]	O/C[d]	WA[e]	NW[f]	W Type	Ventilation	MHW[g]			
Non-heating	July 2017	1.1	NE	60	192	2	13%	13%	8	8	Top-hung outward openings at 2 levels	Single-sided windows at 2 level + louvre	1	Manually	No	H
		1.2	SW													
		1.3														
		1.4														
	Sep 2017	2.6	NW													
		2.7	SE													
		2.8														
		2.9	NW													
Heating	Oct & Nov 2017	3.10	S &W	65	227	2.9	3%	5.8%	2	5	Top-hung outward	Single-sided	1.7	Manually	Yes	L
		3.11	S &W	70	245	3.1	3%	3%	2.2	6		Double-sided	1.6		No	L
		3.12	NW	60	192	2	3.3%	3.3%	2.5	5		Single-sided	2.6	With handle	No	L
		4.13	W	50	130	3.5	1%	4.8%	0.5	2	Top-hung outward	Single-sided	1.8	Manually	Yes	L
		4.14	W	60	156	3.5	0.8%	3.8%	0.5	2			1.8		Yes	L
		4.15	NW	50	175	N/A	0%	0%	0	0	–	No opening	–	No window	No	L
	Jan and Feb 2018	5.16	SW, SE	55	137	2.8	10%	10%	5.7	8	Top-hung openings at 2 levels	Single-sided at two levels	0.5	Manually	No	H
		5.18	SW, NW					10%	5.7	8			0.5		No	H
		5.20	SW, NW					13.6	5.7	8			0.5		Yes	H
		6.21	SE	60	168	3	3%	3%	1.8	4	Top-hung outward opening	Single-sided windows + Louvre openings	2.3	Remote-control	No	L
		6.22													No	L
		6.23													No	L
		6.24													No	L
		6.25													No	L
Non-heating	April and May 2018	7.26	SE, SW	70	252	3.3	5%	5%	3.9	6	Top-hung outward opening	Double-sided	2.7	With handle	No	L
		7.27	SE, SW	55	137	2.4	6%	9.3%	3.3	3		Single-sided	1.65	Manually	Yes	H
		7.28	NE, NW	55	137	2.4	10%	10%	5.4	6		Double-sided	1.6		No	H
		8.29	NE	60	150	4	3.6%	6.6%	2.2	4	Top-hung outward opening	Single-sided	1.4	Manually	Yes	L
		8.30													Yes	L
		8.31	NW	55	137	3.6	4.4%	7.2%							Yes	L
		8.32													Yes	L

[a] vol (m^3)-.
[b] Depth to Height Ratio.
[c] Window area to classroom area (%).
[d] Operable area to classroom area (%).
[e] Window Area (m^2).
[f] Number of Windows.
[g] Minimum Height of windowsill (m).
[h] Exterior Door.
[i] Potentials for natural ventilation.

Fig. 8. Classrooms with single-sided openings at two different sizes (outside and inside).

Fig. 9. Classroom with single-sided openings at one size (outside and inside).

Fig. 10. A classroom in school 1 providing louvre openings alongside windows.

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),

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

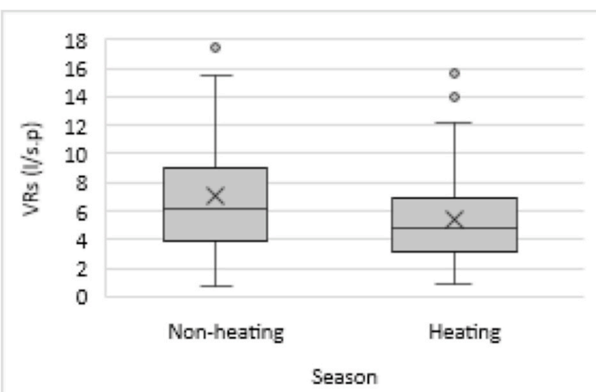

Fig. 12. VRs during heating and non-heating seasons.

