Evaluating the Resilience of VC+ Low Energy Primary Schools to Climate Change

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ABSTRACT

Mitigating the risk of overheating and associated thermal discomfort inside school classrooms is a global concern due to its significant impacts on students' academic performance, health and wellbeing. Thus, rising ambient temperatures resulting from climate change can be challenging, especially in low energy schools designed to optimise their heating season performance. According to recent studies, many low energy school buildings fail to meet comfort standards and experience overheating, resulting in low student productivity and the need for using air conditioning systems. The aims of this study were to, firstly, understand and define resilient cooling for low energy primary school buildings based on four resilience criteria. Secondly, determine the periods of time during the year when classroom environments are vulnerable to overheating and its impacts on students' academic performance (the possibility of overheating risk) and whether ventilative cooling low energy primary schools are resistant under extreme future file. To achieve these aims, two classrooms in one recently built ventilative cooling low energy primary school in Ireland were modelled using IES-VE. The overheating levels in extreme weather conditions were specified based on the number of hours in which classrooms experience overheating when indoor air temperatures exceed upper overheating thresholds according to typical overheating standards and thresholds that reflect academic performance of primary students. The resistance of the classrooms was assessed based on an overheating escalator factor. Findings show that while according to typical overheating standards, the classrooms in Cork and Kilkenny are not vulnerable to overheating in future extreme weather conditions, evaluations based on the overheating escalation factor and recommended threshold for students' productivity showed the classrooms in Cork and Kilkenny were vulnerable to overheating risk and could not resist it.

KEYWORDS

Resilient cooling, Thermal comfort, Primary school, Low energy building, Climate change, Students' academic performance.

1 INTRODUCTION

Educational buildings form around half of the non-residential buildings in Ireland [1]. Primary schools account for the vast majority of these educational buildings [1]. School buildings are one of the most demanding types of buildings in terms of occupant comfort requirements due to a large number of people spending a significant portion of their daily time inside schools and the importance of the students' learning performance [2]. Climate change could lead to an increase in temperature that will significantly affect the indoor thermal environment [3], especially in summer and more broadly during the non-heating season [4]. Rising temperatures may increase overheating risk, particularly in newly built schools designed based on Nearly Zero Energy Building (NZEB) standards, focusing on the airtightness of the building and the insulation of its envelope, which optimise their heating season performance [5].

Overheating has a well-known negative impact on comfort in schools. It can cause unpleasant conditions for the occupants, such as cold and heat stress, leading to increased health risks and a reduction in academic performance [6]. Indoor Environmental Quality (IEQ) and thermal comfort are even more important in school buildings, as they are frequented mostly by young people, who are negatively impacted by a poor thermal environment [7].

Low energy buildings frequently use passive cooling strategies; Ventilative Cooling (VC) is one of these strategies and VC base systems often complimented by passive intervention strategies in schools [8]. This study has adopted the definition of VC from IEA-EBC Annex 62 [9] and will use the acronym VC+ based on recent definition [10] throughout the paper, where the plus refers to the combination of VC and passive interventions. As outlined above and based on annex 80 publications [11][12], this study presents a definition of thermal resilience in VC+ low energy primary schools against overheating, including four resilience criteria. Furthermore, we investigate the vulnerability and resistance of school buildings in future extreme conditions of Ireland's climate by employing dynamic simulation software to evaluate whether VC+ low energy school buildings in Ireland resilient against overheating. Two locations were chosen in this study, Cork as the original location of base building and Kilkenny as the highest currently recognised air temperature (33.3°C) ever recorded in the Republic of Ireland was logged at Kilkenny Castle in 1887 [13]. The objective is to determine the ability of the newly built low-energy school buildings that may not receive significant investment again for 30+ years unless there is an identified and urgent need for this[14], to resist climate change impacts.

1.1 Case Study Building

The primary school studied was a double-storey building consists of 16-classrooms in Cork, Ireland, built in 2020. Classroom 7 (ground floor- eastern orientation) and classroom 11 (first floor-southern orientation) were selected as a case study in this study. Classrooms are rectangular with approximate dimensions of 7.60×8.00×3.20m (W×L×H), situated side-by-side and connected with semi-open corridors, approximately 2m wide. Each classroom has openings along its long side, with slight overhangs The window to wall ratio in both classrooms is the same at 35%. The school was constructed using concrete blocks. The U-values for floors, walls and roofs were measured as 0.21 W/m^2K, 0.30 W/m^2K and 0.20 W/m^2K, respectively. The heating for the school buildings is provided by centralised gas boilers, which are delivered through a pressurised and temperature-controlled hot water system with a local control system. In both classrooms, radiators are installed below the windows. The classrooms are ventilated with manual openable windows, with Low-E double glazing. The toilet facilities are located in the classroom, and each classroom is equipped with a storage wall, an Information Technology (IT) area, and a sink for educational purposes. The occupancy rate was estimated as each classroom is 35 students on weekdays from 8 am to 4 pm with two small breaks and lunchtime.

