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Operations on windows and external doors in UK primary schools and their effects on indoor environmental quality

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ABSTRACT

This study provides a comprehensive analysis of the predictors influencing operations on windows and external doors as well as their impact on IEQ, comfort and energy. The study was carried out in 31 naturally ventilated classrooms in eight primary schools in the UK during non-heating and heating seasons. The state of the windows and external doors was collected by time-lapse cameras and visual observations. Environmental variables impacting window operations were recorded at 10-min intervals. Correlational tests and predictive regression models were used to identify how windows open area (m^2) were affected by environmental predictors. Results show that operative and outdoor temperature during the non-heating season and indoor and outdoor humidity during the heating season were the main predictors of windows open area (m^2). The main driver for the operation of external doors was occupancy patterns, however, the period that they stayed open was dependent on temperature. The impact of windows and external doors' open area (m^2) on operative temperature decreased after 40 min, however, its impact on CO_2 level was only noticeable up to 30 min. Through opening more available windows, operative temperature (34% of the time) and CO_2 levels (28% of the time) could be reduced during the non-heating season. Furthermore, energy waste could be avoided 67% of the time during the heating season by reducing the set-point temperature and training school occupants on when to operate windows. This study suggests several avenues to improve the impact of controls' operation on IEQ, comfort and energy.

Nomenclature

IEQ Indoor Environmental Quality
WOA (m^2) Windows Open Area: The area of the windows' glazing that is open
ppm Parts Per Million
RH Relative Humidity (%)
T_{op} Operative Temperature (°C)
T_{out} Outdoor temperature (°C)
V Air Speed (m/s)

1. Introduction

Occupant behaviour is a physical and psychological response to environmental conditions to manage unsatisfactory conditions [1]. These responses could be adaptive behaviours on controls such as operating windows [2] or personal, such as adjusting clothing insulation or drinking cold/hot beverages [3]. Adaptive behaviours on controls are impacted by contextual (such as background noise level), building-related (type of controls) and occupant-related factors (occupancy patterns) [4]. Contextual and occupant-related factors usually act as drivers to operate controls and impact how long to keep them open or closed, and building-related factors usually impact how often the controls are operated.

On the other hand, occupants' adaptive behaviours on controls impact the Indoor Environmental Quality (IEQ), energy consumption and comfort in buildings [4]. Several studies have highlighted the role of school occupants on schools' energy consumption during the last two years [5–8]. Considering that school buildings are responsible for 15% of the public sector carbon emissions in the UK [9], investigating the role of school occupants on energy consumption can save a significant amount of energy.

Furthermore, studies suggest that the perceived ability or inability to adopt adaptive behaviours in a building has a psychological effect that needs to be considered in comfort calculations [10]. Occupants

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better tolerate poor environmental conditions and report lower levels of dissatisfaction with IEQ when they can adopt behaviours to improve their comfort [11]. Baker and Standeven [12] suggested that restricted adaptive behaviours narrow the comfort zone and eventually lead to increased occupant sensitivity to other stimuli.

Therefore, it is significant to facilitate school occupants' adaptive behaviours through recognizing drivers for operating controls. During the last twenty years, the number of studies on students' thermal comfort in schools has increased, with some of these studies investigating students' personal adaptive behaviour such as clothing behaviour [13–22] as a response to thermal discomfort. However, there are fewer studies that have investigated adaptive behaviours on controls such as window operations and their drivers [23–28].

For example, the study by Zhang and Bluyssen [23] in 54 classrooms in the Netherlands showed that the most common behaviours adopted by teachers and the most frequent request of the children were opening/closing windows due to 'too warm' complaints and thermal discomfort. The study by Heracleous and Michael [25] in school buildings in Cyprus identified that window opening patterns (open or closed) were related to both indoor and outdoor temperature [25]. Similarly, the study by Dutton and Shao [28] in a naturally ventilated elementary school in the UK showed that window closing and opening were significantly influenced by indoor and outdoor temperature during the unheated period and by outdoor temperature during the heated period [28]. The study by Stazi et al. [27] in a school in Italy highlighted that indoor temperature was the best predictor for window opening and closing, however, the outdoor temperature had a lower impact on window operations. The results of the study by Santamouris et al. [26] in 62 classrooms in Greece showed that there was a statistically significant relationship between window opening and the indoor–outdoor temperature difference, with windows being open at lower ambient temperature when the temperature difference was higher.

However, studies with statistical behavioural models in primary schools that have shown the probability or the proportion of windows open as a response to environmental variables are very limited [13,16,29]. For example, the study by Kim and De dear [16] in primary and secondary schools in Australia investigated students' favoured adaptive strategies such as opening windows, using fans, AC or heater as a function of temperature offset from neutrality in probabilistic models. Similarly, the study by Korsavi and Montazami [29] in primary schools in the UK investigated window operation behaviour by plotting the percentage of open areas against T_{diff} ($T_{diff} = T_{op}$-$T_{C(CEN)}$) in polynomial models. As another example, the study by Aparicio-Ruiz et al. [13] in Spanish primary schools examined various thermal adaptive strategies such as opening windows and doors, adjusting blinds, turning on/off fans and turning on/off the light as a function of outdoor temperature in logistic regression models [13].

Most of these studies are focused on window operations in response to indoor temperature, outdoor temperature or temperature differences. This study improves the state of art on behavioural models in schools by focusing on a wider range of environmental predictors (such as humidity or air speed) throughout both non-heating and heating seasons and by applying a different type of statistical model than logistic or probabilistic models. Also, to the authors' knowledge, there are currently no studies investigating the impact of control operations on changes in IEQ in primary schools. Hence, this study aims to bridge the gap on the impact of controls' operations on IEQ and suggesting the potential impact of operations on energy and overall comfort.

Therefore, this study aims to investigate the variables that are related to school occupants' operations on windows and external doors; both the variables that trigger operations and the variables that are impacted by operations. More specifically, the objectives of the paper are:

(i) Developing behavioural models based on the state of windows and related environmental variables; (ii) Identifying the main drivers for the operation on external doors; (iii) Investigating the impact of windows and external doors' open area (m^2) on IEQ, energy and comfort.

2. Methodology

The main steps carried out in this methodology are: 1. Sample selection (climate, buildings and occupants); 2. Data acquisition (visual Observations and environmental measurements); 3. Statistical analyses (descriptive, correlational, predictive and group differences); and 4. Overview of the recorded data.

2.1. Sample selection

2.1.1. Climate

The study was carried out in Coventry, West Midlands, the UK, which according to the Koppen classification [30] has a mild climate. The mild climate was selected to reduce the biased impact of extreme outdoor conditions on controls operations. To represent all climatic conditions, the study was carried out from mid-July 2017 until the end of May 2018.

2.1.2. Buildings

The selected schools in this study were all naturally ventilated because natural ventilation through openable windows is the most common ventilation type in UK schools. Buildings were selected in low-polluted areas to not restrict window operations due to high pollution levels and in quiet areas to not restrict window operations due to high background noise levels and. In total, 31 naturally ventilated classrooms in eight primary schools were selected and studied on 31 distinct days throughout one year, during non-heating (NH) and heating (H) seasons. Table 1 shows an overview of the schools, date of observation, architectural features of classrooms and their controls. The number of studied classrooms was selected similar during both seasons, 16 classrooms during non-heating and 15 classrooms during heating seasons (Table 1), which reduces the bias and increases the validity of the study. In the studied classrooms during the heating season, the heating systems were on and controlled by the head teachers. Nine classrooms on the ground floor have external doors to the playground (Table 1).

Fig. 1 shows the design of windows for classrooms in schools 1 and 2. Both schools were engaged in the Priority School Building Program (PSBP), therefore, the design and number of windows were the same. Classrooms in these two schools have the highest window area (8 m^2) and number of windows (8).

Fig. 2 shows two classrooms in schools 3 and 4 on the ground floor that have external doors to the public playground.

In school 5, windows had the lowest height of windowsill (0.5 m) compared to other classrooms (Fig. 3a) and in school 6 windows were remotely controlled (Fig. 3b).

Fig. 4 shows a classroom in school 7 that has an external door to the playground and a classroom in school 8 that has an external door to a more private courtyard which was used during students' breaks.

2.1.3. Occupants

Among primary school students, children in their late middle childhood (9–11 years old) were selected for this study because they have a better understanding of their environment compared to their peers in early middle childhood (6–9 years old) [29]. Older children have higher heights which allows them to operate controls more comfortably. It is also shown that younger children are kept under stricter supervision whereas older children are allowed to operate controls [31].

Table 1
An overview of the architectural features of the classrooms and their controls.

