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Investigating risk of overheating for school buildings under extreme hot weather conditions

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Abstract. This study examines the risk of overheating of a school building, under extreme hot weather conditions, in 14 locations in the United Kingdom using the overheating criteria defined in Building Bulletin 101 (BB101). The building was modelled as naturally ventilated, mechanically ventilated and in mixed mode and was simulated both for the current and the projected weather conditions of the 2050s. Under the current weather conditions, results of the simulations show that when naturally ventilated, the school building fulfils the BB101 criteria only in the areas of Edinburgh and Glasgow. In the simulations of the building as mechanically ventilated and in mixed mode, mechanical cooling was provided in order for the building to comply with the overheating criteria. A comparison of the required cooling loads between the two scenarios shows that application of mixed mode ventilation results in less cooling loads.

Keywords: overheating; ventilation; school; design summer year

1. Introduction

In the UK schools house about 10 million pupils, who spend about 70% of their time inside a classroom during school days (Bakó-Biró *et al.* 2012). Thermal comfort conditions significantly affect the health and performance of teachers and students in classrooms. Uncomfortable conditions will not enable teachers to work at their best and children learn as well as they could (CIBSE 2015). Overheating of schools is already a problem in many parts of the country (Smith 2015).

Schools represent a challenge to building designers, especially in terms of thermal comfort during the summer months due to overheating. Classrooms are densely occupied spaces with high levels of occupancy and increasingly contain large amounts of IT equipment (Firth and Cook 2010). Apart from the high heat gains due to operating at full or nearly full capacity most of the time with high internal heat gains from equipment, an additional challenge is presented by the intermittent occupancy as pupils move between spaces (CIBSE 2015). In addition to that schools

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are particularly vulnerable to increased temperatures due to the young age of occupants, and limited opportunities for behavioural adjustments to improve thermal comfort in classrooms (Teli *et al.* 2017). A further challenge is posed by recent research which has shown that comfort temperature levels are lower for children than adults (Teli *et al.* 2017). Thermal comfort field surveys during spring and summer in naturally ventilated classrooms in the UK found this comfort temperature difference to be around 2℃ (Teli *et al.* 2012).

The recorded increase in the global average temperature over the past century has raised concerns about the likelihood of overheating in buildings without mechanical ventilation. Furthermore, heat waves have become more frequent and intense (Teli *et al.* 2017). Considering the rise of temperature and the increase in the frequency and intensity of extreme weather events shown in the UK Climate Projections (UKCP09) (Defra 2009b), overheating problems are likely to become more serious in the future.

This paper aims to examine the risk of overheating under extreme hot weather conditions of a new built naturally ventilated school building under the BB101 criteria in 14 different locations in the United Kingdom.

2. Literature review

2.1 UK climate projections

The UK Climate Projections are the key source of climate change information on which research organizations, regulation and policy making bodies, and the insurance industry are basing their responses to changes in our climate. It must be remembered, however, that although there are limitations to the robustness of these projections, they represent our current best knowledge on future UK climate (CIBSE 2014b).

The Projections provide data for three different (high, medium, low) future scenarios of greenhouse gases. These emission scenarios are based on different pathways showing how a range of factors, such as population, economic growth and energy usage, might change over time. For the next two to three decades there is little difference between the scenarios in terms of how they will impact global temperatures. After this point the impact of different emissions levels becomes significant, leading to a very wide difference between low and high greenhouse gas emission scenarios by the 2080s (Defra 2009a).