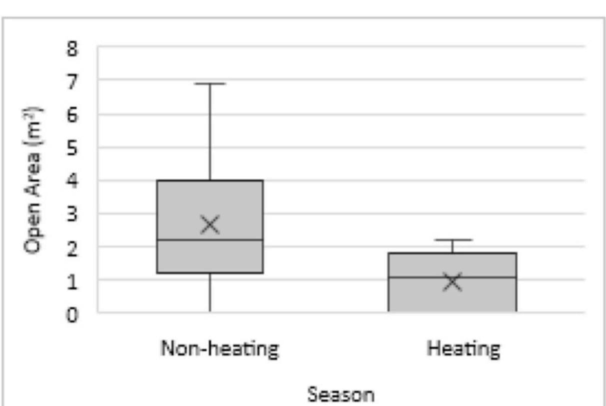

Fig. 13. Open areas (m^2) during heating and non-heating seasons.

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_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].

$$95\%\ CI\ on\ the\ slope = \widehat{m} \pm t_{0.05,n-2}S_m \tag{4}$$

$$95\%\ CI\ on\ intercept = \widehat{b} \pm t_{0.05,n-2}S_b \tag{5}$$

$$An\ Approximation\ of\ the\ 95\%\ confidence\ interval\ on\ Y = \widehat{y} \pm \left[\left(t_{0.025,n-2}S_y\right) / \sqrt{n}\right] \tag{6}$$

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_{NH} = 0.76 ± 0.67 and m_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

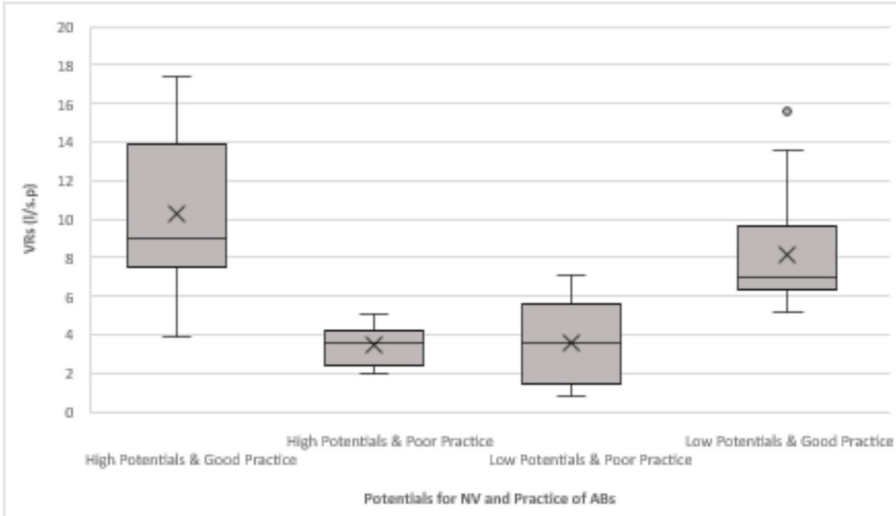

Fig. 14. Mean VRs in each group for potentials and practices of natural ventilation.