General			Classroom		Window Design					Window Operation	External Door
Season	Date	No.	Area	Vo[1]	WA[2]	NW[3]	W Type	Ventilation	MW[4]		
Non-heating	**July/Sep 2017**	**1.1**	60	192	8	8	Top-hung outward openings at 2 levels	Single-sided windows at 2 level + louvre opening	1	Manually	No
		1.2	60		8	8			1	Manually	No
		1.3	60		8	8			1	Manually	No
		1.4	60		8	8			1	Manually	No
		2.6	60	192	8	8	Top-hung outward openings at 2 levels	Single-sided windows at 2 level + louvre openings	1	Manually	No
		2.7	60		8	8			1	Manually	No
		2.8	60		8	8			1	Manually	No
		2.9	60		8	8			1	Manually	No
Heating	**Oct/Nov 2017**	**3.10**	65	227	2	5	Top-hung outward	Single-sided	1.7	Manually	Yes
		3.11	70	245	2.2	6		Double-sided	1.6	Manually	No
		3.12	60	192	2.5	5		Single-sided	2.6	With handle	No
		4.13	50	130	0.5	2	Top-hung outward	Single-sided	1.8	Manually	Yes
		4.14	60	156	0.5	2			1.8	Manually	Yes
	Jan/Feb 2018	**5.15**	55	137	5.7	8	Top-hung openings at 2 levels	Single-sided at two levels	0.5	Manually	No
		5.16	55		5.7	8			0.5	Manually	No
		5.17	55		5.7	8			0.5	Manually	No
		5.18	55		5.7	8			0.5	Manually	Yes
		5.19	55		5.7	8			0.5	Manually	Yes
		6.20	60	168	1.8	4	Top-hung outward opening	Single-sided windows + Louvre openings	2.3	Remote-control	No
		6.21	60		1.8	4			2.3		No
		6.22	60		1.8	4			2.3		No
		6.23	60		1.8	4			2.3		No
		6.24	60		1.8	4			2.3		No
Non-heating	**April/May 2018**	**7.25**	70	252	3.9	6	Top-hung outward opening	Double-sided	2.7	With handle	No
		7.26	55	137	3.3	3		Single-sided	1.65	Manually	Yes
		7.27	55	137	5.4	6		Double-sided	1.6	Manually	No
		8.28	60	150	2.2	4	Top-hung outward opening	Single-sided	1.4	Manually	Yes
		8.29	60	150	2.2	4			1.4	Manually	Yes
		8.30	55	137	2.2	4			1.4	Manually	Yes
		8.31	55	137	2.2	4			1.4	Manually	Yes

1 = Volume (m^3)- 2 = Total Window Area (m^2) in each classroom- 3 = Number of Windows- 4 = Minimum Height of window sill (m)

Fig. 1. Design of windows in school 1, classroom 1.1 (a) and school 2, classroom 2.6 (b).

Fig. 2. Windows and external door in school 3, classroom 3.10 (a) and school 4, classroom 4.14 (b).

Fig. 3. Windows in school 5, classroom 5.16 (a) and school 6, classroom 6.20 (b).

Fig. 4. Windows and external door in school 7, classroom 7.26 (a) and school 8, classroom 8.28 (b).

2.2. *Data acquisition*

2.2.1. *Visual observations*

An observation form (Table 2) that was developed and validated in an earlier study by the lead author [32] was used to obtain information on adaptive behaviours on controls and occupancy patterns at 10-min intervals.

Visual observations were conducted to provide a general overview of the space and identify explanatory predictors influencing operations on windows and external doors to build more valid behavioural models. Through visual observations, total open area (m^2), occupants in charge of operations, the reasons for operations and the frequency of operations were passively recorded by the lead author (Table 2). Total open area (m^2) is the sum of windows' and external doors' (if available) open area and windows open area (WOA) is the sum of all open windows in the classrooms, which could be one or several open windows. To avoid disruption, the reasons for operations were classified into general categories such as, occupancy patterns, IEQ or external factors such as noise, which were obvious to observe without asking questions and intervening. In cases where the cause was unclear, the lead author would ask the reason for the window operation at the end of the teaching period. Visual observations fail to describe the level of environmental variables, therefore, it is also necessary to measure the environmental variables.

Table 2
Observation form for occupancy patterns and adaptive behaviours in the Classroom.

Occupancy Patterns			
No. students in the class?	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			
Environmental Adaptive Behaviours			
Type of controls	State of controls	Reason for adjustment?	Adjustment by who?
Windows	The number of open windows? Total No. of window adjustments? Total windows open area (m^2)? Total open area (m^2)?	☐IEQ ☐wind ☐noise ☐rain or snow ☐upon arrival ☐on departure	☐Teacher ☐Teacher assistant ☐Caretaker ☐Student on his/her will ☐Student on teacher's request ☐Teacher on student's request
Doors	Sate of internal door Connecting door State of exterior door	☐Noise, ☐ventilation, ☐temperature, ☐occupancy patterns	
Heating Systems	On or off?	☐temperature, ☐occupancy patterns	

2.2.2. Environmental measurements

Indoor environmental variables impacting window operations were recorded at 10-min intervals by standalone temperature and humidity data loggers, CO_2 meters (TGE-0011, accuracy: ±50 + 2% of the reading) and multi-functional SWEMA equipment at a height of 1.1 m as recommended by ISO 7726 [33]. The measurement range and resolution of the equipment are shown in Table 3.

Before students' arrival in the morning, the instruments were usually set up in the studied classrooms to record environmental variables for the whole school day (8:50–15:20). To validate open areas (m^2) recorded through visual observations, time-lapse cameras were also installed in front of windows and external doors (if available) to record their state at 10-min intervals. Outdoor environmental variables were taken from local weather stations that were maximum 3 miles away from each study site [34].

2.3. Statistical analyses

The statistical analyses undertaken in this study can be categorised into four main groups:

Descriptive analysis was used to show the minimum, maximum and mean of indoor and outdoor environmental variables.

Correlational analysis was applied to show the strength and direction of the relationship [35] between WOA (m^2) and environmental variables.

Predictive analysis was used to describe how WOA depends on one environmental variable (linear regression) or several environmental predictors (multiple linear regression). Linear regression can produce a line of best fit by minimising the Residual Sum of Squares (RSS) which is the difference between an observed y and that predicted by the model [36]. In behavioural models in this study (WOA = b*(environmental predictor) + a, R^2), element 'b' shows the rate at which changes in the environmental predictors affect WOA. The R^2 value indicates how well the behavioural model implied by the regression equation fits the data [35]. The study has also used adjusted R-squared to determine any inconsistencies in the correlation. Adjusted R^2 has the same meaning as R-squared, however, it adjusts for the number of predictors in a model to determine how much of the correlation is due to the addition of new variables.

Logistic regression models could also provide information on the probability of windows being open or closed in response to environmental predictors. However, they cannot be applied to continuous variables such as windows open area unless they are split into two groups of open (1) and closed (0). The study by Dutton and Shao [28] showed that binary models are limited in their application to spaces with multiple windows because the probability of an individual window being opened is related to the number of windows already opened. Because WOA is a continuous dependent variable and most of the classrooms in this study have multiple windows, linear and multiple linear regression models were used to show how WOA (m^2) depend on environmental variables.

Table 3
Measurement range and resolution of the equipment.

Probe	Variables	Meas. Range	Resolution
SWEMA	Relative Humidity (RH)	0 to 100 %RH,	0.1% RH
	Air temperature (T)	−40 to +60 °C	0.1 °C
	Air velocity (V)	0.05–3.0 m/s at 15–30 °C,	1.1 m/s
	Air temperature (T)	+10 to +40 °C	0.1 °C
	Radiant temperature (Ø globe: approx.150 mm)	0 to +50 °C	0.1 °C
Data Logger	Air temperature (T)	−35 to +80 °C	0.1 °C
	Relative Humidity (RH)	0 to 100 %RH	0.5% RH
TGE-0011	CO_2	0–5000 ppm	1 ppm

Group differences analysis (cause and effect) was used to determine whether two or several groups of categorical data were the same or not. Kruskal- Wallis for not-normally distributed interval scale is used to compare the medians of two or more samples to determine if the samples have come from different populations scores or not [35,36]. In this study, data on WOA and the total number of window operations were not normally distributed, therefore, Kruskal- Wallis was used to compare their medians between different seasons.

The data were analysed using the Statistical Package for Social Sciences (SPSS) 25 software [37].

2.4. Overview of the recorded data

Table 4 shows descriptive statistics of the indoor and outdoor variables during the studied period. Mean operative temperature, outdoor temperature and CO_2 level were 23.8 °C, 17.5 °C and 1050 ppm during the non-heating season and 21.8 °C, 7.1 °C and 1208 ppm during the heating season.

In total, around 1050 data points (at 10-min intervals) on environmental variables, window and external door state were analysed. Fig. 5 shows the frequency for round up of WOA (m^2), with 0 m^2 having the highest frequency (345) and 6 m^2 having the lowest frequency (21). Data on the state of external doors showed that 73% of the time they were closed and 27% of the time they were open. Visual observations showed that for 10% of the studied period, it was raining.

The mean and median of WOA are 2.5 and 2 m^2 during the non-heating season and 0.8 and 0.7 m^2 during the heating season.

3. Results

3.1. Visual observations

Fig. 6 shows the reasons for window operations (window opening and closing). Around 60% of window operations were due to indoor environmental quality (such as a warm or stuffy classroom), however, as the actual IEQ trigger for window operation could not be observed, they were all categorised as IEQ. Operating windows upon arrival was the second most frequent reason (28%), however, they would happen when the classroom was perceived uncomfortable in terms of IEQ. Therefore, they were also dependent on environmental aspects and happened upon teachers' arrival (usually around 8:30 a.m.) and before students arrived in the classroom. Several other factors such as wind moving papers, leaving the classroom (departure), noise from the playground and rain also constituted reasons for window closing.

Fig. 7 shows the Control Logic Diagram for school occupants' window operations based on the visual observations. On some occasions, windows were opened by caretakers before teachers and students' arrival. When windows were not opened by caretakers, they were usually opened by teachers or teacher assistants upon their arrival if the classroom was perceived uncomfortable in terms of IEQ. Once the windows were open, they would be kept open unless disturbing factors such as noise, rain, cold temperature or unwanted wind made the occupants close the windows. The control logic suggests that opening

Table 4
Descriptive statistics of indoor and outdoor variables.