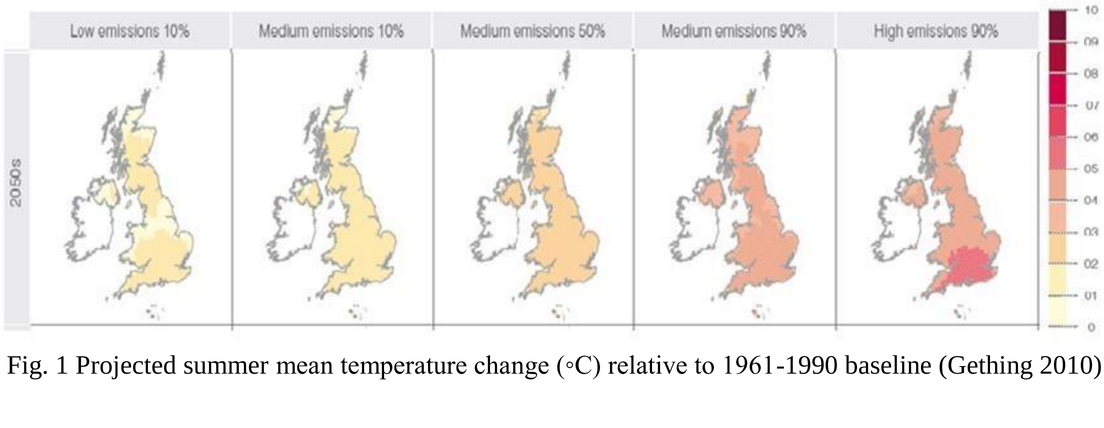

Fig. 1 Projected summer mean temperature change (◦C) relative to 1961-1990 baseline (Gething 2010)

The UKCP09 show that all locations in the UK will get warmer in the future, more so in the summer than in the winter. In addition to that extreme weather events will appear with a higher frequency and intensity (Defra 2009a). Gething in his report “Design for Future Climate” presents a series of maps that have been assembled from UKCP09 data to give overviews of the likely range of change across the country and across all three emissions scenarios for a number of the most relevant climate variables (Gething 2010). Fig. 1 below shows the projected summer mean temperature change (◦C) relative to 1961-1990 baseline for the three emissions scenarios.

2.2 Overheating

The thermal conditions inside a building are determined by the interactions between the external climate and the building, the building shell and the internal space and the internal space and the occupants (Teli *et al.* 2011). Overheating implies that building occupants feel uncomfortably hot and that this discomfort is caused by the indoor environment (Nicol 2013). Thermal discomfort is a sign that the mechanisms that we have in place to remain comfortable are inadequate. So, if a student finds it hard to concentrate during an exam at school because the room is too hot for that particular task, the school building, its services or the building management, have individually or collectively failed in an important task (Nicol 2013).

BB101 defines the regulation standards and provides design guidance for ventilation in school buildings. In BB101 the performance standards for summertime overheating in compliance with Approved document L2 for teaching and learning areas are:

a) The average internal to external temperature difference should not exceed 5℃ (i.e., the internal air temperature should be no more than 5℃ above the external air temperature on average)

b) The internal air temperature when the space is occupied should not exceed 32℃.

c) There should be no more than 120 hours when the air temperature in the classroom rises above 28℃

In order to show that the proposed school will not suffer overheating two of these three criteria must be met (BB101 2006). Overheating analysis is performed for occupied hours of the building for the period from May to September.

2.3 Design summer years

The DSY was introduced in 2002, to represent a ‘near extreme’ warm summer, in recognition of the need to have a sequence of warm weather data for use with dynamic thermal simulation programs for the assessment of overheating risk in naturally ventilated and passively cooled (‘free running’) buildings (CIBSE 2014a). In 2014, TM49 presented probabilistic Design Summer Years for London to represent better the duration and severity of conditions likely to cause thermal discomfort (CIBSE 2014a). The latest release of Design Summer Years updated the weather files for the remaining 13 locations across the UK based on this methodology (Virk and Eames 2016).

The updated methodology uses three metrics to define overheating, the conceptual building, the comfort model and the weighted cooling degree hour (WCDH). The conceptual building is a one in which the internal operative temperature is equal to the outside dry bulb temperature at all times. This conceptual building corresponds physically to a building in which there is always a very high ventilation rate, so that heat gains are quickly removed, and the internal temperature is close to the outside temperature (CIBSE 2014a). The comfort temperature is related to the running mean of the outside dry-bulb temperature, according to the following relationship

$$T_{conf} = 0.33T_m + 18.8 \quad (1)$$

where T_{conf} is the predicted comfort temperature on a given day (℃) and T_{rm} is the running mean daily average temperature given by

$$T_{rm} = aT_{rm-1} + (1 - a)T_{mean-1} \quad (2)$$

where α is a constant (0.8), T_{rm-1} is the running mean temperature for the proceeding day (℃) and T_{mean-1} is the average temperature for the proceeding day

Using the definition of the comfort temperature, the WCDH is a quadratic expression given by (Virk and Eames 2016)

$$WCDH = \sum all\ hours\ \Delta T^2 \quad (3)$$

and

$$\Delta T = T_{op} - T_c\ , T_{op} - T_c > 0 \quad (4)$$

where T_{op} is the internal operative temperature

The weighting puts a much greater emphasis on external temperatures which depart further from the comfort temperature. The WCDH approximation is related to the duration of the exceedance event as well as giving emphasis to more extreme temperatures which therefore takes into account the severity of the event (Virk and Eames 2016).