1.2 Aims and objectives

This paper aims to evaluate overheating risks and the ability of existing VC+ low energy primary schools in Ireland to resist climate change. This research methodology has three phases:

- The first phase defines resilient cooling for low energy primary school buildings based on four resilience criteria.
- The second phase assesses the thermal comfort and vulnerability to overheating risk of the classrooms based on EN16798-1 and recommended temperature for students' schoolwork under extreme weather files for Cork and Kilkenny.
- The third phase investigates building resistance to climate change based on Indoor Overheating Degree (IOD), Ambient Warmness Degree (AWD), and Overheating Escalation Factor (α) metrics.

2 RESILIENT COOLING DEFINITION

Considering the general and building-related definitions of "resilience" from the literature, it is essential to understand and define resilience in the early stages of building design as well as evaluate and adapt designs to incorporate resilient strategies to prevent future "lock-in" of vulnerable design approaches [15]. We find that there appears to be a strong focus on using the term "resilience" during the last decade. However, the recent study [10] reviewed different definitions, metrics and approaches available to quantify indoor thermal resilience. . Therefore, this research presents a definition of thermal resilience in VC+ low energy primary schools against overheating, including four resilience criteria [16][15][10]:

"A VC+ low energy primary school in Ireland is resilient to climate change (vulnerability) when the performance of the ventilative cooling strategy including any complimentary passive interventions in the building allows it to withstand indoor comfort disturbances due to overheating considering academic performance (resistance) and to be able to adapt its cooling capacity in the event of failure (robustness) to mitigate further degradation of indoor thermal comfort and the increased need for space cooling energy (recoverability)."

Regarding the defined definition of resilient cooling by the authors, this study focused on two first criteria of resilient cooling definition vulnerability and resistance.

3 MATERIALS AND METHODS

In order to address the second and third aims of the study, and based on methodologies used in previous studies [7][12], the approach adopted can be divided into four main steps:

3.1. Monitoring outdoor and indoor air temperature and modelling the school building.

3.2. Generating climate scenarios for typical and extreme weather conditions.

3.3. Thermal comfort and vulnerability to overheating risk and its impacts on students' productivity assessment

3.4. Resistant to overheating risk assessment

3.1 Monitoring and Modelling

This study focused on the investigation of outdoor and indoor air temperature to evaluate indoor thermal comfort for each classroom during both the heating and non-heating seasons (April to September except July and August). The field data measurement of two classrooms, 7 and 11, started in April 2021 until the end of June 2021 and September 2021. All rooms were equipped with temperature thermostats. The indoor air temperature was monitored using integrated temperature sensors, with one on the ground floor and one on the top floor, which was at 1.5m above floor level. These sensors had an accuracy of ±0.4 °C. This study used a calibrated dynamic thermal model of using Integrated Environmental Solutions-Virtual Environment (IES-VE) to assess the thermal comfort vulnerability and resilience levels of VC+ low energy school buildings against overheating in Cork and Kilkenny, Ireland [17]. It should be noted that the IES-VE is well-known for its reliability and validity as a tool for evaluating naturally ventilated building stock in dynamic conditions [18]. The school building was modelled as a base using existing information about the geometry, design and thermal characteristic of the used materials (Tables 3.1 and 3.2). Table 3.3 shows the occupancy profile, heating profile and window opening profile from April to June and September during working days (Monday to

Friday). Furthermore, holidays are considered in the occupancy, heating and windows opening profiles. Each classroom has ten windows, four of which cannot be opened, but six windows are openable for natural ventilation (Figure 3.1).

Table 3.1. Construction characteristics

Building Element	Part L- IRELAND	
	U-value (W/m^{2}K)	Thickness (mm)
External Window (including frame)	1.77	24
Internal Ceiling/ Floor	0.6	325
Door	3	37
Ground/ Exposed Floor	0.21	265
Internal Window (including frame)	3	0
Internal Partition	1.81	215
Roof	0.2	420

Table 3.2. Simulated model specifications

Parameter	Units	Value
Construction Standard	-	Actual details of the building
NCM Building Area Type	-	D1: Primary Education
Heating System	-	Central Heating Radiator
Heating Setpoint	°C	20
Internal Gain	W	General Lighting 45W
Occupancy density (person)	Person	35
Maximum sensible gain	W/person	65
Maximum latent gain	W/person	30
Infiltration	ACR	0.145
MET rate	kcal/ kg×h	1
Openable Area	%	40
Max Angle Opening	°	25