Seasons	Descriptive Statistics	Indoor variables				Outdoor variables		
		T_{op}	RH (%)	V (m/s)	CO_2	T_{out}	RH_{out} (%)	V_{out} (m/s)
Non-heating season	Minimum	17.9	35.8	0.0	475	9.6	43.0	0.0
	Maximum	28.1	66.6	0.8	3430	25.1	94.0	7.7
	Mean	23.8	49.7	0.1	1050	17.5	73.1	3.0
Heating season	Minimum	16.2	24.6	0.0	555	0.7	50.0	0.0
	Maximum	27.4	54.9	0.9	2659	14.6	94.0	9.6
	Mean	21.8	38.2	0.1	1208	7.1	80.5	2.8

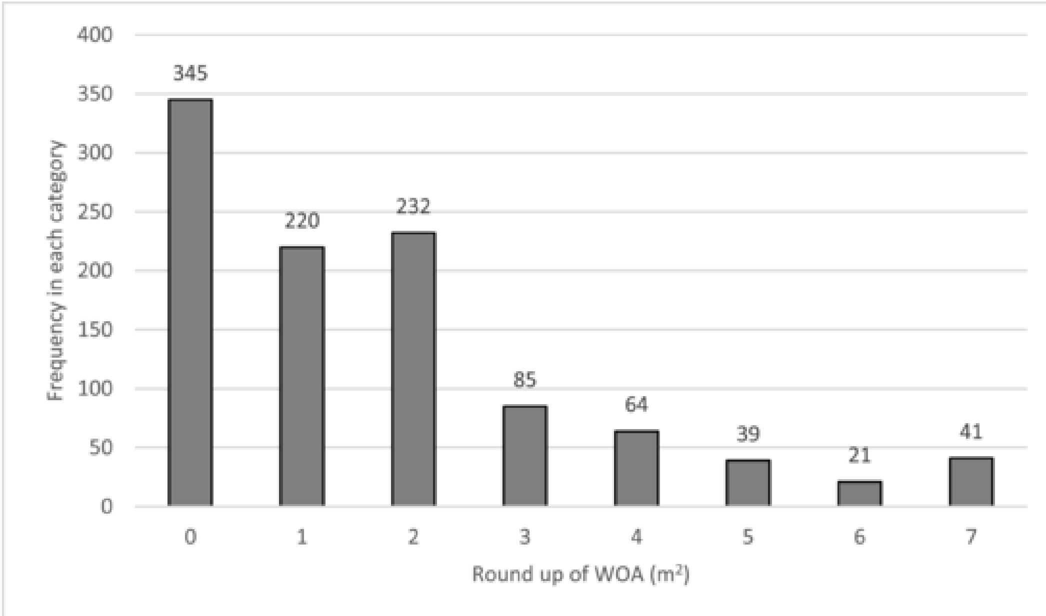

Fig. 5. The frequency for round up of WOA (m^2).

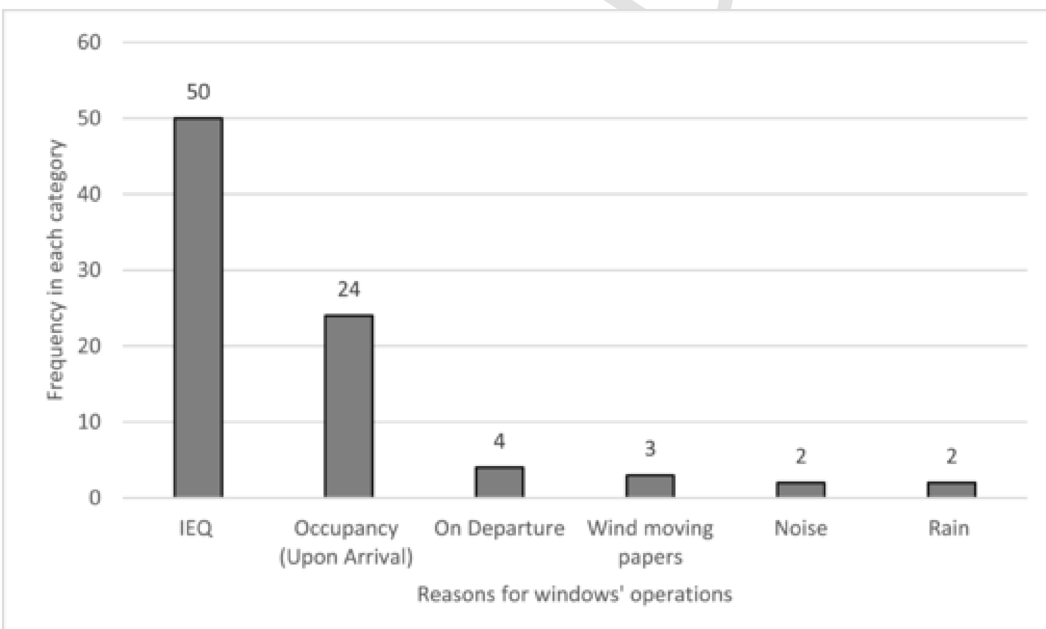

Fig. 6. Reasons for window operations based on visual observations.

or closing windows was dependent on occupancy patterns (upon arrival and departure) and environmental variables. It should be noted that not all window operations followed this control logic, however, this closely represents the scenario in most of the classrooms in this study.

The total number of window operations was calculated per day and its distribution in each season is shown in Fig. 8. Results of Kruskal-Wallis H test show that there is a statistically significant difference in median total number of operations between different seasons ($\chi^2(3) = 352.24$, $p = 0.000$). The median number of operations was the highest during summer (5), followed by spring (3), autumn (2) and winter (1).

Fig. 9 shows the distribution of windows open area (m^2) in each season. Results of Kruskal-Wallis H test show that there is a statistically significant difference in median WOA (m^2) between different seasons ($\chi^2(3) = 79.82$, $p = 0.000$). The median WOA (m^2) was the highest during summer (5 m^2), followed by spring (1.8 m^2), autumn (1.2 m^2) and winter (0.8 m^2).

3.2. Linear regression models for windows open area (m^2)

To achieve a more detailed analysis of window operations as a response to IEQ, windows open area (m^2) instead of the binary state of windows (open or closed) was used. Visual observations showed that the majority of the windows were operated due to IEQ, therefore, environmental measured variables including T_{op}, T_{out}, CO_2, RH (%), RH_{out} (%), V and V_{out} were tested against WOA (m^2). The instances of operations that were not related to environmental variables from the observations (such as closing the windows at the end of school occupancy) were excluded from the analysis. Table 5 shows the results of the Spear-

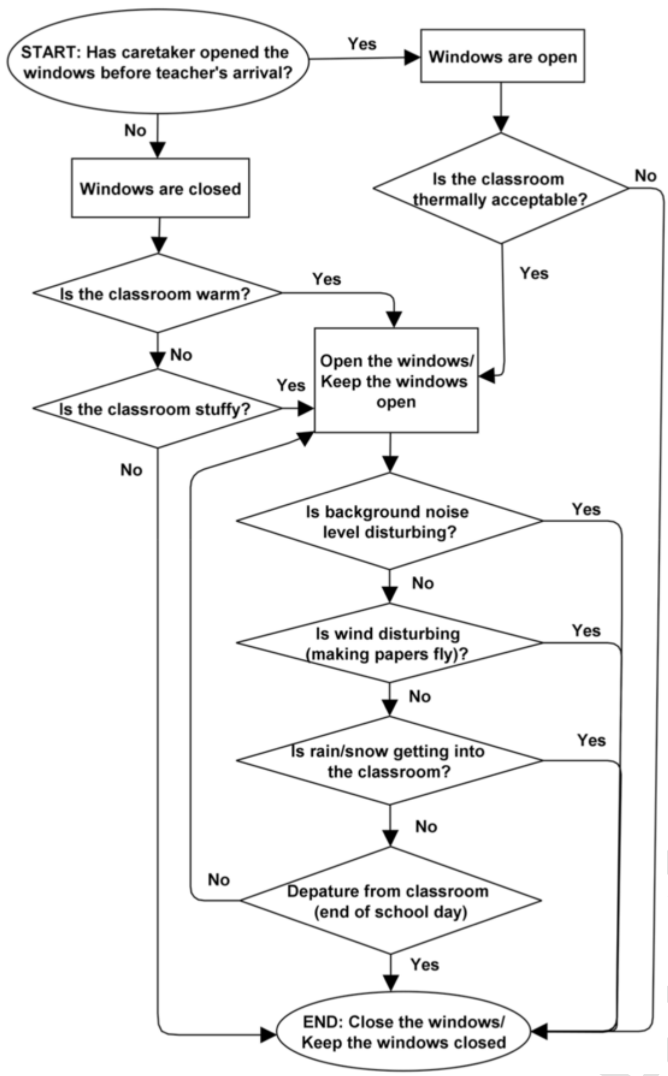

Fig. 7. The Control Logic Diagram for school occupants' window operations based on visual observations.

man correlation between WOA (m^2) and environmental variables. Results of the Spearman correlation in Table 5 show that outdoor temperature (Spearman correlation = 0.704, $P < 0.001$) and operative temperature (Spearman correlation coefficients = 0.548, $P < 0.001$) during the non-heating season and outdoor humidity (Spearman correlation = −0.383, $P < 0.001$) and indoor humidity (Spearman correlation = −0.377, $P < 0.001$) during the heating season have the strongest relationship with WOA (m^2).

A (m^2) that could be explained by environmental variables.

Fig. 10 shows the behavioural models of the relationship between WOA (m^2) and operative temperature (°C) during non-heating and heating seasons. As maximum window openable areas were different during non-heating and heating seasons, the maximum bound on the primary vertical axis (left side) shows the maximum windows' openable areas during the non-heating season (8 m^2) and the maximum bound on the secondary vertical axis (right side) shows the maximum windows' openable window areas during the heating season (5.7 m^2). WOA ranged from 0 to 6.8 m^2 during the non-heating season and from 0 to 3.2 m^2 during the heating season.