The latest Design Summer Years are available for three different representations of hot events (Eames 2016). DSY-1 represents a moderately warm summer year, defined as a year with a static weighted cooling degree hour return period closest to 7 years. DSY-2 represents an intense extreme summer, which is chosen as the year with the event which is about the same length as the moderate summer year but has a higher intensity than the moderate summer. Finally, DSY-3 represents the long extreme year, which is determined by the year with a less intense extreme than the high intensity year, more intense extreme than the moderate summer year but also has a longer duration than the moderate summer year (Virk and Eames 2016). Unlike to the DSY-1 that have a return period close to 7 years, the return period of the DSY-2 and DSY-3 varies based on the examined location.

3. Methodology

For the purpose of this study, thermal and energy simulations of a school building were performed to identify locations in the UK where naturally ventilated school buildings, with similar construction, are likely comply with the BB101 overheating criteria. The examined locations are Belfast, Birmingham, Cardiff, Edinburgh, Glasgow, Leeds, London, Manchester, Newcastle, Norwich, Nottingham, Plymouth, Southampton and Swindon. Modelling and simulation of the building was performed with the aid of EDSL TAS software package. Amoako-Attah and Jahromi have provided a detailed description of the modelling process (Amoako-Attah and Jahromi 2015).

Table 1 Building fabric U-values

Construction	U-Value (W/m^{2}K)
External wall	0.25
Partition wall	0.728
Roof	0.164
Windows	1.538
Ground floor	0.21

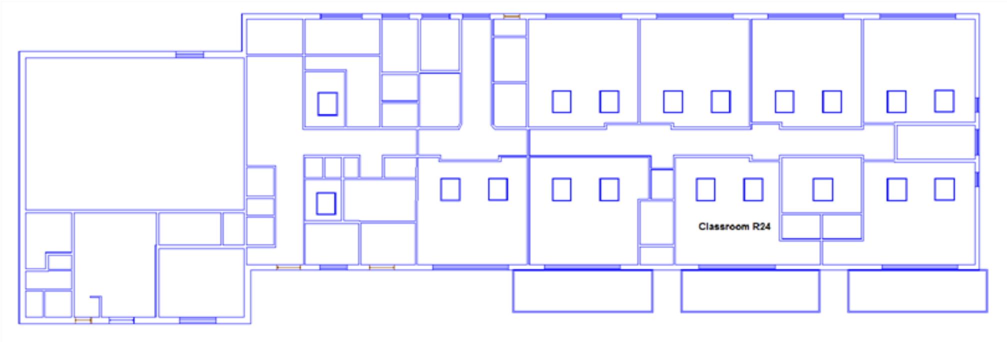

Fig. 2 2D model of the building created in EDSL TAS

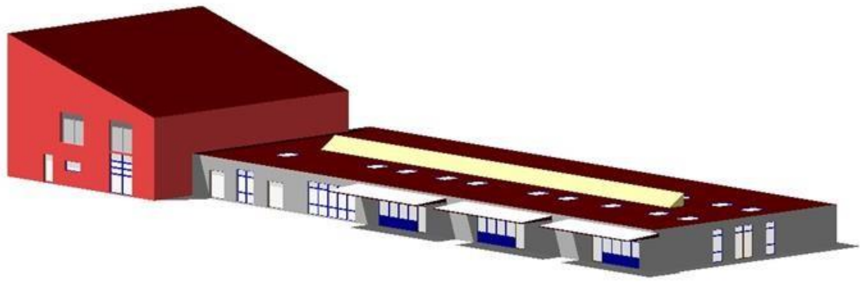

Fig. 3 3D model of the building created in EDSL TAS

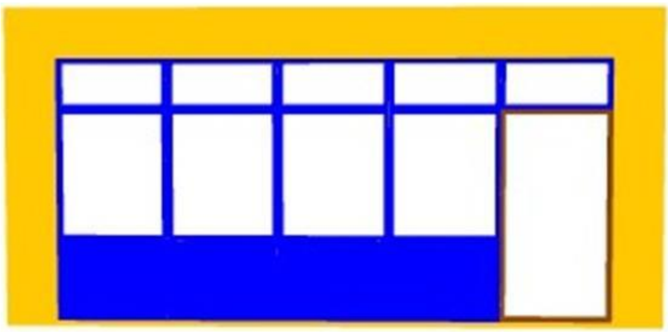

Fig. 4 Window formation of classrooms

The latest DSY weather files, by CIBSE were used.