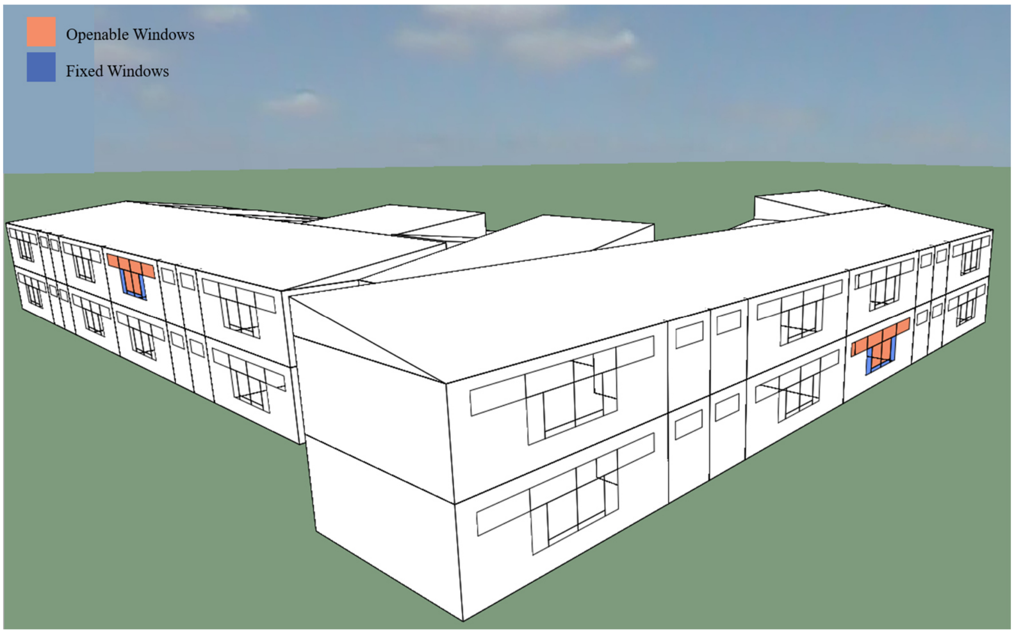
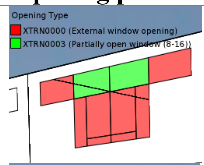
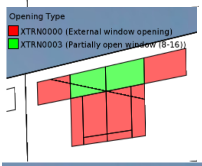
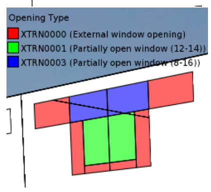
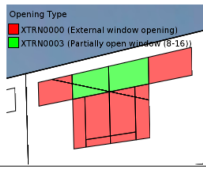


Figure 3.1. Openable area of each window in classroom 7 (Ground floor) and classroom 11 (First floor)

Table 3.3. Occupancy, heating and window operation

Month	Occupancy Schedule	Heating Profile	Windows opening profile		Side view of window opening profile
April	8 am-4 pm	8 am-1 pm	2 windows	8 am-4 pm	
May	8 am-4 pm	8 am-1 pm until 25 May	2 windows	8 am-4 pm	
June	8 am-4 pm	Off	2 windows 2 windows	8 am-4 pm 12 am-2 pm	
July	Off	Off	Off		
August	Off	Off	Off		
September	8 am-4 pm	8 am-1 pm From 22 Sep	2 windows	8 am-4 pm	

3.1.1. Model Verification

A detailed thermal model of two classrooms in the primary school building and its operation was built in IES-VE, as shown in Figure 3.2. The model was simulated based on the 2021 EPW weather file which was generated using Big Ladder software [30] and Cork airport weather data [29].

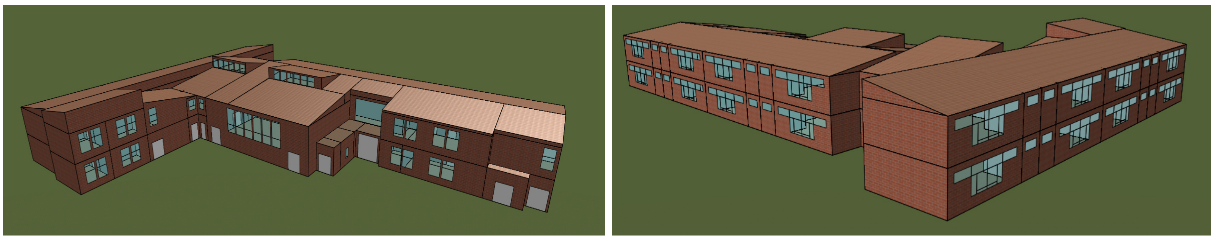


Figure 3.2. 3D views of studied primary school building IES-VE model

In order to evaluate the accuracy of the model, the root mean square error (RMSE), as presents in Eq.1, between measured and predicted indoor temperature, was defined for April to September [19].

$$RMSE = \frac{\sqrt{\sum_{i=1}^{n}(P_i - M_i)^2}}{n} \qquad \text{Eq.1}$$

Where P is the predicted and M is measured temperatures at time i, respectively, and n the total number of data points.

