DYNAMIC THERMAL SIMULATION OF ADVANCED NATURAL VENTILATION IN BUILDINGS: CURRENT AND FUTURE USAGE UK EXEMPLAR

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ABSTRACT

This paper evaluates the use of advanced natural ventilation (ANV) strategies in a range of climatic conditions from four cities in the UK using dynamic thermal simulation. A prototype ANV system was proposed, through which design changes were made to determine the most effective case in mitigating overheating among the changes considered. The most effective case was then assessed under identical simulation conditions for all four ANV strategies. The overheating criteria used in the research include the single temperature criterion from the Chartered Institute of Building Services Engineers' (CIBSE) Guide A and the adaptive thermal comfort overheating criteria from BS EN 15251. Both the current and future 'Design Summer Year (DSY)' weather data were used to examine the thermal performances of the proposed design. The findings show that shading, night cooling and heavy weight structures (ceiling) were all useful in mitigating overheating, with night cooling being identified as the most effective measure. The work assessed the use of ANV in both current and future scenarios to quantify the limits of outdoor environmental conditions under which natural ventilation is an effective strategy for achieving thermal comfort. The adaptive thermal comfort overheating criteria were proved to be easier to meet compared with the CIBSE single temperature criterion. With the adaptive overheating criteria, the given design is predicted to not overheat until 2050 in London Heathrow; and for other places evaluated in the UK (Edinburgh, Manchester & Birmingham), the design passes these criteria. However, with the single temperature criterion, the design fails for all London Heathrow weather data and some of the Manchester weather data. The Centre-in ANV strategies proved to be more effectives than the Edge-in strategies for space cooling due to the extended structure thermal mass. To make designs future proof for overheating in the southeast of the UK, hybrid or mixed ventilation may be needed in the foreseeable future.

Keywords:

Advanced Natural Ventilation, Dynamic Thermal Simulation, Overheating, Design Summer Year, Adaptive thermal comfort

INTRODUCTION

It has been increasingly recognized that climate change prevalently stands as the greatest environmental threat and challenge of modern times. In the UK, up to 37% of its total annual greenhouse gas (GHG) emissions is from the building sector (TSB, 2014). Greenhouse gas emissions generated during the design and construction stage including material manufacture and distribution can contribute up to 18% of a building's whole lifecycle carbon footprint (BIS, 2010). There is a clear link between the whole lifecycle environmental and greenhouse gas emission performance of a building, with the primary focus and investment identified as critical during the design phase – for example, inadequate design, requiring mechanical interventions, will lead to increased operation or maintenance expenditure and reduced environmental performance over the building's whole lifecycle (Bribián et al., 2009). Further, the UK's Department for Environment, Food and Rural Affairs (DEFRA) affirms that improvements made in architectural design will be crucial in reducing emissions (DEFRA, 2013).

Natural ventilation (NV) is appraised to be one of the most efficient and healthy solutions for ventilating a building, offsetting any required cooling energy consumption, the associated energy costs and greenhouse gas emissions of mechanically ventilated buildings (Cheng et al., 2017; Carrilho da Graça & Linden, 2016). However, the potential savings for cooling energy would depend upon the local climate conditions (i.e. temperature and wind), the building's thermal characteristics, internal heat gains, ventilation control and types, and lastly but by no means least, human expectations of thermal comfort (Yao et al., 2009). Supporting this, the PROBE research study (Bordass et al., 2001) provided the empirical evidence to substantiate monitored energy use and CO_2 emissions of 20 public and commercial buildings, comparing to the 'typical and good' practice benchmarks reported in ECON 19 (BRECSU, 2000), and demonstrated that nine out of ten highest CO_2 emitters were air-conditioned or mixed mode buildings, and nine out of the ten lowest emitters were naturally ventilated or used advanced natural ventilation. Architectural features such as stacks, air lightwells and atria have made natural ventilation possible for large and deep plan modern commercial buildings. Lomas (2006) defined the term 'advanced natural ventilation' (ANV) to reflect the use of these architectural features and four different strategies were proposed: Edge-in/Centre-out (E-C); Centre-in/Edge-out (C-E); Edge-in/Edge-out (E-E); and Centre-in/Centre-out (C-C). Such strategies, either one or multiple, have been used in existing buildings. For example, the E-C strategy was used for the Queens Building at De Montfort University, Leicester (BRECSU, 1997; Bunn, 1993); and the C-C and C-E strategies were used for the Frederick Lanchester Library at Coventry University (Field, 2000; Pidwell, 2001). The C-E and E-E strategies were used for the Harm A Webber Library for Judson College, Illinois, in the USA. This particular design used a hybrid approach: ANV and mechanical cooling to manage the warm humid summers and the cold winters (Lomas et al., 2007). Similar hybrid approaches were also used in the design and construction of the Science and Technology Museum in South China (Ji et al., 2009).