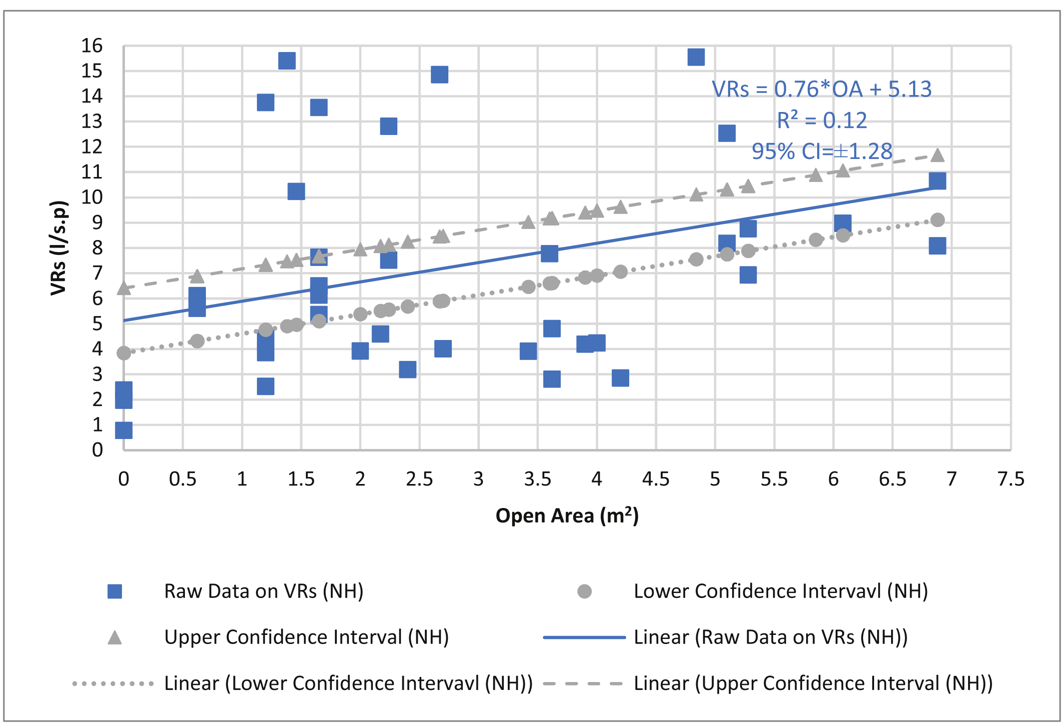

Fig. 15. Influence of open areas (m^2) on VRs (l/s.p) during non-heating seasons.

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 m^2 and 2 m^2 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 m^2) is almost twice than that during heating seasons (2 m^2). 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

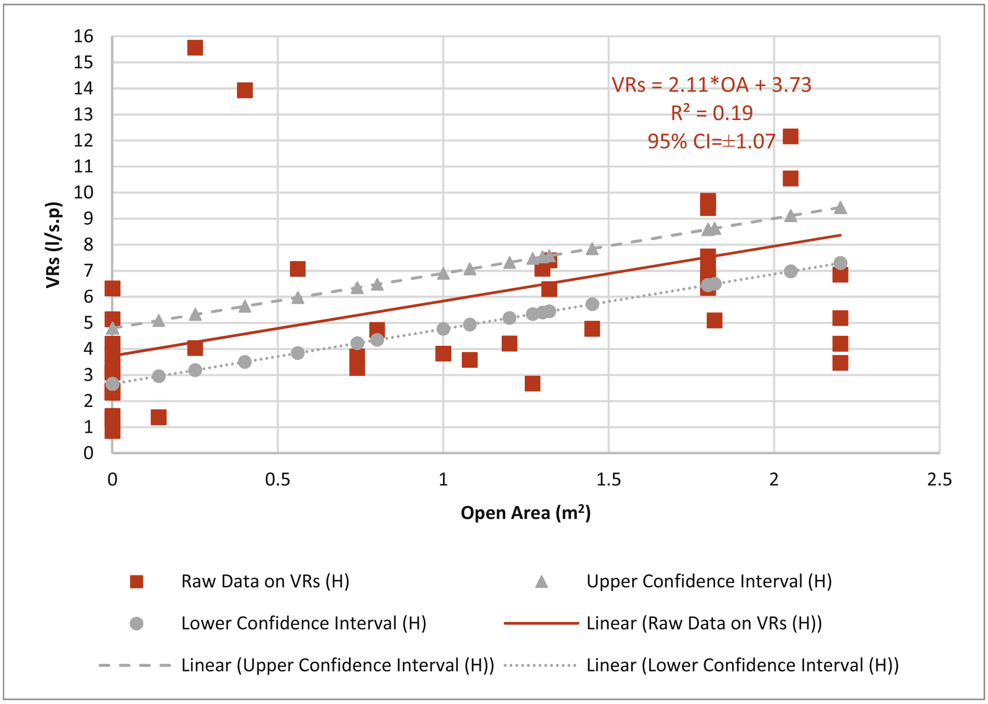

Fig. 16. Influence of open areas (m^2) on VRs (l/s.p) during heating seasons.