To assess the reliability of the model, the study employed the distribution characteristics of the prediction error, as presented in Eq.2, the coefficient of variance root mean square error

(CVRMSE) [19], in Eq.3, mean absolute error (MAE) [20], in Eq.4, the mean bias error (MBE) [21].

$$CVRMSE(\%) = \frac{RMSE}{A_M} \times 100\% \qquad \text{Eq.2}$$

Where RMSE is calculated for the given period and A_M is the average measurement temperature during the period

$$MAE = \frac{\sum_{i=1}^{n} |P_i - M_i|}{n} \qquad \text{Eq.3}$$

$$MBE(\%) = \frac{\sum_{i=1}^{n} (P-M)_i}{\sum_{i=1}^{n} M_i} \times 100\% \qquad \text{Eq.4}$$

Where P is the predicted and M is measured temperatures at the time i, respectively, and n is the total number of data sets.

3.2 Climate Scenarios

In this study, the typical meteorological year (TMY) and future extreme weather file (2100-10 years) were generated using Meteonorm (v.8.1.1) for Cork and Kilkenny, Ireland. Notably, the TMY refers to the period 2000-2019 for temperature values [22]. Extreme weather files were created using the ten-year extreme temperature model and selecting the worst-case IPCC scenario (A2). Initially, climates were analysed for each location using extreme ten-year 2100. Simulations were conducted using the extreme weather files for Cork and Kilkenny, as shown in Figure 3.3.

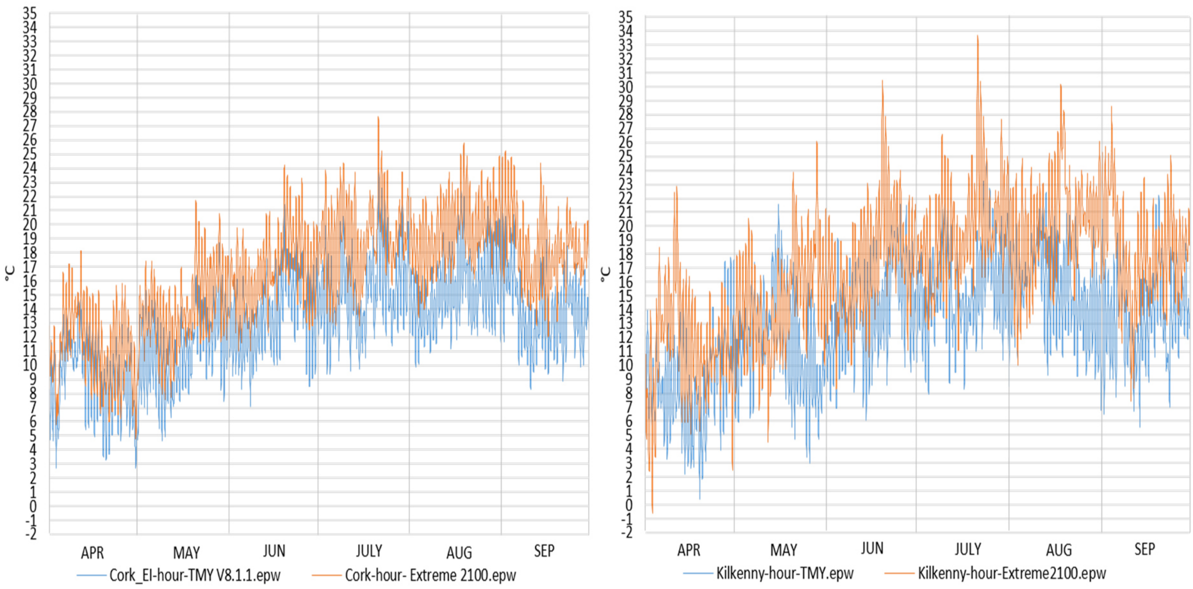


Figure 3.3. Comparison of hourly outside air temperature based on TMY and extreme (2100-10 years) weather files in Cork (left-side) and Kilkenny (right–side)