As this study aims to study the risk of overheating under extreme hot weather conditions, the DSY-2 weather files, which represent the most intensive warm spell were selected. The performance of the building under the projected weather conditions of the 2050s was examined using the high emission scenario (90% percentile change). When examining the performance of the building for London the London Weather Centre weather file was used.

Initially the building was modelled as naturally ventilated and the risk of overheating was investigated for all the examined locations. In the following, for the locations where the building failed to comply with the overheating criteria, the building was simulated in mixed mode and as mechanically ventilated and the amount of cooling loads required to achieve thermal comfort conditions was quantified. Finally, the performance of the building was examined under the projected weather conditions of the 2050s.

3.1 Examined building

The examined building is a one floor new built school building with a total area of 1343 m^2. The internal space of the building consists of classrooms, interview rooms, offices, WC, kitchen, plant room and circulation areas. It has seven similarly sized classrooms with an average area of 65.25 m^2. Three classrooms are south facing and four are north facing. External shading is provided to the south facing classrooms by polycarbonate roof panels. On the top of the roof a photovoltaic solar system is installed. All classrooms have the same window formation as shown in Fig. 4. The upper windows have an area of 0.55 m^2 and the middle windows have an area of 1.43 m^2. The bottom part of the formation consists of aluminum panels.

Table 1 shows the modelling and simulation parameters of the building fabric used in this study. Figs. 2 and 3 show the plan and the 3D model of the building as they were created in EDSL TAS.

3.2 Ventilation modes

Different functions were set to control the ventilation of the building in the examined scenarios. In the mixed mode and mechanical ventilation scenario mechanical cooling is provided to ensure that the zone's temperature will not go above 28℃.

For the modelling of natural ventilation, a function was defined to control the opening of the window based on the temperature of the adjacent zone. The aperture was set to begin to open if the dry bulb temperature in the adjacent zone exceeds 2℃ and it will be fully opened if the dry bulb temperature reaches 23℃. The openable proportion of the window was set at 30%. This function was applied, both to the upper and middle window of the window formation of the classrooms as shown in Fig. 4.

Similarly, to the natural ventilation mode, the function that controls the mixed mode ventilation is controlled by the adjacent zone dry bulb temperature. Opening of the aperture functions as in the natural ventilation mode, however in this scenario the aperture will begin to close if the temperature in the adjacent zone reaches 25℃ to allow mechanical ventilation to be used. Furthermore, if the external temperature exceeds the internal temperature, the aperture will begin to close.

In the mechanical ventilation mode, a minimum ventilation rate was set at 2.0 l/s/m^2.This ventilation rate was selected to cover the minimum daily average rate of 5 l/s per person (BB101 2006). Furthermore, additional ventilation can be provided if it is required. The additional ventilation is controlled by the zone's dry bulb temperature. It starts when the temperature in the zone reaches 21℃ and increases proportionally until the temperature reaches 25℃. At this point the additional ventilation rate plus the minimum value is applied to the zone. The additional ventilation starts to reduce when the inside and outside temperatures are equal and is completely off when the outside temperature is one full degree above the inside. The additional ventilation rate was set at 1.2 $l/s/m^2$ to ensure the capability of the mechanical ventilation system to provide 8 l/s per person at any occupied time (BB101 2006).

Table 2 Compliance to BB101 overheating criteria for current weather conditions

Location	Criterion 1 (˚C)	Criterion 2 (˚C)	Criterion 3 (hours)
Belfast	7.21 (F)	36.14 (F)	41.5
Birmingham	6.3 (F)	39.7 (F)	139 (F)
Cardiff	6.5 (F)	36.48 (F)	82
Edinburgh	7.21(F)	30.68	23.5
Glasgow	7.41(F)	31.46	17.5
Leeds	6.61 (F)	35.41 (F)	64
London	6.05 (F)	36.9 (F)	195 (F)
Manchester	7.08 (F)	34.21 (F)	68.5
Newcastle	7.27 (F)	33.13 (F)	32
Norwich	6.11 (F)	35.53 (F)	75
Nottingham	6.67 (F)	35.60 (F)	69
Plymouth	6.50 (F)	33.38 (F)	59.5
Southampton	6.11 (F)	33.20 (F)	104
Swindon	6.11(F)	35.38 (F)	103