Table 7
Calculation of Confidence Intervals for the linear relationship between open area and VRs.

	Calculations	Non-heating, Fig. 15	Heating, Fig. 16
1	Slope, m	0.76	2.11
2	S.E. of the slope, S_m	0.33	0.64
3	Intercept, b	5.13	3.73
4	S.E. of intercept, S_b	1.10	0.82
5	S.E. of dependents, $S_{(y, x)}$	4.06	3.72
6	Degree of freedom (n-2)	39	47
7	t-multiplier ($t_{0.05,n}$)	2.02	2.01
8	Δm=(t-multiplier × S.E.) = $t_{0.05,n}$*S_m	0.67	1.28
9	$\Delta b = t_{0.05,n}{*}S_b$	2.23	1.66
10	$\Delta y = t_{0.025,n-2} S_y/\sqrt{n}$	1.28	1.07
95% confidence interval on		**(NH)**	**(H)**
11	Slope sample estimate±(t-multiplier × S.E.)	0.76 ± 0.67 = 0.09 to 1.43	2.11 ± 1.28 = 0.83 to 3.39
12	Intercept sample estimate±(t-multiplier × S.E.)	5.13 ± 2.2 = 2.93 to 7.33	2.0 ± 1.6 = 0.4 to 3.6
13	Dependent sample estimate±(t-multiplier × S.E.)	Y±1.28	Y±1.07
15	**Equation**	**VRs = 0.76*OA + 5.13**	**VRs = 2.11*OA + 3.73**

°C lower than that during non-heating seasons (17.6 °C). 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 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):

$$Q_v = \frac{1}{3} * C_D * A * \sqrt{\frac{(T_i - T_e) * g * (H_t - H_b)}{\overline{T}}} \quad (7)$$

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),
$\overline{T}$ is the average temperature (K),
g is the gravitational acceleration (m/s^2), about 9,81 m^2/s,
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 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].

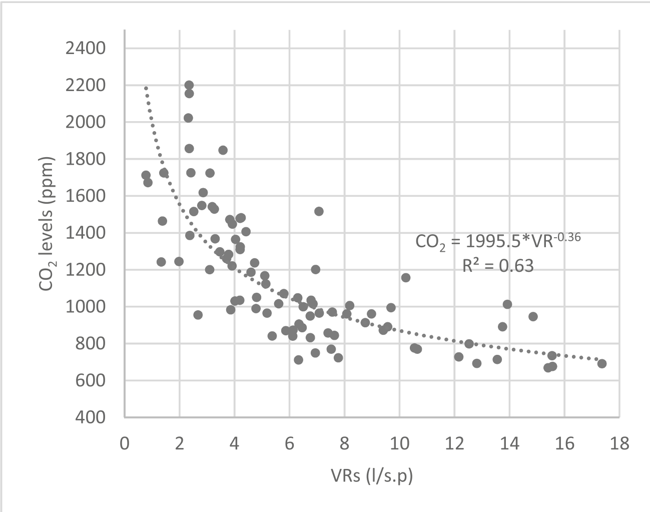

Fig. 17. Impact of hourly VRs (l/s.p) on their corresponding average CO_2 levels (ppm).

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.