3.3 Thermal Comfort and Vulnerability Assessment

Thermal comfort category descriptions used in BS EN 15251 [23] and EN16798-1 [24] are also used in the Building Bulletin 101: Guidelines on ventilation, thermal comfort and indoor air quality in schools. Previous studies used the optimal comfort temperature T_c in EN15251 and EN16798-1, as shown in Eq.5 [25]. Categories of comfort are typically determined with varying category range limits for those with a normal level of expectation (±3, Category II) and special cases or those with a high level of expectation (±2, Category I). However, in the recent revision of EN15251 (EN16798-1), the low limits were changed, which led to an asymmetric range (i.e. +3–4) [26].

$$T_c = 0.33 \times T_{rm} + 18.8 \pm T_{lim} \qquad \text{Eq.5}$$

Where T_c is optimal comfort temperature, T_{rm} is running mean temperature and T_{lim} is category range limit of comfort. This study, in order to assess the vulnerability of classrooms based on optimal comfort temperature (Eq.5), used overheating criteria in EN16798-1 with a high level of expectation (±2, Category I) recommended for young children [24], based on the simulated operative temperature (To) exceeding the values shown in Eq.6:

$$T_O > 0.33 \times T_{rm} + 18.8 + 2 \qquad \text{Eq.6}$$

Where T_o is operative temperature and T_{rm} is running mean temperature. According to another study [27] on the children's performance at tasks resembling typical schoolwork, it was reported that the performance of two arithmetical and two language-based tests when the temperature was reduced to 20 °C improved significantly. In order to determine how overheating affects primary students' academic performance in classrooms under extreme future weather file, the temperature at which high performance occurs (20 °C) [28] is also evaluated in this study.

3.4 Resistant Assessment

Based on the literature review [11][12], the resilience assessment method in this study consists of three metrics called Indoor Overheating Degree (IOD), Ambient Warmness Degree (AWD), and Overheating Escalation Factor (α) [29]. IOD, as shown in Eq.7, quantifies the severity and frequency of indoor overheating risk.

$$IOD = \frac{\sum_{z=1}^{Z}\sum_{i=1}^{N_{occ}(z)}\left[(T_{fr,i,z} - T_{op,i,comf,z})^{+} \times t_{i,z}\right]}{\sum_{z=1}^{Z}\sum_{i=1}^{N_{occ}(z)} t_{i,z}} \qquad \text{Eq.7}$$

Where t is the time step, i is occupied hour counter, Z is total building zones, N_{occ} is the total number of occupied hours, $T_{fr,i,z}$ is the free-running indoor operative temperature in zone z at time step i [°C], $T_{op,i,comf,z}$ is the comfort temperature in zone z at time step i [°C]. Only positive values of $(T_{fr,i,z} - Ti,o,_{comf,z})^{+}$ are considered. In this study $T_{i,o,comf,z}$ set at 18°C. AWD, as shown in Eq.8, is used to assess the severity of outdoor air temperature over a reference temperature T_b. The reference temperature in this study was set at 18°C.

$$AWD_{18°C} = \frac{\sum_{i=1}^{N}\left[(T_{a,i} - T_b)^{+} \times t_i\right]}{\sum_{i=1}^{N} t_i} \qquad \text{Eq.8}$$

Where $T_{a,i}$ is the outdoor dry-bulb air temperature at time step i [°C], T_b is base temperature set at 18 °C, N is the number of occupied hours. α, as shown in Eq.9, is the slope of the regression line between IOD and AWD. It shows the resistance of the building toward global warming.

$$\alpha_{IOD} = \frac{IOD}{AWD_{18°C}} \qquad \text{Eq.9}$$

An overheating escalation factor greater than the unit ($\alpha_{IOD} > 1$) means that the building is not resilient to overheating, and indoor thermal conditions get worse when compared to outdoor thermal stress. On the other hand, an overheating escalation factor lower than the unit ($\alpha_{IOD} < 1$) means that building is resilient to overheating and can resist some outdoor thermal stress [29].

4 RESULTS

This section presents the assessment results of the overheating risk and primary school building resistance. The accuracy of the simulated model was analysed and presented in Section 4.1. In Section 4.2, overheating is assessed using Indoor overheating degree (IOD), Ambient warmness degrees ($AWD_{18°C}$) and overheating escalation factor (α_{IOD}).

4.1 Calibration and Validation

The simulation model was performed from April to June and September in the year 2021, the occupation hours were Monday to Friday, between 8am - 4pm, when the school building was in operation, excluding Irish holidays. The findings indicate that the simulation tool is roughly accurate and credible when it comes to predicting indoor air temperature. The captured air temperature from sensors in the classroom was compared with the simulation results of classroom air temperature. The error analysis is summarised in Table 4.1. The RMSE ranges from 1.24°C to 1.35°C, the RMSE change is less than 1.5%, and the MBE is less than 10% for all periods.