Fig. 10 shows that 33% of changes in WOA (m^2) during the non-heating season could be explained by operative temperature (R^2 = 0.33) while it is less than 1% during the heating season (R^2 = 0.007). The slope and intercept of the behavioural model for the non-heating season are significantly higher than those for the heating season.

School occupants started opening windows at an operative temperature of 18 °C during both seasons, however, at temperatures below 21.5 °C, WOA (m^2) was higher during the heating season than the non-heating season. The gap between behavioural models was observed to increase as operative temperature increased. At an operative temperature of 27 °C, the WOA was 4.5 m^2 during the non-heating season and 1 m^2 during the heating season; a gap of 3.5 m^2.

For the heating season behavioural model, there are a total of 320 data points at 10-min intervals (more than 53 h) that the windows were open while the heating system was on, which is also an indication of energy waste.

Fig. 11 shows the behavioural models for the relationship between windows open area and outdoor temperature (°C) during non-heating and heating seasons. Fig. 11 shows that outdoor temperature accounts for 50% changes in WOA (%) during the non-heating season (R^2 = 0.50) while they do not show a significant trend during the heating season (R^2 = 0.005). Fig. 11 shows that occupants started opening windows at outdoor temperatures as low as 2 °C during the heating season, which is an indication of poor temperature control.

Fig. 12 shows the behavioural models on WOA (m^2) and indoor humidity during non-heating and heating seasons. Fig. 12 shows that an increase in indoor humidity triggers a decrease in WOA (m^2) during both seasons. Visual observations confirmed that at the time of rain (10% of the time), windows would be closed, especially if rain could get into the classroom. Although operative temperature and outdoor temperature could not significantly explain the changes in WOA during the heating season, 13% of them could be explained by indoor humidity (R^2 = 0.13). During the non-heating season, indoor humidity accounted for only 4% of changes in WOA (R^2 = 0.04).

Behavioural models for non-heating and heating seasons in Fig. 12 have similar slopes, however, for the same indoor humidity between 35 and 55%, WOA was around 2 m^2 higher during the non-heating season. In this study, indoor humidity ranged from 25 to 55% during the heating season and ranged from 36 to 67% during the non-heating season. European standard EN 15251 recommends a humidity range of 30–50% for optimal humidity [38]. There are 256 data points during the non-heating season and 133 data points during the heating season that humidity was out of this range.

Fig. 13 shows the behavioural models on windows open area (m^2) and outdoor humidity during non-heating and heating seasons. Fig. 13 shows that an increase in outdoor humidity results in a decrease in WOA (m^2) during both seasons. Outdoor humidity (%) accounts for 21% and 16% of changes in WOA (m^2) during non-heating and heating seasons.

Windows open area (m^2) is correlated with air speed during non-heating (Spearman Correlation = 0.11, $p < 0.001$) and heating seasons (Spearman Correlation = 0.10, $p < 0.05$), however, low R^2 values could not explain changes in WOA by air speed (Table 5). Windows open area (m^2) is not correlated with outdoor air speed during both seasons ($P > 0.05$).

Results of the Spearman correlations in Table 5 shows that WOA (m^2) is negatively correlated to CO_2 level during the non-heating (Spearman correlation = −0.297, $P < 0.001$) and heating seasons (Spearman correlation = −0.315, $P < 0.001$), which is not expected. This could be explained by the negative correlation between operative temperature and CO_2 level (Spearman correlation coefficients = −0.109, $P < 0.001$) and the positive correlation between CO_2 level and humidity (Spearman correlation = 0.12, $P < 0.001$).

3.2.1. *Multiple linear regression*

To investigate the holistic impact of all environmental variables on WOA, multiple linear regression is run with predictors that were correlated with WOA in Table 5. Results of the multiple linear regression in

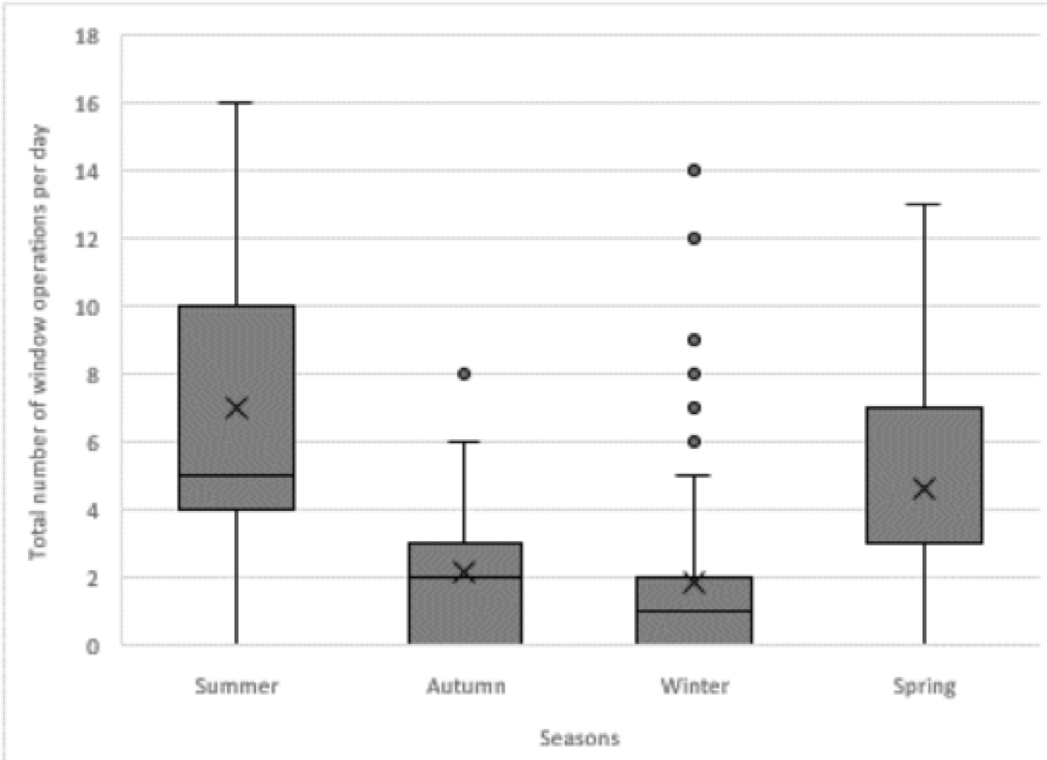

Fig. 8. The distribution of total number of window operations per day in each season.

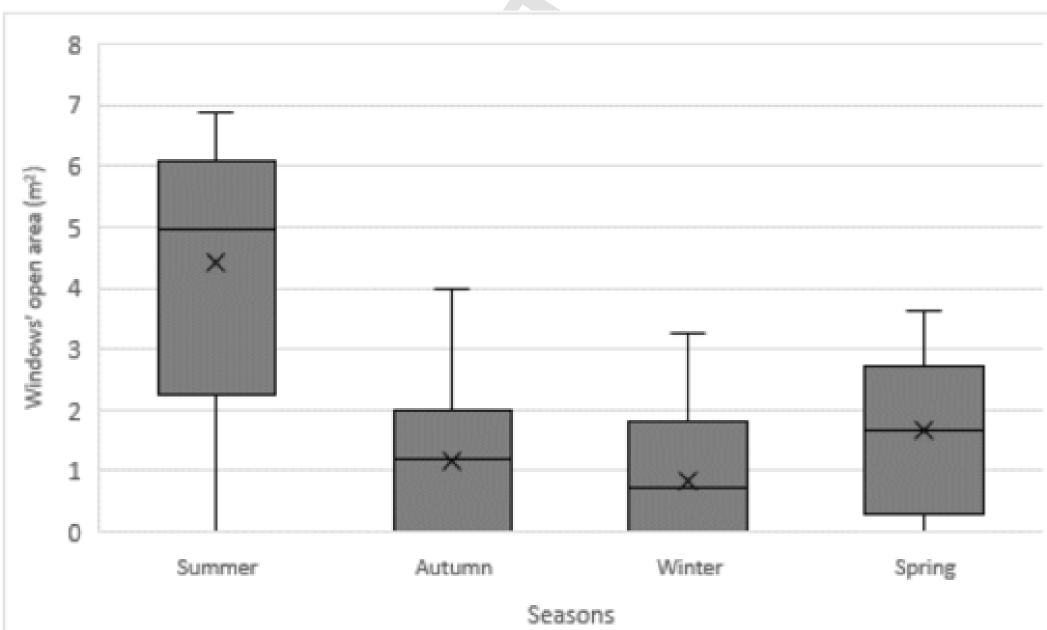

Fig. 9. The distribution of WOA (m^2) in each season.

Table 6 show that the group of environmental predictors (T_{op}, T_{out}, RH, RH_{out}, V, CO_2) explain 61% and 44% of changes in WOA (m^2). Adjusted R^2 in Table 6 suggests that the model is a reliable fit for the data because adjusted r-squared has increased by adding useful predictors.

The comparison of standardized coefficients in Table 7 shows that WOA (m^2) is more sensitive to changes in outdoor temperature (0.58) and operative temperature (0.33) during the non-heating season and more sensitive to outdoor temperature (0.62) and humidity (−0.58) during the heating season.

3.3. External door operations

More than 85% of external door operations were carried out by teachers or teacher assistants. Visual observations showed that external doors were mainly operated for letting the children into the classroom in the morning or letting them out during breaks or at the end of the school day or both. Sometimes when the external door was opened in the morning, it stayed open to cool the classroom and it would be closed due to noise from the playground or cold temperature. It was observed

Table 5
Correlation and regression values between WOA (m^2) and environmental variables.