The climatic suitability and potential operation of NV over the lifespan of a building must be considered at the outset; a design may endure the existing climatic condition but may not withstand future climatic conditions. Thus, it is imperative during the design stage to chart how a building design performs in the future climate scenarios. As we spend 80-90% of our time inside buildings, poor internal conditions will not only affect comfort but also impair occupant health and productivity. Thus, Emmerich et al. (2001) proposed the use of dynamic thermal simulation for evaluating the climatic suitability of a given location for direct ventilation cooling. Therefore, this paper reports on the use of dynamic thermal simulation tools to evaluate the current and likely future climate conditions within buildings with different ANV strategies.

Dynamic building simulations were developed in the 1950s, although it was not until the energy crisis of the 1970s that the scientific community utilised them to improve energy performance in buildings. This work proposes a hypothetical ANV building, through which all four ANV strategies can be evaluated. Both the current and future weather conditions of the UK are used given as a case study exemplar. The design was also evaluated for different geographic locations in the UK to examine whether such ANV strategies can mitigate the likelihood of overheating in buildings, in particular, with the possible future elevated temperature in mind, to proffer lessons for the use of ANV in the longer term to quantify the limits of outdoor environmental conditions, under which natural ventilation is an effective strategy for achieving thermal comfort.

METHODOLOGY - THE HYPOTHETICAL DESIGN AND ITS MODEL

Figure 1 below shows the plan view of the hypothetical design of the ANV building. The design incorporates all four of the aforementioned ANV ventilation strategies (E-E, E-C, C-C & C-E) described in the introduction section of this paper. As shown in Figure 1, there are four identical office spaces with internal dimensions of 13.0m × 7.0m × 3.6m (width × depth × height). Wrapped in the centre by the four office spaces is the central atrium with perimeter dimensions of 6.0m × 6.0m and the projected roof light glazing area is 10m^2. Embedded with the atrium there are four stacks/ shafts which are designed for serving as either the inlet or outlet of an individual office. The internal glazing area between the office spaces and the atrium is 11.4m^2. Two external vertical shafts are attached to each office space on its long external perimeter. These shafts were used as airflow paths when needed and in the meanwhile they provided extruded shading for the external glazing (with an area of 12m^2). Overhang shading right above the glazing is shown in the design.

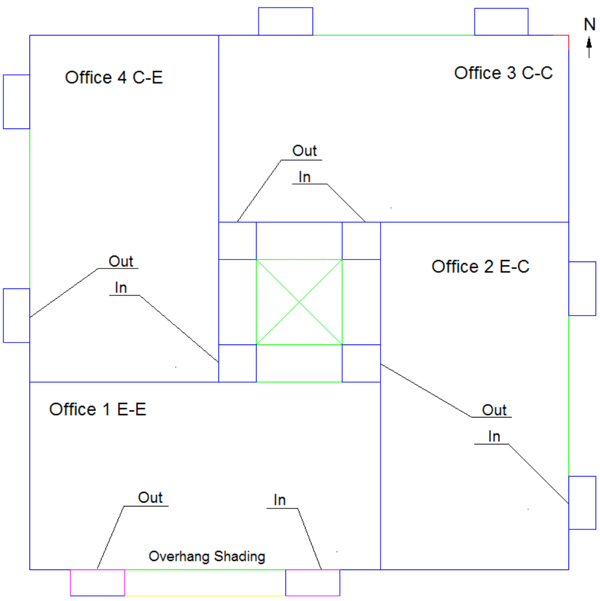

Figure 1: the plan view of the hypothetical design with all four ANV strategies

The hypothetical design has been purposely arranged to ensure the evaluation of each of the four ANV strategies under the same simulation conditions. As shown in Figure 1, the Edge-in/Edge-out strategy has a south-facing window. The south facing office and its connection to the adjacent atrium and stacks will be firstly evaluated, with the other remaining office spaces with different ANV strategies being 'turned off' in the meantime . The design is then rotated 90 degree clockwise, the Edge-in/Central-out strategy now has a south facing window. 'Turns on' this office space and 'turn off' all the others, then the E-C strategy with its used atrium and stacks is evaluated individually. By rotating the design, all four ANV strategies can be examined under the same south facing orientation simulation condition.