Table 4.1. The error analysis of simulated indoor hourly air temperature

	Classroom 7	Classroom 11
RMSE (°C)	1.24	1.35
CVRMSE (%)	6.38	6.92
SAE	4484.10	4920.78
MAE	1.02	1.12
MBE (%)	5.22	5.73

4.2 Vulnerability and Resistance

Figure 4.1 presents the hourly air temperature of classroom 7 on the left side and classroom 11 on the right side under extreme weather files in Cork and Kilkenny. The studied school building was simulated during the warmest six months, from April to September. This study does not consider indoor air temperature in July and August when school is unoccupied and off, as shown in Figure 4.1 with a grey rectangle. The maximum indoor air temperature in classroom 7 during the academic period occurred in September at 26.2°C for Cork and in June at 27.8°C for Kilkenny. In classroom 11, the maximum air temperature occurred in September at 27.2°C for Cork and in June at 28°C for Kilkenny.

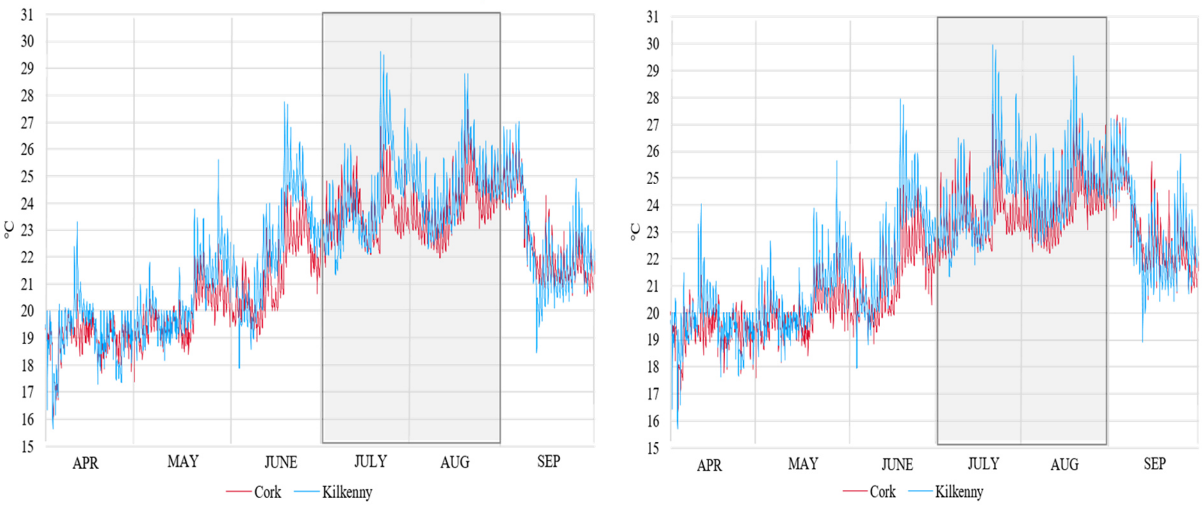


Figure 4.1. Comparison of an hourly air temperature of classrooms 7 (left side) and 11 (right side) under extreme weather files (2100-10 years) in Cork and Kilkenny

Table 4.2 displays the evaluation of simulation results based on EN16798 overheating criteria and recommended temperature for primary students' academic performance (20°C)[27]. According to EN16798 overheating criteria for Cat I- high expectation (Eq.6), the VC+ low energy primary classrooms from April to June and September meet the comfort criteria for greater than 99.45% of occupied hours in extreme future conditions. In contrast, based on recommended temperature for primary students' academic performance (20°C), the VC+ low energy primary schools in 51 to 52% of occupied hours and in Kilkenny 42 to 45% of occupied hours passed the criteria (T_a<20°C). It should be noted that in this study, Ta ≤ 20 °C was used to evaluate students' academic performance, due to the heating system set point in April and May is 20 °C and indoor air temperatures under extreme weather files during June and September are greater than 20 °C.