Seasons	Correlation/Regression of WOA with …	T_{op}	T_{out}	RH	RH_{out}	V	V_{out}	CO_2
Non-heating	Correlation Coefficient	.548[a]	.704[a]	-.226[a]	-.461[a]	.110[a]	−0.038	-.297[a]
	R^2 value	0.32	0.5	0.04	0.21	0.0001	–	0.09
Heating	Correlation Coefficient	.113[b]	.125[a]	-.377[a]	-.383[a]	.100[b]	−0.033	-.315[a]
	R^2 value	0.007	0.005	0.13	0.16	0.0006	–	0.13

[a] Correlation is significant at the 0.01 level (2-tailed).
[b] Correlation is significant at the 0.05 level (2-tailed).

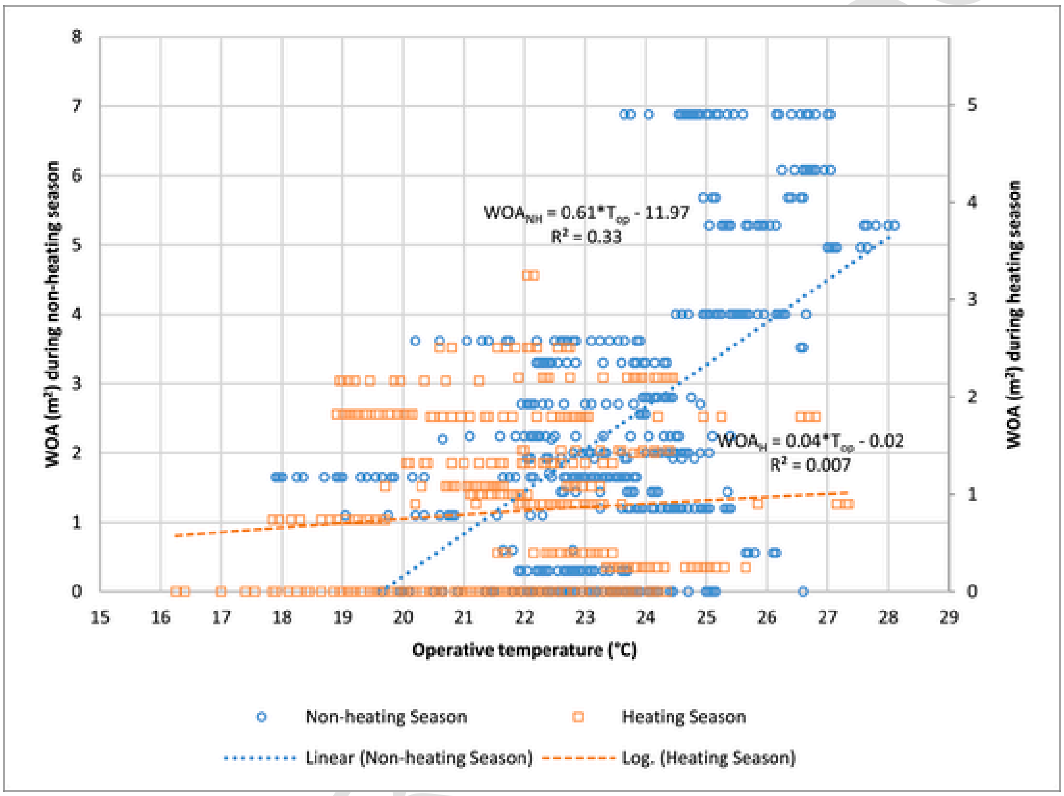

Fig. 10. Behavioural models showing the relationship between WOA (%) and operative temperature (°C).

that the duration they stayed open was largely dictated by temperature or noise. Fig. 14 shows the reasons for external door operations and their frequency. The highest number of external door operations happened when students left the classroom for a break or for going home at the end of the school day.

External doors in this study were either opened towards a public playground (noisy and for all students) or a private playground or courtyard (quiet and for a group of students). It was observed that when external doors were connected to a quiet playground or courtyard, they would stay open for a longer period and it would impact ventilation rates and IEQ more significantly, especially when internal and external doors were on opposite sides of the classroom to enable cross-ventilation. It was also observed that when external doors were connected to a quiet courtyard, part of the teaching happened in the courtyard on two different occasions. Several students also preferred to spend their breaks in more private courtyards instead of going to the public playground.

3.4. *Impact of open area (m^2) on IEQ*

The amount that windows and external doors are open or closed (m^2) and the duration that they stay open or closed will have different impacts on IEQ in a classroom. Therefore, this part of the study considers how much operative temperature and CO_2 level change after the open area (m^2) has increased or decreased at different time intervals. To consider the impact of the control operations on IEQ, cases in which operative temperature and CO_2 level were significantly impacted by school occupants' occupancy pattern (for example, type of activity) were removed from the analysis. In the remaining cases, the school occupants' occupancy patterns did not change significantly, therefore, drops or rises in CO_2 level and operative temperature could more confidently be attributed to changes in open area (%). Open area (m^2) is the sum of the windows' and external doors' (if available) open area (m^2).

3.4.1. *Impact of open area (m^2) on T_{op}*

Fig. 15 shows changes in operative temperature after 10 min, 20 min, 30 min and 40 min of changing open area. The vertical axis shows changes in operative temperature and the horizontal axis shows changes in the open area (m^2). Positive numbers on x- and y-axis indicate that the open area (m^2) and operative temperature increased and negative numbers indicate that they decreased.

The regression lines in Fig. 15 and their equations in Table 8 show that changes in operative temperature are impacted by changes in the open area (m^2) and how long (10, 20, 30 or 40 min) they have been open or closed. Changes in operative temperature (%) are less sensitive to changes in the open area (m^2) 10 min after operations (S_{10} = 0.088

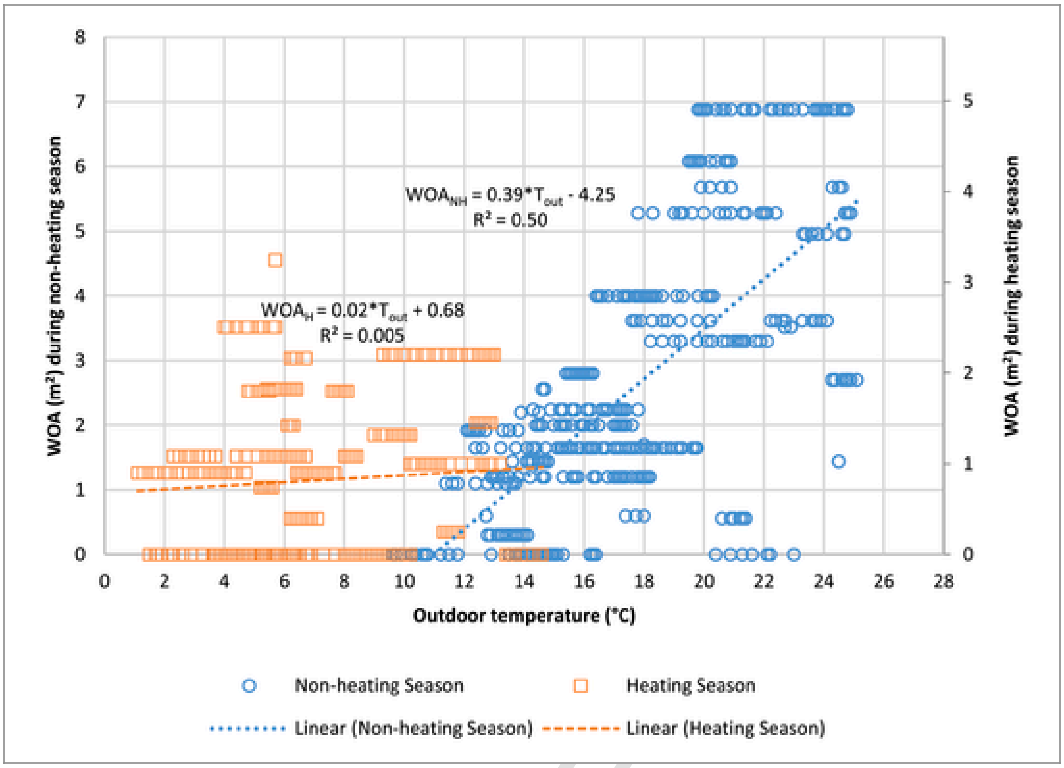

Fig. 11. Behavioural models for WOA (m^2) and outdoor temperature (°C).