Figure 2 shows the C-C strategy using the axonometric view of the IESVE model developed by the hypothetical design. IESVE is a well-established dynamic thermal simulation program for analysing the dynamic responses of a building based on the hourly input of weather data (IES 2017). The office spaces examined in this paper are on level 2 (in between the upper and lower levels). Only the south facing façade with the external window is exposed to ambient conditions, the other facades which are connected to other office/atrium spaces become internal partitions or ceiling/floor. The total height of each floor is 4.0m (finished floor level (FFL) to FFL). The stack height above the notional roof level is 3.0m, so the total height of the stacks and shafts is 15.0m.

As shown in Figure 2, with the C-C strategy, the two vertical shafts at the external perimeter do not serve as a ventilation path. Although these shafts are not used as airflow paths, they are there for external extruded shading purposes to provide the same simulation conditions for all four ANV strategies, keeping these shafts therefore is necessary for this purpose. It is worth noting that the external window is not openable for the cases considered. The hypothetical structure is assumed to be in a typical urban condition. A 'semi-exposed wall' exposure type is used in IESVE to represent this. The shading influence from the structure itself is dealt by the ‘SunCast’ programme within IES through which an averaged shading effect throughout a year was calculated, and this shading effect will be included when the core thermal engine is used for calculating the dynamic thermal responses of the building models (IES 2017).

In this study, 1.5% of the total usable floor area of one office space is used as the free opening area along the airflow path (equals 1.4m^2). This presumption is taken from Lomas (2006) where the 4 ANV strategies were defined and discussed in detail. For Edge-in strategies, ambient air will flow through the perimeter shafts to the serving office spaces, but for Central-in strategies, ambient air will pass an under-floor plenum before reaching the central shafts. Figure 2 illustrates the C-C strategy, ambient air flows through the under-floor plenum, to the central vertical shaft on the right-hand side, and then to the low level of the office space. Following, the exhaust air leaves the office space at high level openings, to the central shaft on the left, and then exhausted through the outlet at the top of the central shaft (the roof terminal).

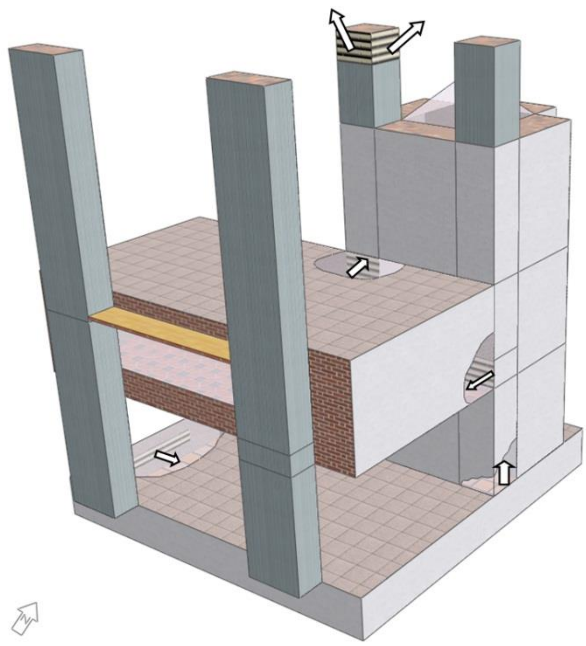

Figure 2: IESVE model with C-C ANV strategy – only the south facing office space is shown, other spaces were turned off to achieve adiabatic condition for partitions, floor/ceiling.

