Are Irish Low Energy School Designs Resilient Against Overheating?

Elahe Tavakoli*, Adam O' Donovan, Paul D. O'Sullivan

Department of Process, Energy and Transport Engineering, Munster Technological University (Cork Campus), Rossa Avenue, Bishopstown, Cork, Ireland
MaREI, the SFI Research Centre for Energy, Climate and Marine, Beaufort Building, Environmental Research Institute, Ringaskiddy, Cork, Ireland
**Corresponding author: elahe.tavakoli@mycit.ie*

ABSTRACT

The challenges posed by climate change and related thermal discomfort in school classrooms are a worldwide challenge. Recent research indicates that numerous low energy school buildings do not comply with comfort criteria and suffer from overheating. This study aimed to determine when indoor air temperature conditions in classrooms were vulnerable to overheating risk. Secondly, quantify the contribution and correlation of outdoor air temperature and individual building features on the indoor air temperature in Irish low energy naturally ventilated schools.
To achieve these objectives, this research analysed 45 classrooms in five low energy naturally ventilated schools in Ireland. Advanced sensors were employed to gather precise and extensive air temperature readings across various classrooms and schoolyards. The investigation utilised an extensive database detailing the school buildings' features as well as indoor and outdoor air temperatures. The study applied advanced statistical methods to analyse and understand temperature dynamics in school buildings. A descriptive statistical analysis was used to uncover patterns and fluctuations in temperature within the school buildings. The analysis of variance for hypothesis testing was employed to reveal significant temperature differences between various school classrooms and levels. Cohen's d statistic was also used to quantify the effect sizes, providing insight into how specific building features impact indoor air temperatures.
The findings show that the classrooms are able to meet overheating thresholds in the present, so they scored high on their indoor thermal resilience under future climate scenarios. They have sufficient natural ventilation potential to ensure thermal building resilience in current weather conditions. The field study-based approach adopted in the study offered a useful method to evaluate indoor thermal resilience in the existing building when the opportunity to avoid vulnerability "lock-in" is greatest. This study also comprehensively explains the relationship between school building features and indoor air temperature. The analysis using Cohen's d effect sizes prioritised certain building features when designing or retrofitting school buildings to improve the thermal comfort performance of classrooms against overheating. This study recommends utilising natural ventilation, developing robustness and recoverability plans for passive cooling systems, and occupant performance in overheating situations.

KEYWORDS

Resilient cooling, Schools, Natural ventilation, Low energy building, Overheating risk

1 INTRODUCTION

Most non-residential buildings in Ireland are educational, with primary schools making up the largest portion [1]. School buildings have some of the most demanding requirements for occupant comfort due to the large number of people spending a significant amount of time inside and the importance of students' learning performance [2]. As climate change progresses, rising temperatures may significantly impact the indoor thermal environment, especially during the non-heating and summer seasons [3][4]. This could increase the risk of overheating, particularly in newly constructed schools designed to meet Zero Energy Building (ZEB)

standards, which focus on optimising heating season performance through airtightness and insulation [5].
Climate change presents significant challenges worldwide, particularly in the educational sector, where extreme classroom temperatures can affect students' and staff's learning and well-being [6]. Recent research has indicated that many low energy school buildings, designed with sustainability in mind, fail to meet comfort criteria, particularly during extreme temperatures, leading to overheating and associated risks [7][8].

Overheating not only results from climatic conditions but also from factors intrinsic to school buildings, such as solar heat gains through large windows, high internal heat gains and inadequate ventilation [5][9], posing significant health risks, including heat-related mortality [10][11]. Compounding this issue is the physiological vulnerability of students, especially those under the age of 12, whose developing thermoregulatory systems make them more susceptible to heat [12]. Despite limited epidemiological studies specifically addressing heat mortality among students, there is a well-documented impact of overheating on cognitive functions and learning performance [12][7][13][14], highlighting the urgency of addressing thermal comfort in schools to safeguard the health and academic success of students in the face of escalating overheating.