Table 3 Compliance to BB101 overheating criteria for future weather conditions

Location	Criterion 1 (˚C)	Criterion 2 (˚C)	Criterion 3 (hours)
Belfast	6.53 (F)	37.60 (F)	74
Birmingham	5.77 (F)	41.54 (F)	208.0 (F)
Cardiff	5.98 (F)	38.43 (F)	159.0 (F)
Edinburgh	6.38 (F)	32.61 (F)	48.5
Glasgow	6.62 (F)	32.91 (F)	48.5
Leeds	6.03 (F)	37.06 (F)	104.5
London	5.64 (F)	41.89 (F)	488 (F)
Manchester	6.41 (F)	35.99 (F)	105
Newcastle	6.57 (F)	34.60 (F)	66
Norwich	5.62 (F)	37.33 (F)	131 (F)
Nottingham	6.03 (F)	37.41 (F)	110.5
Plymouth	5.86 (F)	35.40 (F)	97
Southampton	5.67 (F)	35.38 (F)	196.5 (F)
Swindon	5.68 (F)	37.30 (F)	206.5 (F)

4. Results

Results for both the current weather conditions and the projected weather conditions of the 2050s are shown for classroom R24, which is south facing and has a total area of 66.3 m^2. Exact location of classroom R24 in the building plan can be seen in Fig. 2. For the scenario where the building is considered to be naturally ventilated each location is examined against the three criteria defined in BB101. Whenever the results of the simulation fail to fulfil one of the criteria this is presented with the letter (F) next the value. When the building is considered to be in mixed mode or mechanically ventilated, mechanical cooling is also provided to keep the temperature at maximum 28 ℃ during occupied hours. As a result, in these two scenarios the building does not overheat for any of the examined locations and weather conditions. For these two scenarios, the required amount of cooling loads to achieve comfort conditions is presented.

4.1 Natural ventilation

As it can be observed from Table 2 only Edinburgh and Glasgow fulfil the BB101 criteria under the current weather conditions. In the other twelve examined locations, the classroom overheats. Furthermore, it is worth noting that London and Birmingham are the only two areas in which the air temperature in the classroom rises for more than 120 hours above 28 ℃ and they also have two of the highest maximum internal air temperatures. Southampton, Plymouth and Newcastle are all less than 1.5℃ above the maximum allowed internal air temperature.

Results of the simulations for the projected weather conditions of the 2050s show that all the examined locations fail the BB101 criteria for overheating. In London, the examined classroom is above 28℃ for 488 hours and in Birmingham for 208. Except London and Birmingham, Cardiff, Norwich, Southampton and Swindon also show more than 120 hours above 28 ℃. Glasgow and Edinburgh are both less than 1℃ above the maximum allowed internal air temperature.

4.2 Mixed mode and mechanical ventilation

Table 4 below shows both for the mixed mode and mechanical ventilation scenario and for all the locations, the required cooling loads to keep the internal temperature of the examined zone below 28 ℃ under the current weather conditions. These cooling loads are the total loads required for the examined period. It can be observed that for all locations mixed mode requires less energy compared to mechanical ventilation. The highest amount of cooling loads is required in London and equals to 526.1 kWh for the mixed mode scenario and 598.8 kWh for the mechanical ventilation scenario. The least amount of cooling loads is required in Edinburgh, Glasgow and Newcastle. The difference of the cooling loads between the two examined scenarios is small. The highest difference is 99.5 kWh and is shown in Belfast.

Table 5 shows the required cooling loads, for the mixed mode and mechanical ventilation scenario under the projected weather conditions of the 2050s. Similarly, to current weather condition scenario the cooling loads required in the mixed mode scenario are less than the ones required in the mechanical ventilation scenario for all the examined locations. The highest amount of cooling loads is required in London and is 3.31 times higher compared to the current weather conditions. For Edinburgh, comparison of the cooling loads between the two examined ventilation scenarios, shows that the cooling loads are 30% more when the building is modelled with mechanical ventilation.