Table 1 shows the construction details used for the proposed model. The external wall U-value (0.35W/m^{2}K) is taken from the Approved Document L2A (Building Regulations 2010). Relatively large U-values for ceilings and internal partitions will not have significant impact on heat loss as they are attached to the surrounding office spaces. These spaces are 'turned off' in the IESVE model. This way the internal partitions and ceilings are treated as adiabatic condition in the model (assuming the indoor temperatures are the same so no heat transfers between office spaces). The sufficient insulation for shafts and stacks is purposely made in order to avoid thermal conduction of heat into these air flow paths, making sure that the natural ventilation driving force relies on the indoor and outdoor temperature difference only.

Table 1: The construction details of the hypothetical model

BUILDING ELEMENTS	CONSTRUCTION DETAILS	U-VALUES
External exposed Walls	Brickwork 100mm + EPS insulation 58.5mm + Concrete Block (medium) 100mm + Plastering 15mm.	0.35 W/m^2 K
Partition	Plaster 13mm + Brick work 105mm + plaster 13mm.	1.69 W/m^2 K
Heavy weight Ceiling	Plastic tile 3mm + Screed 75mm + Cast Concrete (dense) 200mm.	1.88 W/m^2 K
Light weight Ceiling	Plastic tile 3mm + Screed 75mm + Cast Concrete (dense) 100mm + Cavity 400mm + Ceiling tile 10mm.	1.22 W/m^2 K
Roof light	Suncool glass – Plkington K 6mm + Cavity 16mm + Clear float 6mm	1.2 W/m^2 K
External Glazing	Standard clear low-e double glazing	1.98 W/m^2 K
Stack and shaft construction	Aluminium 3mm + Dense EPS insulation 300mm + Aluminium 3mm.	0.08 W/m^2 K

Following the guidance of CIBSE Guide A (2015), lighting gains are assumed as 12W/m^2, and the same gain is used for office equipment. Each office is occupied by 6 occupants, considering moderate office work, with the maximum sensible heat gain for each occupant is 75W and 55W is the maximum latent gain; the total internal heat gain is therefore 29W/m^2 by adding averaged lighting, equipment, and occupants' gains. These heat gains are only present during 9am to 5pm, 5 days a week, with the lunch break not being considered. The background infiltration of 0.25 ach^{-1} is taken from the CIBSE Guide A, table 4.16 (CIBSE Guide A, 2015), which is used for the four strategies discussed in this work. Simple ventilation control was assigned to the model: the ventilation openings were fully open during working hours from May to September inclusive (9am to 5pm). For non-working hours, the ventilation openings will be either fully opened when the night-time ventilation was modelled, or fully closed when the night-time ventilation is not necessary. It must be noted that, passive ventilation at night time or night purging in summer will be mostly effective in the UK, the reason is that, even in the warmest part of the country – southeast of England, the night-time outdoor air temperature rarely gets over 24°C.

The network airflow model used in IESVE is the Macro-Flo. This Macro-Flo tool allows users to carry out studies of natural ventilation, infiltration, façade analysis and mixed-mode design. Macro-Flo uses a fast multi-zone thermo-fluid solver to simulate the interactions between airflows, pressures and thermal conditions. For a NV building design, the worst-case scenario for ventilation is often assumed to be the windless condition. In this research, we excluded wind driven ventilation by sheltering the ventilation openings(so the impact from wind-driven forces under different urban settings was no longer relevant), this way only the buoyancy-driven force was considered in Macro-Flo to examine the worst-case scenario.

It is worth noting that when the ambient temperature is similar or higher than the interior air temperature, the buoyancy driven force will be very small (significantly less than 1 pascal) and the fresh airflows will be very low, reverse flow may also happen. In the IESVE model, in order to avoid inadequate ventilation, a low speed fan provided a minimum volume of fresh air required by BSI's (2017) BS EN 16798, 60 l/s in total, 10 l/s per person, which is the average of IDA2 (medium) and IDA3 (moderate) requirements of BSI (2017). The fan operating conditions are: either the CO_2 concentration becomes below 950 ppm or when $T_o - T_a \leq 2.0$K (where T_o is office air temperature and T_a is the ambient air temperature).

METHODOLOGY - WEATHER DATA

Local weather and climate greatly affect the performance of buildings, and therefore, good quality weather data is essential to ensure that the modelled building performances are reliable. In this context, weather data enables analysts to stress-test building performance for atypical conditions such as heat waves or cold snaps, since such conditions are more likely to cause performance failures.