In light of these considerations, this paper explores the thermal resilience of classrooms in five low energy, naturally ventilated (NV) schools in Ireland, investigating their ability to maintain comfortable indoor temperatures. The study collected detailed indoor and outdoor air temperature data and building information from 45 classrooms in the schools, using advanced sensors to provide a robust dataset of indoor and outdoor environmental conditions.
The research aims to accomplish two objectives:

- 1. To determine the specific conditions under which indoor temperatures in these classrooms are at risk of overheating.
- 2. To quantify how outdoor air temperature and specific building characteristics correlate with and influence indoor air temperatures, using descriptive statistics, ANOVA analysis, and the calculation of effect sizes using Cohen's d statistic.

This analysis aims to understand the effectiveness of current design features and the potential need for additional strategies to enhance thermal comfort.

2 METHODOLOGY

This methodology section elaborates on the systematic process of creating a detailed database for studying five naturally ventilated, low energy schools across Ireland. The comprehensive database, depicted in Figure 1, from 45 different zones within these schools, integrates meticulous indoor and outdoor air temperature measurements and essential school building information. The process thoroughly analysed the varied building parameters and their respective impacts on indoor air temperatures.

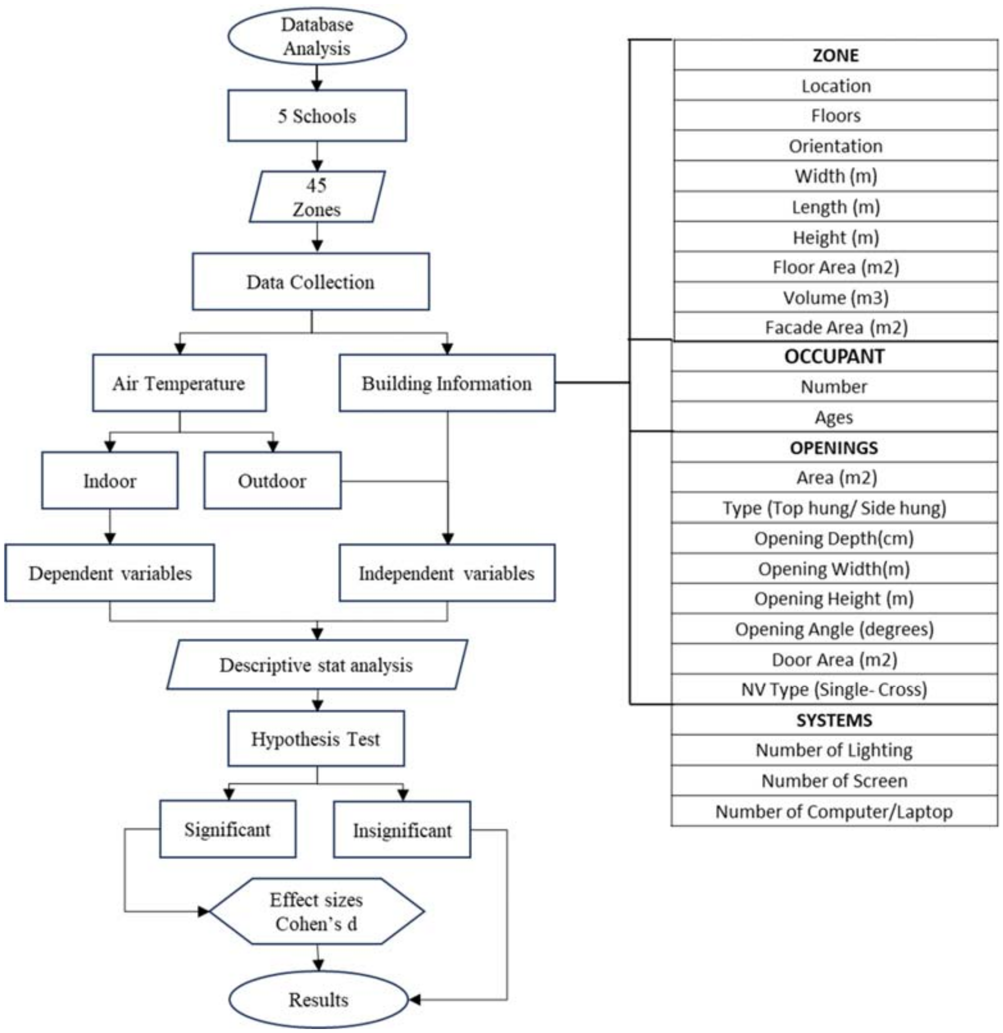

Figure 1: Methodology Process

2.1 Data Collection

A detailed and strategic data collection process was implemented using advanced sensor technology to comprehensively assess the thermal environment within the classrooms. The sensor types used and their specifications are presented in Table 1. These sensors were positioned within each classroom at the height of 1.5m, ensuring that data collection encompassed diverse environmental conditions across different parts of the schools.

Table 1: The sensors model and their specifications

Sensor Model	Temperature Accuracy	Humidity Accuracy	CO2 Accuracy	Ref
LASCAR EL-SIE	±0.3°C	±2% RH	N/A	[15]
TESTO 440	±0.3°C to ±0.4°C (NTC)	±(0.6% RH + 0.7 % of m.v.) (0 to 90% RH)	N/A	[16]
Airthings	±0.5°C at 25°C, ±1.0°C in 0-65°C range	±1.8% RH (10 to 90%RH @ +25°C)	Optimum accuracy of ±30ppm ±3% after initial calibration	[17]
LASCAR WIFI-TH	±0.2°C (0 to +60°C)	±1.8% RH (10 to 90%RH @ +25°C)	N/A	[18]

2.2 Data Analysis Techniques