Table 4 Required amount of cooling loads (kWh) for current weather conditions

Location	Mixed Mode (kWh)	Mechanical Ventilation (kWh)
Belfast	131	230.5
Birmingham	389.1	438.5
Cardiff	202.5	268.3
Edinburgh	49.4	72.1
Glasgow	42.6	69.3
Leeds	153.5	178.6
London	526.1	598.8
Manchester	144.8	168.7
Newcastle	63.3	76.1
Norwich	176.4	214.4
Nottingham	155	180.2
Plymouth	131.1	161.3
Southampton	212.8	278.2
Swindon	261.2	331.7

Table 5 Required amount of cooling loads (kWh) for future weather conditions

Location	Mixed mode (kWh)	Mechanical ventilation (kWh)
Belfast	195.7	230.5
Birmingham	578.1	719.6
Cardiff	438.1	506.4
Edinburgh	125.6	178.0
Glasgow	124.5	165.4
Leeds	273.0	319.4
London	1745.2	1799.8
Manchester	250.7	284.7
Newcastle	127.3	161.3
Norwich	354.3	418.4
Nottingham	283.8	333.3
Plymouth	259.2	315.7
Southampton	530.0	586.9
Swindon	583.4	656.1

5. Conclusions

This study examined the risk of overheating for a school building in 14 different locations in the UK using the latest CIBSE DSY weather data sets. It identified locations in the UK where naturally ventilated school buildings with similar construction are likely to achieve thermal comfort conditions even under extreme hot weather conditions. Furthermore, it examined the performance of the building in mixed mode and as mechanically ventilated and it quantified the amount of cooling loads required in order to comply with the BB101 criteria. Finally, it performed simulations of the building under projected weather conditions of the 2050s and presented a comparison between the current and the future weather conditions.

The results of the simulations show that in most parts of the UK examined in this paper, schools with similar characteristics with the one investigated in this case study, are likely to have problems to pass the overheating standards under both the current and the projected weather conditions of the 2050s. More specifically, under the current weather conditions and when the building is modelled as naturally ventilated, only Edinburgh and Glasgow comply with the overheating criteria. For all the other areas that failed to pass the overheating criteria set in BB101, additional measures should be adopted in order to avoid the risk of overheating. Simulations of the building with the projected weather conditions show that none of the examined areas complies with the overheating criteria in the future.

In both the mixed mode and mechanical ventilation scenario, cooling at 28℃ was provided to the classroom and thus the overheating criteria are met in both the current and the projected weather conditions, but with an energy penalty. Schools in the UK have been traditionally designed as naturally ventilated and as such currently spend no or little energy for cooling. Depending on the location of the building the additional energy needed to cover the cooling loads required to achieve thermal comfort conditions will have a different impact on the total energy consumption of the building. School buildings in the south regions of the UK are likely to experience more serious overheating problems than the ones in the north and therefore the amount of energy required to comply with the overheating criteria will be higher. More specifically, in London, where the highest amount of cooling loads is needed, in order to comply with the overheating criteria under the current weather conditions and when the building is considered to have mixed mode ventilation a total of 7.94 kWh/m^2 for cooling is required and when the building is modelled is as mechanically ventilated the required amount of cooling loads is 9.03 kWh/m^2. When examining the future weather conditions, these figures rise to 26.32 kWh/m^2 and 27.15 kWh/m^2 respectively. According to Good Practice Guide from Carbon Trust the typical annual consumption of electricity for a primary school in England is 32 kWh/m^2. Cooling loads will need to represent over 25% under the current weather conditions and over 82% under the future weather conditions of the annual electricity consumption to comply with the overheating criteria. Comparison of the required cooling loads both for the current and the projected weather conditions, in all the examined locations shows that mixed mode requires less energy to comply with the overheating criteria.

In conclusion, this study has shown that the examined classroom, when simulated as naturally ventilated and under the current weather conditions, complies with the overheating criteria set in BB101 only in Edinburgh and in Glasgow. Classrooms of naturally ventilated school buildings in Edinburgh and in Glasgow with a similar design and construction parameters with the one investigated in this case study are more likely to not have overheating problems compared to the rest of the examined locations. In addition to that, this study presented results that show a significant increase in the amount of cooling loads required to achieve thermal comfort conditions. Mixed mode ventilation should be preferred over mechanical ventilation strategy, as it results in less energy consumption.

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