Table 4.2. Comparison of overheating assessment of simulation results based on EN 16798 [24] *and recommended temperature for primary students' academic performance under extreme weather files (2100-10 years)*

		Cork		**Kilkenny**	
	Criteria for Schools	**Classroom 7**	**Classroom 11**	**Classroom 7**	**Classroom 11**
Overheating	Cat I- High Expectation $T_o > 0.33\ T_{rm} + 18.8 + 2$	100% Occ-hr Passed	100% Occ-hr Passed	99.45% Occ-hr Passed	99.45% Occ-hr Passed
Recommended temperature for primary students' academic performance	$T_a \leq 20$ °C	52% Occ-hr Passed	51% Occ-hr Passed	45% Occ-hr Passed	42% Occ-hr Passed

As defined in Section 3.4, the AWD has qualified the severity of outdoor warmness based on a reference temperature of 18°C. Base temperature of 18 °C was chosen because this value is lower than every minimum summer comfort temperature limit [29]. The IOD which quantifies the overheating risk, taking into account both the intensity and the frequency of indoor overheating, regarding the chosen limit temperature (20°C) at which the highest students' academic performance would occur, as recommended by Wargocki and Wyon (2017). Previous two indicators, AWD and IOD, lead to the $\alpha_{IOD/AWD_{18°C}}$ indicator, which represents the slope of the regression line between the AWD and the IOD, describing the sensitivity of the obtained indoor operative temperature to change regarding outdoor temperature changes in free-running mode during June and September. Figure 4.2 and Figure 4.3 compares the regression lines between AWD and IOD and their equations under TMY and extreme weather files for classrooms 7 and 11 in Cork and Kilkenny. The IOD in Figure 4.2 and Figure 4.3 were assessed based on comfort criteria of EN16798 (IOD_{Comf}) and 20°C at which the highest students' academic performance would occur (IOD_{Perf}), respectively.

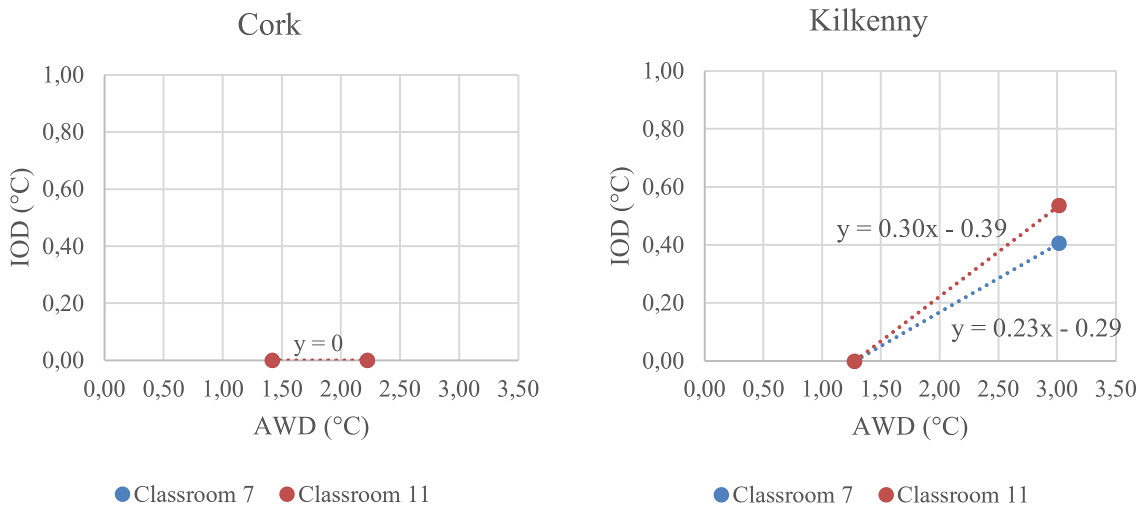


Figure 4.2. The comparison of the regression line between AWD and IOD_{Comf} under TMY and extreme weather files (2100-10 years) for classrooms 7 and 11 in Cork (left side) and Kilkenny (right side).