The hourly weather data used in thermal simulation models represents a single complete year. Two types of hourly weather data have been widely used for building dynamic thermal simulations in the UK: Test Reference Year (TRY) and Design Summer Year (DSY) (Levermore & Parkinson, 2006). A TRY represents an averaged or typical weather condition based on the historical weather data, i.e. statistically selecting the most representative months from historical weather data (20 or more historical years) and combines them as a complete year. A TRY weather data set is often used for predicting energy consumptions and CO_2 emissions of buildings. A DSY represents a near extreme weather condition, a complete year is selected from historical weather years and it is often used to assess overheating in naturally ventilated buildings. The method used to select DSYs was different. Prior the new release of the CIBSE weather data in 2016, the DSY was the 'third' warmest year among 20 year historical weather data (or mid-year of the upper quartile in case more than 20 year historical weather data were used). The warmth of weather was ranked based on summer (April-September) average dry bulb temperature (CIBSE Guide J, 2002). The base weather years used for selecting DSYs in the recent release are from 1984 to 2013, and a new metric was used to rank these weather years during the selection process (Eames, 2016). The metric was 'weighted cooling degree hours (WCDH)'. The WCDH metric assumes that the outdoor weather dry bulb temperature equals the indoor operative temperature. This is often unrealistic in practice, however, the metric does have the merits of not only accounting for overheating occurrences, but also giving emphasis on overheating severity. The quadratic nature of WCDH is broadly consistent with the relationship between fraction of people uncomfortable and the departure from the comfort temperature (CIBSE TM49 2014). Mathematically, the metric is defined as per Ji et al (2016) (adapted from CIBSE TM49):

$$WCDH = \sum_{i=1}^{N}\left(T_{dbt}^{i} - T_{comf}^{i}\right)^2 | T_{dbt}^{i} > T_{comf}^{i} \qquad (1)$$

$$T_{comf} = 0.33Max(10, T_{rm}) + 18.8 \qquad (2)$$

$$T_{rm} = \alpha T_{rm-1} + (1-\alpha)T_{dm-1} \qquad (3)$$

where T_{comf}^{i} is the comfort temperature from adaptive thermal comfort definition (BS EN 15251, 2007) with i stands each individual hour, T_{dbt}^{i} is the outdoor dry-bulb temperature at hour i, under the conceptual building assumption in CIBSE TM49 it also represents the indoor operative temperature, and N is number of hours from April to September inclusive (4392 hours). T_{dm-1} and T_{rm-1} are the daily mean and running mean temperatures of the immediate previous day. α is a constant between 0 to 1, in this work 0.8 is used for α as recommended by BS EN 15251. T_{comf} is the limiting comfort temperature, it correlates with the daily running mean temperatures. The limits of overheating temperatures in BS EN 15251 were divided into three categories (Category I, II & III) and the upper and lower limiting temperatures for these categories are shifted from T_{comf} by 2°C, 3°C and 4°C, respectively.

The CIBSE weather data 2016 release (Eames, 2015; Ji et al 2017) included 14 cities (16 weather stations in total) across the UK: Belfast, Birmingham, Cardiff, Edinburgh, Glasgow, Leeds, London (3 stations: London Heathrow, Weather Centre & Gatwick), Manchester, Newcastle, Norwich, Nottingham, Plymouth, Southampton, and Swindon. Three probabilistic DSY were produced in each location to represent different types of warm events, i.e. pDSY-1 represents "a moderately warm summer"; pDSY-2 has "a more intense single warm spell"; and pDSY-3 has "a long period of persistent warmth". Higher WCDH leads to a longer return period, which indicates more severe summer warmth. For future climate scenarios, each of these pDSYs has projections of the year 2020, 2050 and 2080. In 2020, only 'high' emission scenario was included; 2050 projections included 'medium' and 'high' emission scenarios; and for 2080, all three emission scenarios (low, medium & high) are included (IPCC, 2000). For any of the emission scenarios considered there are three probabilistic projections at the 10, 50 and 90 percentiles. The total number of the DSY future weather years for all 16 stations in the UK is 864. In this research, we used Edinburgh, Manchester, Birmingham and London to represent the geographic difference across the UK and their corresponding DSYs were used for potential overheating analysis. Table 2 below shows the calculated WCDHs which indicate the level of warmth judged by this metric. Broadly speaking, London is warmer than all the other three cities. For future projected weather data, we used 50 percentile (central estimate) data of medium emission scenario for 2050 and 2080, while for 2020, high emission scenario is used (only option available).