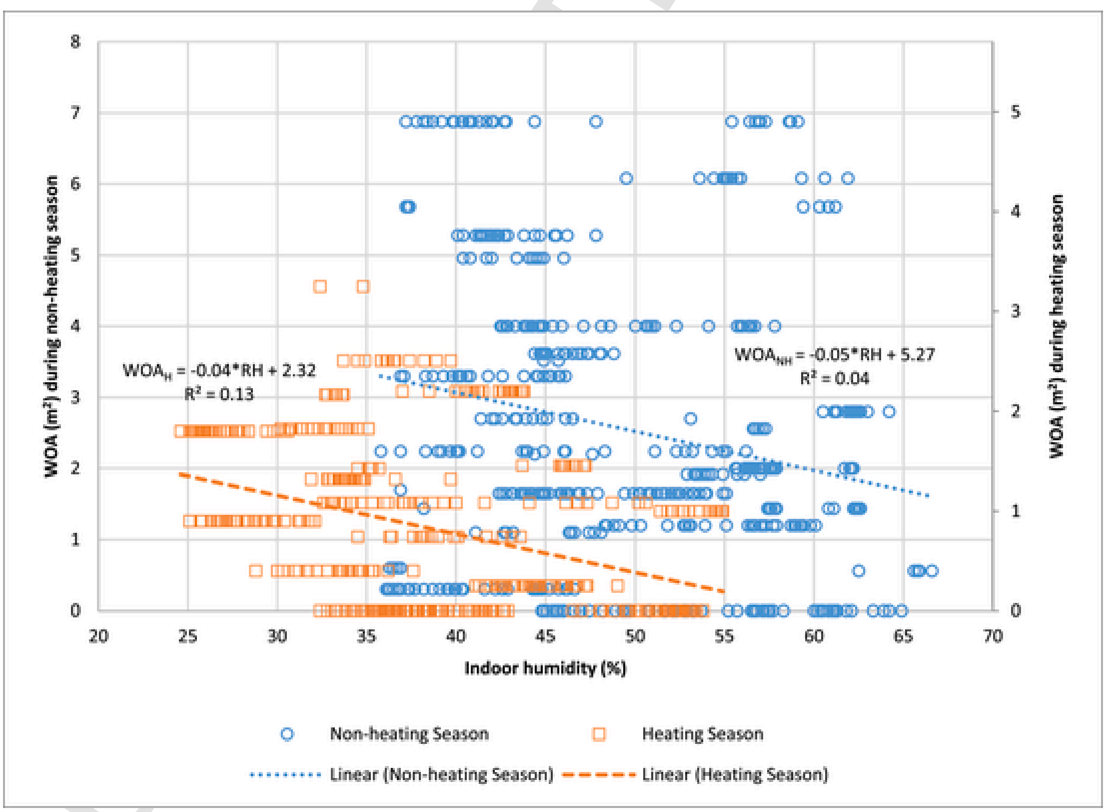

Fig. 12. Behavioural models on WOA (m^2) and indoor humidity.

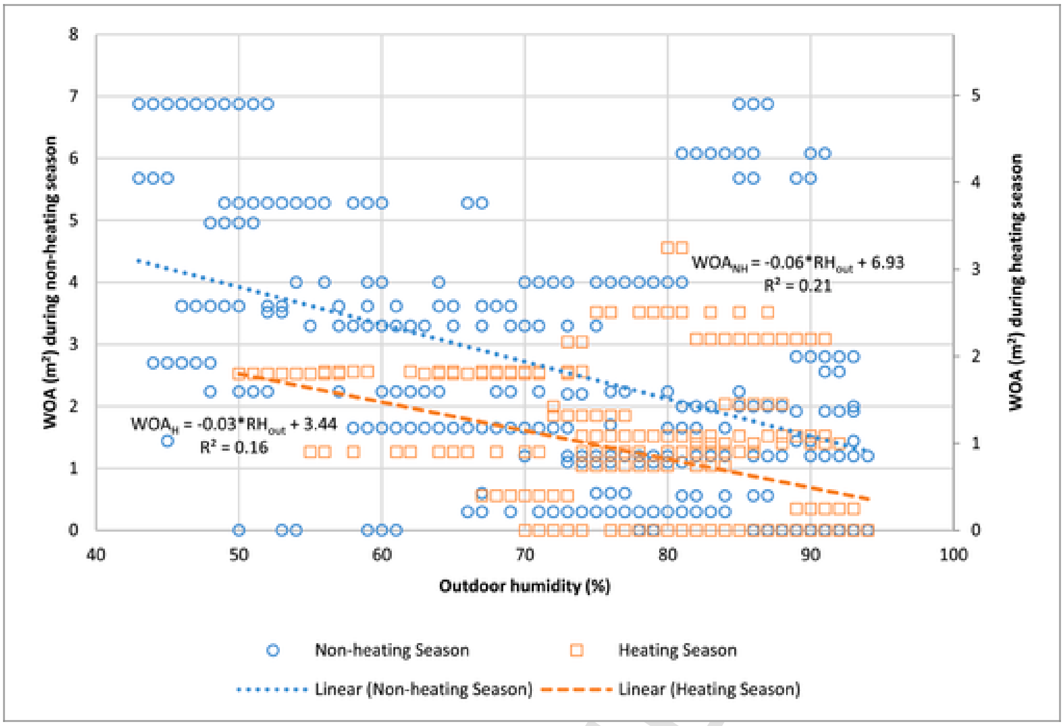

Fig. 13. Behavioural models for WOA (m^2) and outdoor humidity.

Table 6
Multiple linear regression between WOA and environmental predictors.

Multi-linear regression	R	R^2 value	Adjusted R^2	Std. Error of the Estimate
Non-heating	0.78[a]	0.61	0.60	1.3
Heating	0.66[a]	0.44	0.43	0.57

[a] **Predictors: T_{op}, T_{out}, RH, RH_{out}, V, CO_2.**

Table 7
Standardized coefficients in the multiple linear model.

Seasons	Dependents	Standardized Coefficients	Sig.
Non-heating	T_{op}	.33	.000
	T_{out}	.58	.000
	RH	-.06	.000
	RH_{out}	.11	.315
	V	.07	.224
	CO_2	-.14	.037
Heating	T_{op}	-.16	.000
	T_{out}	.62	.001
	RH	-.58	.000
	RH_{out}	-.20	.000
	V	.13	.003
	CO_2	-.06	.001

and$R^2_{10} = 0.25$) than 20 min (S_{20} = 0.302 and$R^2_{20} = 0.59$), 30 min (S_{30} = 0.341 and$R^2_{30} = 0.54$) or 40 min (S_{40} = 0.572 and$R^2_{40} = 0.65$) after operations.

The slope and R^2 value of the regression lines start to decrease after 40 min (Table 8), suggesting that changes in the open area would be less accountable for changes in operative temperatures after 40 min. The longer open areas (m^2) were open, up to 40 min after the operation, operative temperature changed more from the base temperature.

3.4.2. *Impact of open area (m^2) on CO_2 level*

Fig. 16 shows changes in CO_2 level after 10 min, 20 min, 30 min and 40 min of changing the open area. The vertical axis shows changes in CO_2 level (ppm), positive numbers on the y-axis indicate that CO_2 levels increased and negative numbers indicate that they decreased. Changes in CO_2 level (%) are less sensitive to changes in the open area (m^2) 10 min after operations (S_{10} = 56 and$R^2_{10} = 0.42$) than 20 min (S_{20} = 172 and$R^2_{20} = 0.61$), 30 min (S_{30} = 245 and$R^2_{30} = 0.51$) or 40 min (S_{40} = 254 and$R^2_{40} = 0.53$) after operations.

The slope and R^2 value of the regression lines 30 and 40 min after the operation (Table 9) are very similar, suggesting that changes in CO_2 level were only noticeable up to 30 min after the operation.

3.5. *Impact of adaptive behaviours on increasing comfort*

For optimal comfort temperature in primary school classrooms, an earlier study by the lead author [29] on the same subjects showed that students' comfort temperature was 20.9 °C during the non-heating season and 20.2 °C during the heating season. Considering students' thermal comfort band ($T_{C(students)} \pm 2K$), temperatures above 22.9 °C during the non-heating season and 22.2 °C during the heating season are likely to be considered uncomfortable by students.

For optimal CO_2 level, ASHRAE standard 62 [39] and EN 13779:2007 [40] for Categories I and II buildings have suggested a CO_2 level of 1000 ppm.

In total, there were 557 data points (93 h) during the non-heating season.

- For 34% of this data, operative temperature was higher than students' thermal comfort band ($T_{op} > 22.9$ °C) and at least half of the windows were closed.
- For 28% of the time, CO_2 level was higher than 1000 ppm and at least half of the windows were closed.
- For 23% of the time, operative temperature was higher than students' thermal comfort band and CO_2 level was higher than 1000 ppm and yet at least half of the windows were closed.

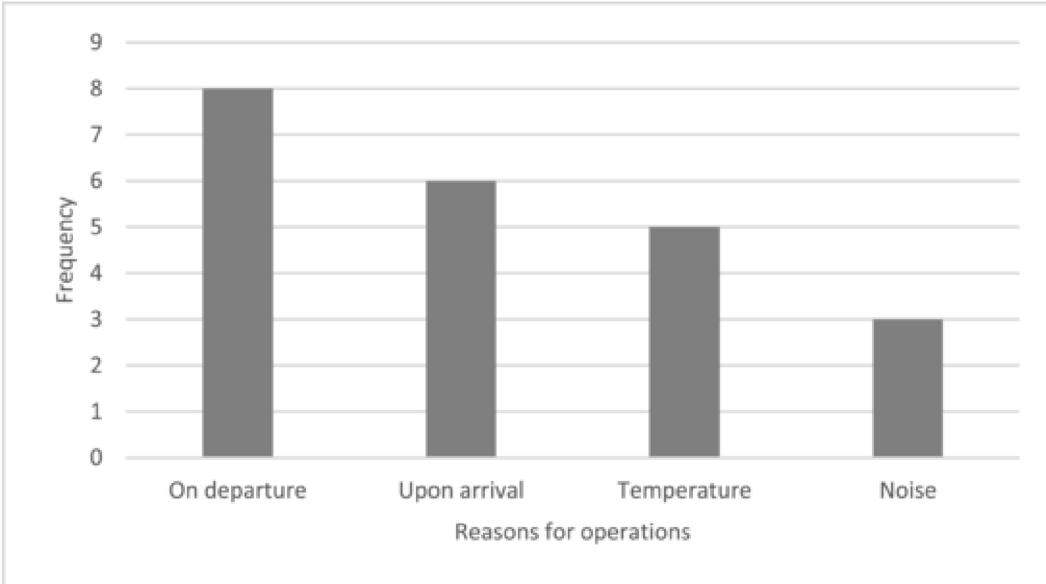

Fig. 14. The reasons for external door operations and their frequency.