The study uses several data analytic techniques to analyse indoor and outdoor air temperature trends and building specifications. The comprehensive descriptive statistical analysis was conducted to calculate key descriptive statistics, such as the number of observations (N), the mean temperature, standard deviation (SD), minimum and maximum temperatures, quartiles (Q1 and Q3), median temperature, and the interquartile range (IQR) for each classroom zone which helped in understanding the central tendencies and variability within the data.
Additionally, a comprehensive correlation and regression analysis was conducted to find the relationship between indoor and outdoor air temperatures. This method sought to determine how closely aligned the fluctuations in outdoor air temperatures are with those of indoor temperatures and provided critical insights into how indoor conditions might be predicted based on outdoor environmental changes. This statistical approach involved calculating the Pearson correlation coefficient, which quantifies the degree to which two variables are related linearly. It is calculated using the formula (1).

$$r = \frac{\sum(X_i - \bar{X})(Y_i - \bar{Y})}{\sqrt{\sum(X_i - \bar{X})^2 \sum(Y_i - \bar{Y})^2}} \tag{1}$$

Where X_i and Y_i are the individual sample points indexed with i, $\bar{X}$ and $\bar{Y}$ are the means of the X and Y variables, respectively. This formula results in a value between -1 and 1. A value of 1 indicates a perfect positive linear relationship, -1 indicates a perfect negative linear relationship, and 0 indicates no linear relationship between the variables.
This study employed hypothesis testing, where the null hypothesis (H_0) assumes no significant disparity in indoor air temperature across the various zones of the selected Irish schools. On the other hand, the alternative hypothesis (H_1) proposes a significant difference in temperature readings between these distinct areas. To navigate through these hypotheses, an Analysis of Variance (ANOVA) was employed to compare the means of air temperatures across multiple classrooms, zones, and floor levels.
Lastly, the study utilised Cohen's d to determine the effect size and quantify the tangible magnitude of differences observed. This measure offers a quantitative interpretation of the magnitude of differences observed, shedding light on the practical significance that each building characteristic might have on the temperature dynamics. Cohen's d statistic is specifically calculated as the difference between two group means, normalised by the pooled standard deviation, with thresholds established for small (0.2), medium (0.5), and large (0.8) effects. Cohen's d statistic was meticulously computed for each parameter, reflecting how different building characteristics within classroom zones influence indoor air temperature. The formula (2) used is as follows:

$$d = \frac{M_1 - M_2}{SD_{pooled}} \tag{2}$$

Where M_1 and M_2 are the means of two groups, and SD_{pooled} is the pooled standard deviation, calculated as formula (3):

$$SD_{pooled} = \sqrt{\frac{(n_1 - 1)SD_1^2 + (n_2 - 1)SD_2^2}{n_1 + n_2 - 2}} \tag{3}$$

Where n_1 and n_2 are sample sizes of two groups. SD_1 and SD_2 are the standard variations of two groups.
This study assessed the vulnerability of classrooms, identifying and addressing risks based on overheating criteria in CIBSE TM52 [19] and BB101 [20] standards, refer to Table 2. Based on

adaptive thermal comfort descriptions used in the mentioned standards, as shown in formula (4), the indoor comfort temperatures are influenced by the outdoor running mean temperature.

$$T_c = 0.33 \times MAX(10, T_{rm}) + 18.8 \pm T_{lim} \quad (4)$$

Where T_c is comfort temperature, T_{rm} is running mean temperature and T_{lim} is category range limit of comfort. In this study T_{lim} is defined as a high level of expectation (±2, Category I) recommended for young children [21][22].

Table 2: Overheating Assessment Criteria

Criteria	**Name**	**Formula**	**CIBSE TM52 2013**	**BB101 2018**
Criterion 1	Hours of Exceedance	$He = \sum_{i=1}^{n}(T_{int,i} - T_{comf})$ $T_{int,i} > T_{comf} + 1°C$	≤ 3% of occupied hours	≤ 40 occupied hours
Criterion 2	Daily Weighted Exceedance	$We = \sum_{i=1}^{24}(T_{int,i} - T_{comf})$	≤ 6 occupied days	≤ 6 occupied days
Criterion 3	Upper Limit Temperature	$T_{upp} = T_{comf} + 4°C$	$T_{int} \leq T_{upp}$	$T_{int} \leq T_{upp}$

$\boldsymbol{T_{int}}$: Indoor air temperature
$\boldsymbol{T_{comf}}$: Threshold comfort temperature
$\boldsymbol{T_{upp}}$: Upper limit temperature

3 RESULT

The descriptive statistical analysis conducted within this study has illuminated significant variances in the indoor air temperatures of the studied classrooms. The boxplots in Figure 2 illustrate the distribution of temperature readings inside classrooms and in the outdoor environments of GGA, CBS, BRC, GMC, and LIN schools. The comparison of boxplots showed that each school exhibits its own unique thermal characteristics, both indoors and outdoors, with specific trends. The indoor median temperatures across the classrooms in all schools are consistent, suggesting a stable thermal environment likely maintained by the schools' heating and NV systems. However, BRC displays a wider range of classroom temperatures, indicated by longer whiskers and larger interquartile ranges, hinting at more significant temperature fluctuations or diverse classroom conditions.

Outdoor temperatures, marked in orange, for all schools, show greater variability than indoor temperatures, as evidenced by broader interquartile ranges and longer whiskers in the outdoor boxplots. Outliers in schools like CBS and LIN suggest occasional deviations from typical temperatures, which could be due to specific weather events or irregularities in indoor climate management. Despite these anomalies, the overall temperature distribution in the schools' points to generally effective regulation of indoor climates, contrasting with the natural variability experienced outdoors.