Table 2: The weighted cooling degree hour (WCDH) of the current weather data for 4 cities across the UK (calculated using equation 1, the selected years for pDSYs are in bracket, the table is adapted from Ji et al (2018)).

Locations	CIBSE weather data 2016 release, calculated WCDH (selected year)			
	TRY	pDSY-1	pDSY-2	pDSY-3
Edinburgh	0	109 (1989)	299 (1975)	110 (2006)
Manchester	146	282 (1997)	970 (1990)	1326 (1995)
Birmingham	340	765 (1989)	1890 (2006)	1966 (1995)
London Gatwick	-	1201 (1989)	2984 (2003)	3547 (1976)
London Heathrow	629	1808(1989)	3146 (2003)	3972 (1976)
London Weather Centre	-	1105 (1989)	3133 (2003)	2920 (1976)

For future projected weather data, Figure 3 shows the level of temperature elevation using pDSY-2 as an example. For example, with the current DSY in London, it has 255 hours over 25°C for a year, that number is increased in future years: by 2080 there will be 734 hours over this temperature. Other places show the same trend of temperature elevation. It is worth noting that, in Manchester and Edinburgh, the number of hours over 25°C by 2080 (207 and 152) is still less than what London has today (255). Although the 'number of hours over' temperatures do not reflect the characteristics of warmth in detail (i.e. the way how the probabilistic DSYs were selected), it has the merit of simplicity when comparing individual weather years. By examining the number of hours over temperatures in Figure 3 it clearly shows London is the warmest, and Edinburgh is the coolest, with Birmingham and Manchester in between, which is consistent with the warmth judged by the WCDHs in Table 2.

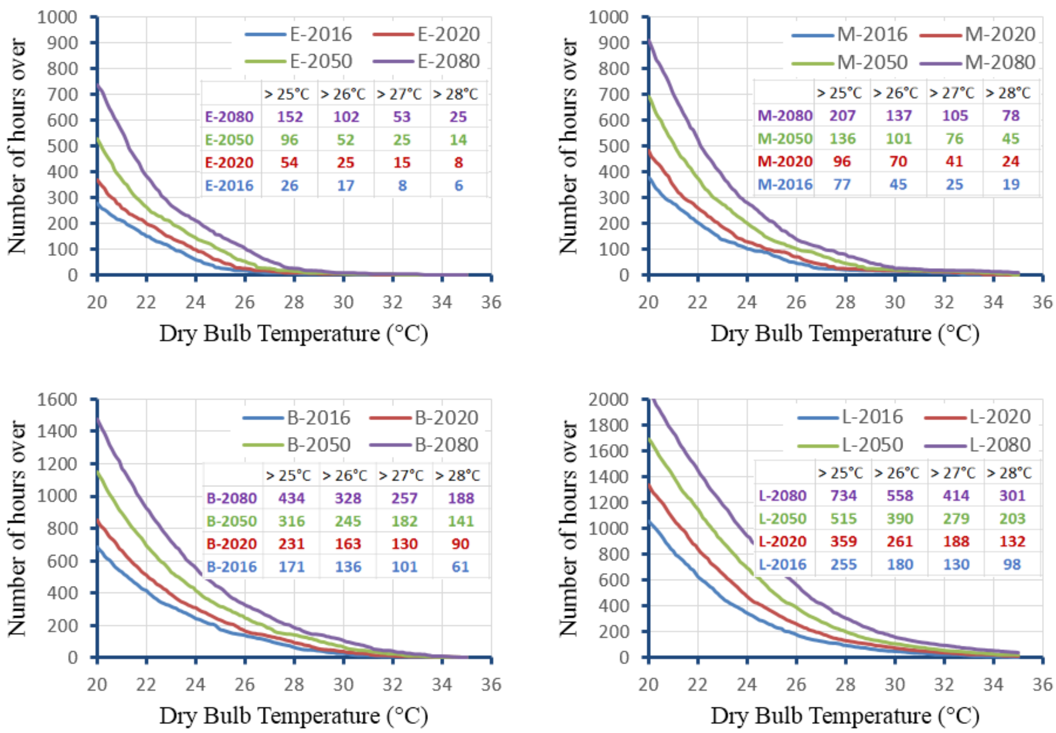

Figure 3: Number of hours over outdoor temperatures for four UK cities – Edinburgh, Manchester, Birmingham & London (Heathrow)