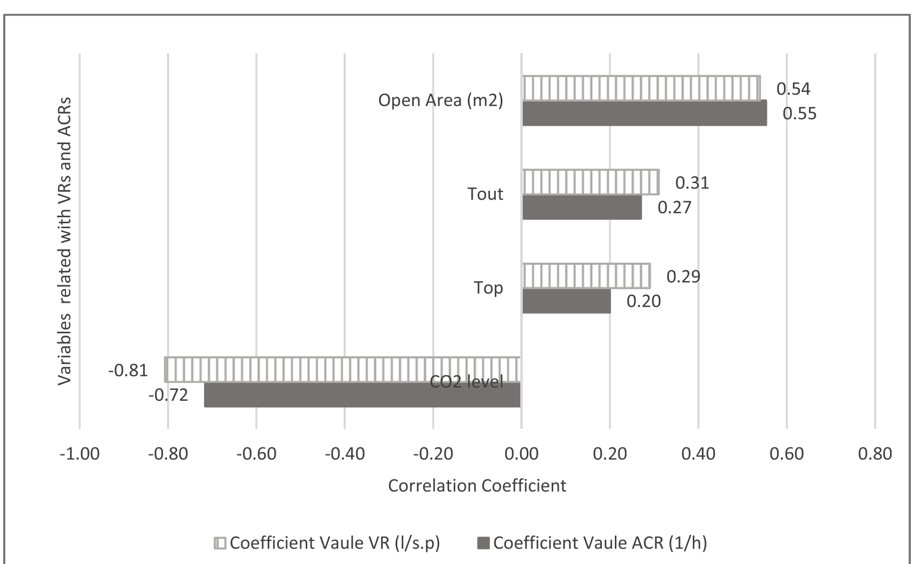

Fig. 18. Correlation coefficients (Spearman Rank) for variables related to ACRs and VRs.

Table 8
Mean CO_2 levels and VRs in each classroom against standards.

Type	No.	COB factors affecting IAQ							IAQ metrics		Comparing with Standards[g]				COB not met[h]?
		Building		Contextual Factors			Occupant				EN 13779 [68]		ASHRAE [23]		
		Orientation	B[a]	DI[b]	V[c]	C[d]	OA[e]	O[f]	CO_2	VRs	CO_2	VRs	CO_2	VRs	
Renovated	1.1	NE	H	SW	0.9	×	5.8	G	1058	5.5	×	×	×	×	C
	1.2	SW	H	NE	4.5	✓	4.9	G	961	7.0	✓	✓	✓	×	–
	1.3	SW	H	NE	3.1	✓	5.3	G	772	13.1	✓	✓	✓	✓	–
	1.4	SW	H	NE	1.3	×	2.2	P	781	10.2	✓	✓	✓	✓	CO
	2.6	NW	H	SW	1.9	×	1.1	P	1119	3.6	×	×	×	×	CO
	2.7	SE	H	SW	1.1	×	1.2	P	1352	2.6	×	×	×	×	CO
	2.8	SE	H	NE	1.1	×	1.2	P	1228	9.1	×	✓	×	✓	CO
	2.9	NW	H	SW	3.5	×	2.5	P	1434	3.6	×	×	×	×	CO
Existing	3.10	S &W	L	E	0.8	×	0.9	P	1202	5.4	✓	✓	×	×	COB
	3.11	S &W	L	E	1.1	×	2.0	G	993	5.6	✓	✓	✓	×	CB
	3.12	NW	L	SW	0.8	×	0.6	P	1369	2.6	✓	×	×	×	COB
	4.13	W	L	E	2	×	1.6	G	890	9.0	✓	✓	✓	✓	B
	4.14	W	L	E	1.1	×	1.8	G	881	9.6	✓	✓	✓	✓	CB
	4.15	NW	L	W	0.8	×	0.0	P	1273	4.2	✓	✓	×	×	COB
	5.16	SW, SE	H	W	3.5	×	0.1	P	1979	2.6	×	×	×	×	CO
	5.18	SW, NW	H	W	3.4	×	1.3	P	1308	4.1	✓	✓	×	×	CO
	5.20	SW, NW	H	SE	3.3	×	1.0	P	1261	6.1	✓	✓	×	×	O
Renovated	6.21	SE	L	W	2.6	×	1.3	G	964	7.4	✓	✓	✓	×	CB
	6.22	SE	L	SW	6.7	×	0.0	P	1740	1.9	×	×	×	×	COB
	6.23	SE	L	NW	6.3	✓	0.0	P	1249	5.3	×	×	×	×	OB
	6.24	SE	L	W	3.3	×	1.1	G	909	6.9	✓	×	✓	×	CB
	6.25	SE	L	SW	1.6	×	0.0	P	980	3.8	✓	×	✓	×	COB
Existing	7.26	SE, SW	L	NE	5.7	✓	0.3	P	956	5.8	✓	✓	✓	×	OB
	7.27	SE, SW	H	NE	4.1	✓	3.9	G	761	12.7	✓	✓	✓	✓	–
	7.28	NE, NW	H	W	1.6	×	2.5	P	1218	3.9	✓	×	×	×	CO
	8.29	NE	L	SW	4.4	✓	1.7	G	887	6.0	✓	✓	✓	×	B
	8.30	NE	L	SW	4.0	✓	1.6	G	899	10.5	✓	✓	✓	✓	B
	8.31	NW	L	NE	3.9	×	0.0	P	2487	0.9	×	×	×	×	COB
	8.32	NW	L	NE	3.5	×	1.7	H	1404	6.3	×	✓	×	×	CB