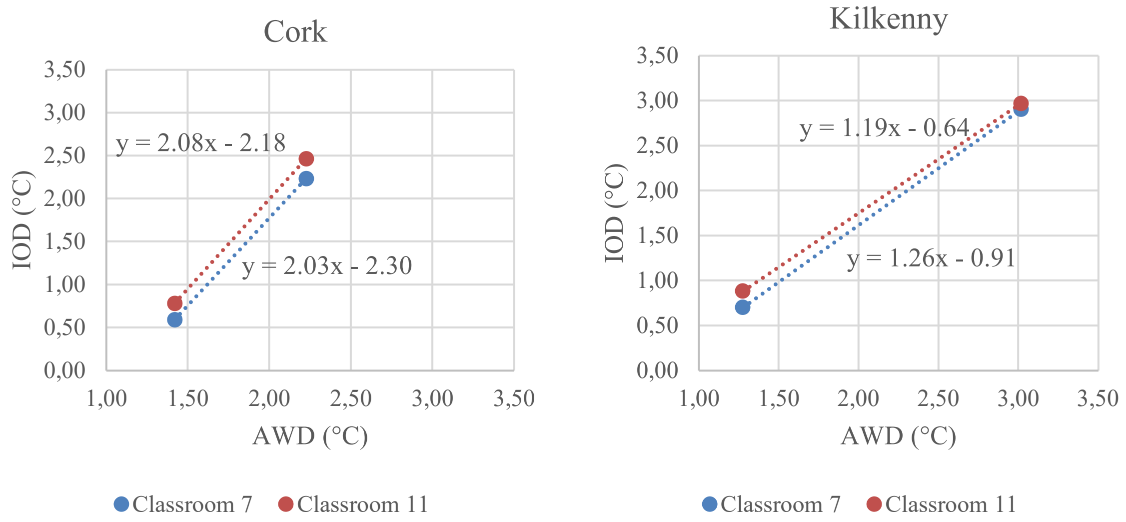


Figure 4.3. The comparison of the regression line between AWD and IOD_{Perf} under TMY and extreme weather files (2100-10 years) for classrooms 7 and 11 in Cork (left side) and Kilkenny (right side).

Table 4.3 shows the slope of regression lines between AWD and IOD based on their equations for classrooms 7 and 11 in Cork and Kilkenny. The $\alpha_{IOD_{Comf}/AWD_{18°C}}$ for both classrooms in both locations are less than unit ($\alpha_{IOD_{Comf}/AWD_{18°C}}<1$), which indicates that VC+ low energy primary schools in Cork and Kilkenny are resilient to overheating and could resist the outdoor thermal stress under extreme weather files. However, The $\alpha_{IOD_{Perf}/AWD_{18°C}}$ for both classrooms in both locations is greater than unit ($\alpha_{IOD_{Perf}/AWD_{18°C}}>1$), which indicates that VC+ low energy primary schools are unable to provide the recommended air temperature for students to perform well at schoolwork under extreme weather files. Additionally, the $\alpha_{IOD_{Perf}/AWD_{18°C}}$ of the VC+ low energy primary school in Cork is greater than in Kilkenny, which means the number of occupied hours greater than 20°C in Cork were more than Kilkenny.

Table 4.3. Overheating and Climate Resistance Assessment

ID	Model	$\alpha_{IOD_{Comf}}/\mathrm{AWD}_{18°C}$		$\alpha_{IOD_{Perf}}/\mathrm{AWD}_{18°C}$	
		Classroom 7	**Classroom 11**	**Classroom 7**	**Classroom 11**
1	Cork	0	0	2.03	2.08
2	Kilkenny	0.23	0.30	1.26	1.19

5 CONCLUSIONS

The impact of climate change on the overheating risk and its impact on students' academic performance in low energy primary schools is evaluated in the current study. This study aims to assess the sensitivity of VC+ low energy primary schools by applying long-term indicators that numerically quantify the vulnerability and resistance of a chosen verified case study of a VC+ low energy primary school in Cork and Kilkenny to overheating and students' academic performance in June and September under extreme weather files. The main findings are summarised as follows:

- Overheating assessment of results based on EN 16798 comfort threshold shows the classrooms in Cork 100% and in Kilkenny 99.45% of occupied hours can resist overheating risk.
- The chosen case study in Cork and Kilkenny is vulnerable to students' academic performance under overheating risk, and roughly half of occupied hours could not resist the outdoor thermal stress under extreme weather files.
- The results show that overheating escalation factor based on EN 16798 comfort threshold ($\alpha_{IOD_{Comf}}/\mathrm{AWD}_{18°C}$) in both classrooms and both locations is less than unity (<1), which means VC+ low energy primary schools in Cork and Kilkenny are resilient to overheating risk. Conversely, the overheating escalation factor based on recommended temperature (20°C) for students' academic performance ($\alpha_{IOD_{Perf}}/\mathrm{AWD}_{18°C}$) in both classrooms and both locations is more than unity (>1), which means VC+ low energy primary schools in Cork and Kilkenny are unable to provide recommended air temperature for students to perform well at schoolwork academic under extreme weather files.
- The comparison of, overheating escalation factor based on EN 16798 comfort threshold ($\alpha_{IOD_{Comf}}/\mathrm{AWD}_{18°C}$) and based on recommended temperature (20°C) for students' academic performance ($\alpha_{IOD_{Perf}}/\mathrm{AWD}_{18°C}$) show that there is a difference between overheating assessment and its effect on students' academic performance to illustrate the resilience of the VC+ low energy primary schools to overheating risk.

6 ACKNOWLEDGEMENTS

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