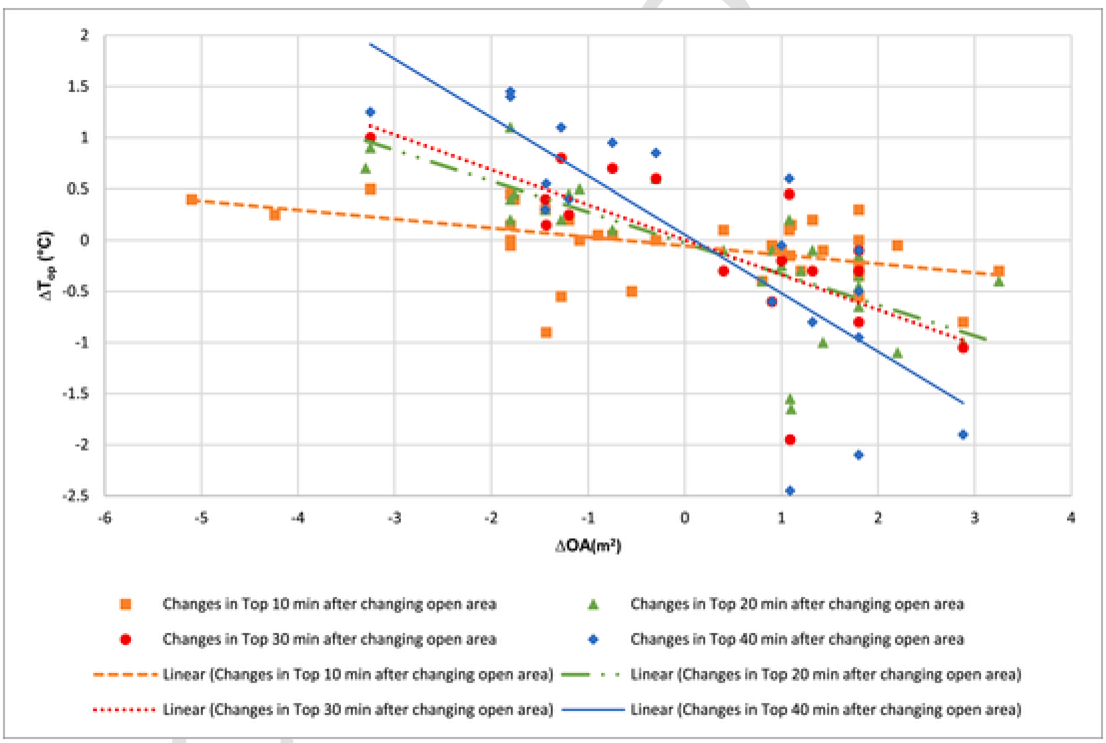

Fig. 15. Impact of changes in open area (m^2) on T_{op}.

3.6. *Impact of adaptive behaviours on energy*

Opening windows during the heating season indicates a waste of energy as the heating systems are on while windows are open. The studied students' preferred temperature was 20.2 °C during the heating season [29], therefore, the heating setpoint temperature should be defined to provide a thermal environment of around 20.2 °C.

In total, there were 474 data points (79 h) during the heating season.

- For 67% of data during the heating season (53 h), windows were open and the heating system was on.
- For 56% of this data (44 h), windows were open, the heating system was on and the operative temperature was more than 20.2 °C. This could be avoided by reducing the heating setpoint temperature.
- For 11% of this data (9 h), windows were open, the heating system was on and the operative temperature was below 20.2 °C. This suggests occupants' inefficient window operation at lower temperatures which could be avoided by asking the head teacher to turn the heating system off first before opening the windows.

Table 8
Impact of changes in the open area (m^2) on T_{op}.

Changes in T_{op} after operating windows	Equation	Changes in the open area (m^2)							
		-4m^2	-3m^2	-2m^2	-1m^2	+1m^2	+2m^2	+3m^2	+4m^2
10 min	$\Delta T_{op} = -0.088*\Delta OA-0.055$ ($R^2 = 0.25$)	0.30	0.21	0.12	0.03	−0.14	−0.23	−0.32	−0.41
20 min	$\Delta T_{op} = -0.302*\Delta OA-0.028$ ($R^2 = 0.59$)	1.18	0.88	0.58	0.27	−0.33	−0.63	−0.93	−1.24
30 min	$\Delta T_{op} = -0.341*\Delta OA-0.004$ ($R^2 = 0.54$)	1.36	1.02	0.68	0.34	−0.35	−0.69	−1.03	−1.37
40 min	$\Delta T_{op} = -0.572*\Delta OA-0.054$ ($R^2 = 0.65$)	2.23	1.66	1.09	0.52	−0.63	−1.20	−1.77	−2.34
50 min	$\Delta T_{op} = -0.216*\Delta OA+1.021$ ($R^2 = 0.35$)	-	-	-	-	-	-	-	-

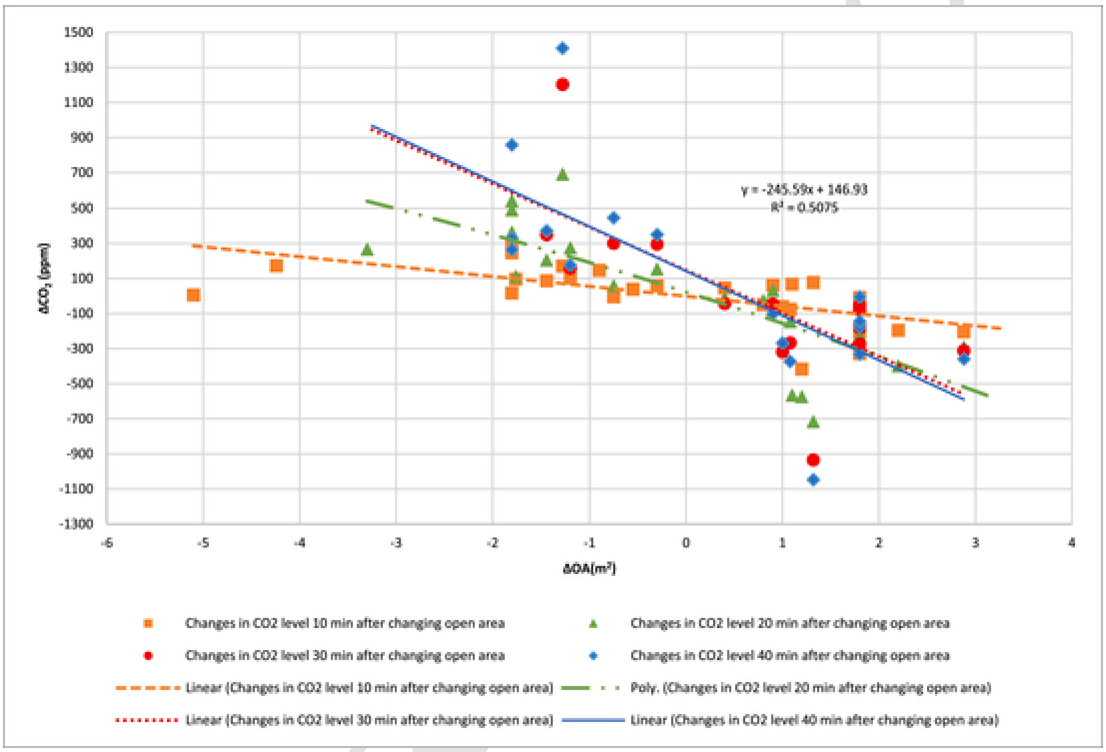

Fig. 16. Impact of changes in open area (m^2) on CO_2 levels.

Table 9
Impact of changes in the open area (m^2) on CO_2 level.

Changes in CO_2 after operating windows	**Equation**	**Changes in WOA (m^2)**							
		-4m^2	-3m^2	-2m^2	-1m^2	+1m^2	+2m^2	+3m^2	+4m^2
10 min	$\Delta CO_2 = -56.35*\Delta OA-1.14$ ($R^2 = 0.42$)	224	168	112	55	−57	−114	−170	−227
20 min	$\Delta CO_2 = -172.41*\Delta OA+9.14$ ($R^2 = 0.61$)	699	526	354	182	−163	−336	−508	−680
30 min	$\Delta CO_2 = -245.59*\Delta OA+146.93$ ($R^2 = 0.51$)	1129	884	638	393	−99	−344	−590	−835
40 min	$\Delta CO_2 = -254.04*\Delta OA+141.98$ ($R^2 = 0.53$)	1158	904	650	396	−112	−366	−620	−874
50 min	$\Delta CO_2 = 35.646*\Delta OA+646.97$ ($R^2 = 0.002$)	–	–	–	–	–	–	–	–

4. Discussion

4.1. Variables impacting window' operation

The results show that school occupants' window operations were impacted by occupancy patterns (arrival and departure) and contextual factors (such as season, noise and environmental variables). The impact of environmental variables on window operations was found to be different during non-heating and heating seasons. This study shows that operative temperature and outdoor temperature during the non-heating season and indoor and outdoor humidity during the heating season were the main predictors of WOA (m^2). As highlighted earlier in the introduction, previous studies in schools confirmed that the key stimuli for window operations were indoor temperature [23–25,27,28], outdoor temperature [13,25,27,28], indoor-outdoor temperature difference [26]. Only a few studies in primary schools have shown the probability or the proportion of windows open as a response to environmental variables (indoor temperature, outdoor temperature or temperature offset from neutrality) in statistical models [13,16,29].