Table 3: Comparative Pearson correlation coefficient of indoor and outdoor temperature across four studied schools

GGA	**C3**	**C7**	**C11**	**C14**	**C16**	
	0.80	0.80	0.77	0.80	0.81	
CBS	**C6**	**C9**	**C13**	**C19**	**C22**	
	0.80	0.83	0.82	0.79	0.77	
GMC	**C2**	**C10**	**C11**	**C13**	**C21**	**C22**
	0.75	0.75	0.74	0.75	0.76	0.75
LIN	**C2**	**C5**	**C6**	**C10**	**C11**	
	0.30	0.46	0.49	0.41	0.32	

Table 3 presents the Pearson correlation coefficient reflecting the relationship between indoor and outdoor temperatures for various classrooms within the studied schools. The classrooms of GGA and CBS schools show high correlation coefficients (around 0.80), suggesting a strong and consistent positive relationship between indoor and outdoor temperatures across these classrooms. This implies that the indoor temperatures in these schools are closely aligned with the variations in outdoor temperatures.

GMC classrooms have slightly lower coefficients, with values mostly around 0.75, which still indicates a strong positive correlation but slightly less so than GGA and CBS. The indoor temperatures in GMC classrooms follow outdoor temperatures closely, but factors such as insulation or ventilation might affect the tightness of this relationship.

In contrast, classrooms in LIN schools show a lower correlation between indoor and outdoor temperatures, with coefficients ranging from 0.30 to 0.49. This significant drop suggests that indoor temperatures in LIN classrooms are much less influenced by outdoor temperatures, which could be due to various factors like better insulation, more effective thermal control systems, or differing building orientations and designs that minimise the impact of outdoor temperature fluctuations. Overall, the table indicates that while some schools may have indoor climates that are remarkably influenced by outdoor conditions, others manage to maintain a more controlled indoor environment regardless of external temperature changes.

All the studied classrooms successfully met the overheating assessment criteria as defined by the standards explained in Table 2. According to Criterion 1, the classrooms remained within the permissible limits for hours of exceedance, where the indoor air temperature did not exceed the comfort temperature by more than 1℃ for over 3% of occupied hours based on CIBSE TM52 or 40 hours based on BB101. Additionally, Criterion 2, daily weighted exceedance, was within the acceptable range of no more than six occupied days with temperature exceedances. Finally, the indoor temperatures stayed below the upper limit temperature by more than 4°C based on Criterion 3.