[a] Building-related factors: **High (H)** or **low (L)** potentials for NV.
[b] Prevailing Direction of Wind.
[c] Air Speed.
[d] Contextual factors: **Favourable (✓)** or Not **Favourable ( )**.
[e] Average open area (m^2) in each classroom.
[f] Occupant-related factors: **Good practice (G)** or **Poor practice (P).**
[g] Standard Met **(✓)** or Standard Not Met **( )**.
[h] Which COB factors are not met in each classroom?.

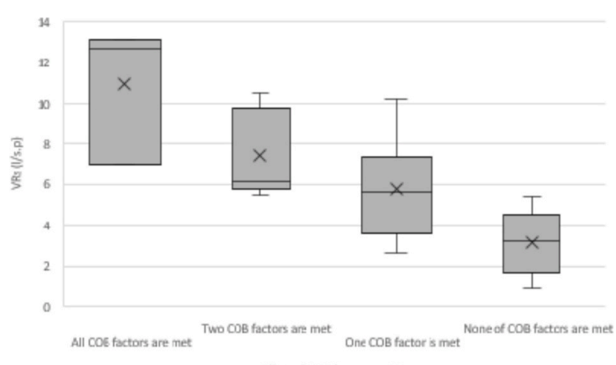

Fig. 19. Changes in VRs by the number of COB factors.

- ***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 5.7 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 renovated classrooms and average of 7.1 l/s.p for existing classrooms. Furthermore, **21%** of the classrooms meet the criteria recommended by ASHRAE Standard [23] with the average VR of 10.6 l/s.p.

5. Conclusion

This study acknowledges contextual, occupant and building-related factors have a significant influence on providing natural ventilation, which should all be considered as part of the design process. To provide conditions in which windows as the main components of NV schools can provide adequate VRs, the following three steps are recommended:

Step 1: School designers should have comprehensive knowledge about contextual factors, however, some of these factors can be controlled more than others. For example, sample selection in this study was controlled in relation with acceptable background noise level and air pollution level to not restrict window operation due to these contextual factors. Seasonal variations can also be predicted by meteorologists and climate studies; however, it is more challenging to control them.

Step 2: School designers should consider all aspects of windows' design (i.e. window area, window/room ratio, arrangement, orientation, operation method, supplements) to provide high potentials for natural ventilation. To reflect all the above aspects effectively, it is important to consider contextual factors in windows' design. For example, the same opening can provide an airflow rate of 1150 m^3/h during non-heating seasons and 1852 m^3/h during heating seasons. Therefore, ventilation openings should be designed differently for heating and non-heating seasons; purpose ventilation openings by avoiding draughts and controlling the airflow rate can provide IAQ during heating seasons.

Step 3: School stakeholders should consider school occupants' interaction with buildings' controls. Several classrooms in this study have high potentials for maintaining acceptable VRs, however, they fail to maintain acceptable VRs due to occupants' poor interaction with window. Therefore, occupants should be educated to interact with the building to adopt suitable Adaptive Behaviours.

The above three steps highlight the role and responsibility of school stakeholders (regulators, designers, school authorities, and school occupants) in providing the required level of VRs and maintaining IAQ. The focus of this study is investigating naturally-ventilated primary schools which are sustainable solutions for providing indoor air quality. To not restrict controls' operation due to background noise level or pollution level, schools are selected in quiet and low-polluted areas. Future studies are recommended to focus on schools in different contexts with different means of ventilation.

Declaration of competing interest

None.

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