In this study, CO_2 concentration did not show a meaningful relationship with WOA which could be related to occupants not sensing CO_2 concentrations. Previous studies in schools have highlighted that CO_2 concentration was not the main driver for window operation [27,28]. The study by Stazi et al. [27] showed that CO_2 concentration had no statistical meaning with window operations in schools. Similarly, the study by Dutton and Shao [28] showed that CO_2 concentration was not the driver for window operation during the heating period and was the least important driver for window operation during the unheated period.

Results of this study showed that an increase in indoor and outdoor humidity would trigger occupants to close windows more during both seasons. Outside rain could also prevent window opening, shorten the period that the window was left open and keep the windows closed. This could be related to the negative impact of high humidity levels on perceived air quality and thermal sensation, which has been suggested in several earlier studies [41,42]. Previous studies have also shown that a high level of relative humidity may cause additional problems such as mould or condensation which are very unhealthy for children and other occupants [43–45]. Relative humidity is one of the parameters that characterises indoor environment [13] and is measured in several studies in schools with regards to thermal environment or to calculate Predicted Mean Vote (PMV) index [46–48], however, it has received little attention with its relationship with window operations.

In this study, air speed did not show a meaningful relationship with window operations. This could be related to the negligible mean air speed of 0.1 m/s, which could marginally impact school occupants' thermal sensation and therefore, their operations on controls. Air speed can impact comfort limits in terms of skin wetness [12], offset high indoor air temperatures and lower the mean thermal sensation [18]. It is also measured in several studies in schools with regards to the thermal environment [18,19,25,49], however, their relationship with window operations is not treated comprehensively.

Future studies are recommended to apply statistical behavioural models to investigate the relationship between window operations and less studied environmental variables such as humidity and air speed and other contextual variables such as pollution and background noise level.

4.2. Variables impacting external doors' operation

In this study, external doors were kept closed due to noise and were occasionally opened or stayed open to cool the classroom, as highlighted in previous studies [50,51], however, the main driver for opening or closing external doors was the occupancy pattern (arrival or departure). Although external doors were not designed to improve IEQ, each time that external doors were opened to let the students in or out, accumulated heat and CO_2 could be removed, especially when the internal door in the classroom was open for cross-ventilation, as supported by Mumovic et al. [52].

Due to security reasons, it is not recommended to use external doors as a control to moderate temperature and air quality. Mumovic et al. [52] suggest that this behaviour does not comply with safety regulations because all fire doors should be closed when not in use. However, the optimal design of external doors onto a more private playground or courtyard can provide a pleasant connection between inside and outside for teaching activities and breaks. It can also provide separate entry and exit paths for students, preventing excessive noise for other classrooms.

4.3. Impact of adaptive behaviours on IEQ, comfort and energy

Indoor Environmental Quality: By investigating the impact of open area (m^2) on operative temperature and CO_2 level, three main findings were evident.

Firstly, the impact of open area (m^2) on operative temperature would decrease significantly after 40 min and its impact on CO_2 level would not be noticeable after 30 min. This could be related to the impact of accumulated heat and exhalation rate from school occupants on environmental variables, especially CO_2 levels. It is previously shown that CO_2 levels are emanated through occupants' respiration and sweating [31,45], therefore, the longer students stay in the classroom, CO_2 is increasing more. To decrease CO_2 levels and operative temperatures, windows should be opened more or occupancy should be changed (leaving the classroom for a break) to evacuate accumulations. This highlights that IEQ should be evaluated and improved after 30–40 min. Opening windows at a certain proportion upon arrival and not changing their state until departure (observed in 25% of the classrooms) cannot guarantee healthy IEQ.

Secondly, the impact of opening controls (windows and external doors) on decreasing T_{op} was very similar to the impact of closing controls on increasing T_{op} (the difference is within a band of 0.11 °C). However, the impact of closing controls on increasing CO_2 was more than the impact of opening controls on decreasing CO_2 level (the difference could be up to 300 ppm after 30 min of the operation). This is mainly because occupants' presence in the classroom increases CO_2 level more than operative temperature and this increase becomes more significant over time.

Thirdly, by comparing the impact of open area (m^2) on operative temperature and CO_2 level, it was evident that the immediate impact of window operation (after 10 min) on CO_2 level ($R^2 = 0.42$) was higher than on operative temperature ($R^2 = 0.25$). The slope of the regression line 10 min after window operation ($S_{10} = 0.088$) was significantly lower than 20 min ($S_{20} = 0.302$), 30 min ($S_{30} = 0.341$) or 40 min ($S_{40} = 0.572$) after the operation, suggesting that operative temperature does not change suddenly by adjusting operable areas. This is presumably due to heat stored in the thermal mass of the studied buildings, which does not apply to pollutants.

The impact of open area (m^2) on CO_2 level and the operative temperature was not separated by seasons due to the limited number of data. It should be highlighted that the impact of open area (m^2) on reducing CO_2 level and operative temperature could be higher during the heating season. The temperature difference between inside and outside was higher during the heating season (Average of 21.8 °C inside and 7.1 °C outside) than the non-heating season (Average 23.8 °C inside and 17.5 °C outside) which can increase exchange rates for the same amount of openings, as supported in several studies [53–57].

It is evident that the impact of controls' operations on IEQ could vary by building-related factors (such as orientation, windows' design, heating systems) and contextual factors (such as outdoor temperature, outdoor air speed, wind direction). Therefore, the results should not be applied to other studies without considering these differences.

Comfort and Energy: This study suggests that through opening a higher number of available windows, operative temperature 34% of the time, CO_2 28% of the time and both operative temperature and CO_2 23% of the time during the non-heating season could be lowered to provide more thermally acceptable environments and higher air quality. The results of this study suggest that energy waste could be avoided 67% of the time during the heating season by reducing the setpoint temperature, according to children's thermal comfort temperature, and training school occupants on turning off heating systems before opening windows. Considering the thermal lag in the heating systems and heat generated by occupants and their activity, heating setpoints should be lower than 20.2 °C. A higher setpoint temperature indicates a waste of energy and uncomfortable thermal conditions. The exact setpoint temperature would depend on environmental variables (outdoor temperature), type and number of heating systems, number of occupants, their occupancy patterns and adaptive behaviours. Considering that space heating makes up the largest proportion of energy use and associated costs in schools [9], lowering setpoint temperatures in primary schools which are occupied with children with lower comfort temperatures than adults can save a significant amount of energy. Another study by Simanic [6] showed that occupant-related parameters such as space heating setpoints and running times account for at least 33% of measured energy consumption [6].

The impact of school occupants' adaptive behaviours and their energy awareness on energy consumption is supported in several other studies [5–8]. For example, the study by Pietrapertosa et al. [5] aimed at increasing energy efficiency in buildings by raising energy awareness in public schools and showing the importance of students' role to promote energy savings through adaptive behaviours. The results showed that in the school with energy-saving measures and technical interventions, a decrease in natural gas consumption was observed [5]. Another study by Simanic [7] aimed to increase awareness in school buildings about the impact of user-related parameters on energy consumption variations. Similarly, the study by Drosos [8] which studied 510 school managers in Greek primary and secondary schools highlighted the need to intensify environmental education programs in schools to increase the environmental awareness of both students and teachers.

4.4. Recommendations

The results suggest several avenues to improve the impact of controls' operations on IEQ, comfort and energy:

For teachers and students:

- Evaluating IEQ by teachers at shorter intervals (each 30–40 min during teaching activities)
- Using the maximum potential of windows during the non-heating season to increase ventilation rates and evacuate accumulated heat and exhalation rates
- Not allowing students to eat their lunch in the classroom during lunch break (observed in two classrooms), which contributes to further increase of CO_2 levels
- Encouraging students to engage with window operations or expressing their preferences.

For schools' maintenance team:

- Lowering the heating setpoint temperatures to respond to students' lower thermal comfort temperature
- Turning off heating systems on the request of teachers and students to avoid subsequent heat and energy loss during the heating season
- Training and informing teachers and students of the impact of their window and external door operations on energy consumption during the heating season and for improving IEQ during the non-heating season.

For school designers:

- Designing windows to not let rain in when it is raining outside
- Designing external doors onto quiet and private playgrounds or courtyards
- Equipping primary schools with CO_2 warning devices

5. Conclusion

Primary schools are occupied by children who have limited control over the environment and have a different perception of IEQ than adults. Furthermore, children are usually not aware of the impact of their environmental adaptive behaviours on IEQ, comfort and energy. Therefore, investigating operations on controls is important in primary schools.

This study investigated the variables that were related to operations on windows and external doors in naturally ventilated primary schools in the UK. During the non-heating season, an increase in operative and outdoor temperature would trigger occupants to open windows more. During the heating season, an increase in indoor and outdoor humidity would trigger occupants to close windows more.

When the operable area was modified, it had different impacts on IEQ depending on how much (m^2) they were opened or closed and how long they stayed open or closed. For example, the impact of open area (m^2) on operative temperature would decrease significantly after 40 min of operation and its impact on CO_2 level would not be noticeable after 30 min. This could be related to the impact of accumulated heat and exhalation rate from school occupants on environmental variables, especially CO_2 concentrations. The results suggest that operative temperature in 34% and CO_2 in 28% of the time during the non-heating season could be reduced through opening more available windows. Furthermore, energy waste could be avoided 67% of the time during the heating season by reducing the setpoint temperature and raising school occupants' energy awareness.

This study highlights the impact of school occupants' adaptive behaviours on IEQ, comfort and energy and suggests several avenues for schools occupants (teachers and students), the school maintenance team and school designers to improve this impact.

The study contributes to behavioural models in schools and bridges the gap on the impact of controls' operation on IEQ. The implication of this study is increasing energy awareness of school occupants, and designing and maintaining schools to facilitate adaptive behaviours, improve IEQ, increase overall comfort and reduce energy consumption.

Declaration of competing interest

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

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