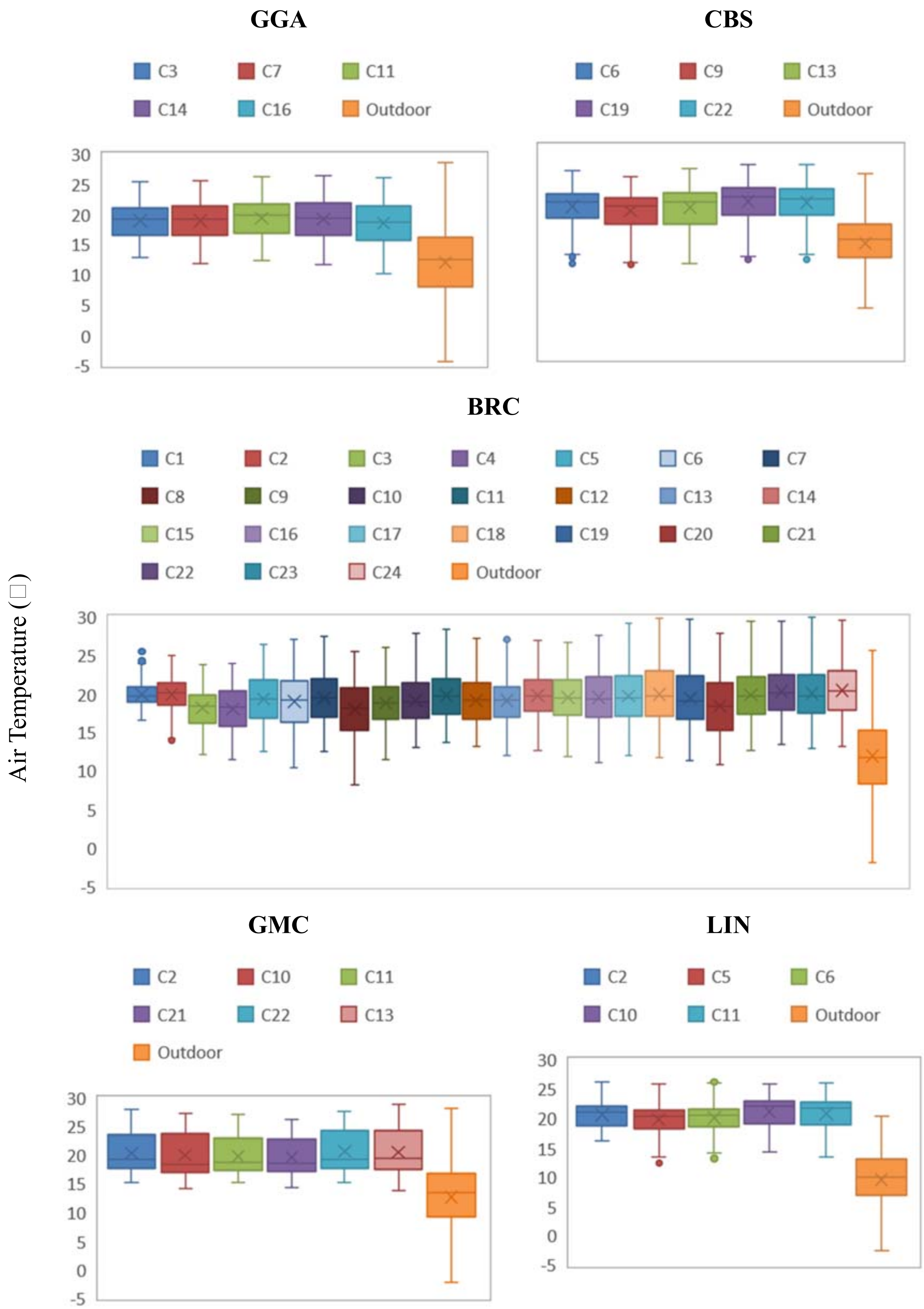

Figure 2: Comparative box and whisker plots of measured indoor and outdoor temperature readings across different studied schools and classrooms

Figure 3 illustrates Cohen's d effect sizes for various factors impacting indoor air temperature in classrooms. These effect sizes vary in magnitude, reflecting the relative influence each factor has on indoor temperature. Remarkably, all studied parameters exhibit effect sizes greater than 0.8, signifying a large effect. Among these, factors such as floor level, NV type (Single/Cross NV), openable window type (top/side/bottom hung), average height of opening, orientation, and the height and colour of internal walls show particularly high effect sizes. This indicates that they have a significant influence on indoor air temperature. The factors such as outdoor temperature, number of occupants, facade area, and opening depth, while they have a large effect size of greater than 0.8, have relatively smaller effect sizes compared to other studied parameters. This implies that these factors have a lesser impact on indoor temperature. This analysis provides valuable insights into the critical parameters affecting indoor air temperature, which can be effective in devising strategies to optimise thermal comfort in classrooms.

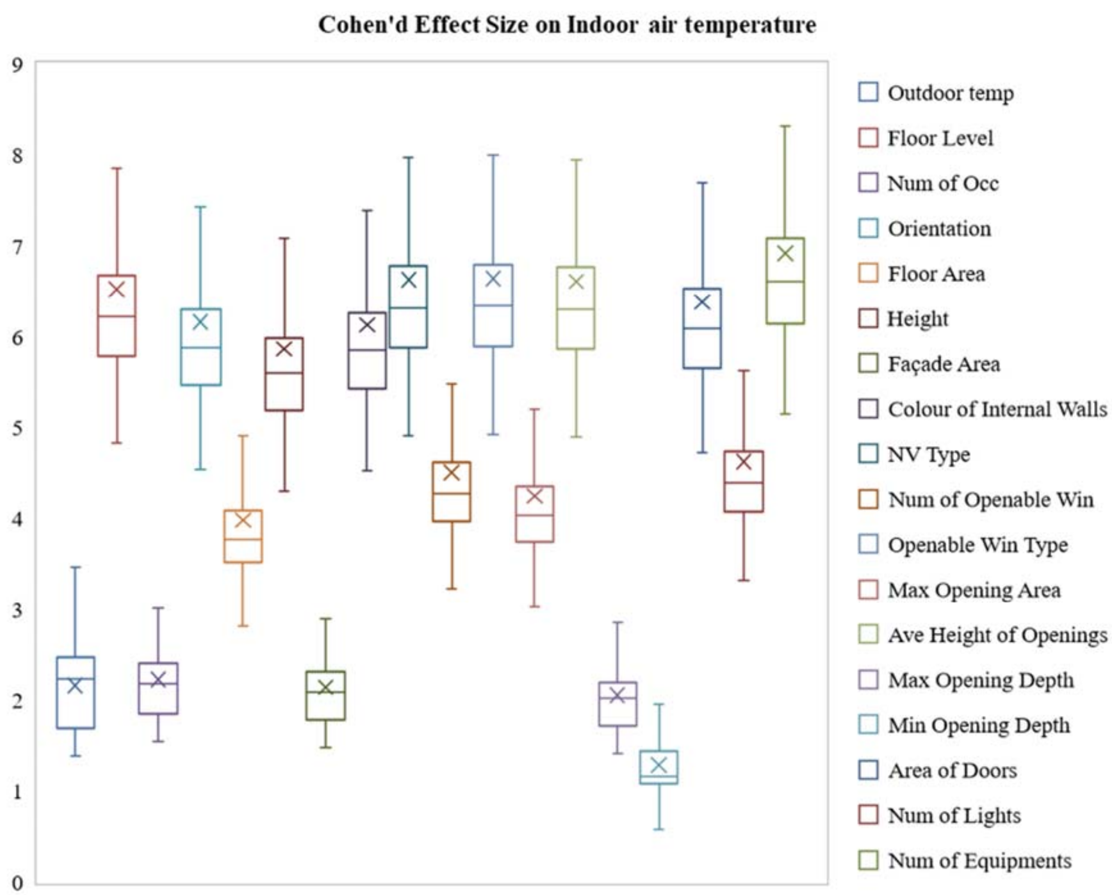

Figure 3: Comparative box and whisker plots of Cohen's d effect size for outdoor air temperature and studied building information parameters on indoor air temperature

4 CONCLUSIONS

This study provides a comprehensive assessment of the resilience of Irish low energy school buildings against overheating, with a focus on NV classrooms. The findings indicate that the classrooms currently exhibit high thermal resilience. Key conclusions drawn from the research are as follows:

- The schools generally maintain a stable indoor air temperature relative to the more variable outdoor temperatures. In addition, the classrooms met the overheating assessment criteria defined by CIBSE TM52 and BB101 standards, with current designs able to adequately ensure thermal comfort during warmer periods. This suggests that the existing NV systems contribute positively to indoor climate regulation.
- The Pearson correlation coefficients indicate a strong relationship between indoor and outdoor temperatures in most schools.
- The analysis using Cohen's d effect sizes revealed that certain building features such as floor level, NV type (single/cross NV), openable window type (top/side/bottom hung), average height of opening, orientation, and the height and colour of internal walls, have a substantial impact on indoor air temperature. These factors should be prioritised when designing or retrofitting school buildings to improve thermal comfort.

To address these findings, the following recommendations are proposed:

- Improvements in the design and implementation of NV systems are critical. This includes optimising the types and positions of openable windows and enhancing the height and orientation of openings.
- Educating occupants about effective NV practices and encouraging behaviours that support thermal comfort can further improve indoor conditions.

The insights from this study are expected to guide future strategies for designing resilient, low energy school buildings that can better withstand the challenges of climate change, which can influence both comfort and cognitive performance within the learning spaces.

5 ACKNOWLEDGEMENTS

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