METHODOLOGY- OVERHEATING CRITERIA

For naturally ventilated buildings in the UK, the early edition of CIBSE Guide A (2006) recommended 25°C as an acceptable indoor operative temperature in summer. The overheating criterion was defined as 'the number of hours of indoor operative temperature over 28°C should be less than 1% during occupancy (assuming the office spaces were occupied from 9am to 5pm during weekdays, the maximum number of hours over 28°C should be less than 20 hours)'. This single number overheating criterion is simple to use, however, it only accounts for the occurrence but not the severity of overheating in buildings. The recent recommendations on overheating assessment of naturally ventilated buildings follows the adaptive approach from BS EN 15251 (2007). The overheating limiting temperatures are related to the three categories (Category I - "*High level of expectation and is recommended for spaces occupied by very sensitive and fragile persons with special requirements like handicapped, sick, very young children and elderly persons*"; Category II - "*Normal level of expectation and should be used for new buildings and renovations*"; & Category III - "*An acceptable, moderate level of expectation and may be used for existing buildings*"). Mathematically, the upper limiting temperatures are defined in equations 4 to 6 below. The calculated upper overheating limiting temperatures during the period of May to September are shown in Figure 4 using London Heathrow current pDSY-3 (ref: Table 2) weather year as an example. The limiting temperatures vary with the running mean outdoor temperature. The adaptive thermal comfort criteria are defined against the difference between the indoor operative temperature T_{ot} and these upper comfort limiting temperatures T_{upp} (equation 7, which category is used depends on the comfort expectation and building types).

$$T_{upp-Cat.I} = T_{comf} + 2 \qquad (4)$$
$$T_{upp-Cat.II} = T_{comf} + 3 \qquad (5)$$
$$T_{upp-Cat.III} = T_{comf} + 4 \qquad (6)$$

$$\Delta T = T_{ot} - T_{upp} \quad (7)$$

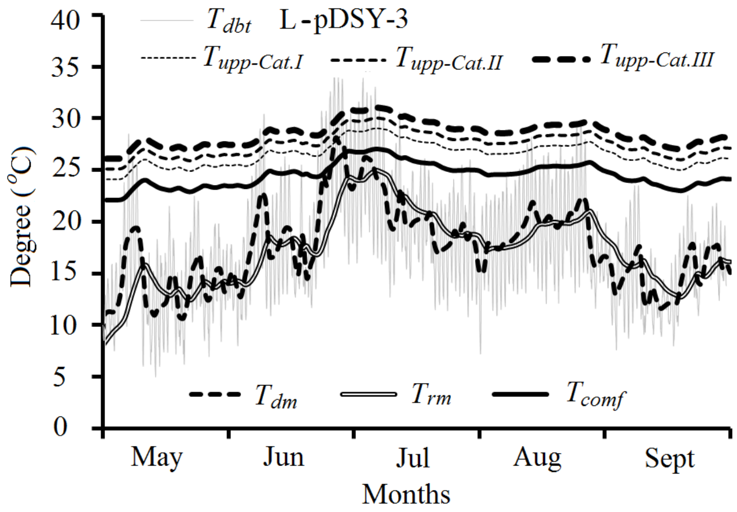

Figure 4: The upper limiting temperatures for London Heathrow pDSY-3 calculated using equations 4-6 for the three categories I, II & III (Daily mean T_{dm}, Running mean T_{rm} and the comfort temperature T_{comf} are also plotted for references using equations 2 & 3)

Using the adaptive approach, three criteria are proposed to determine whether an existing building is classified as overheating, or a proposed building is likely to be overheated (CIBSE TM52, 2013). These criteria are defined in relation the temperature difference ΔT (equation 7), and ΔT is rounded to the nearest whole degree.

- Criterion 1: Hours of exceedance (H_e) – considers overheating occurrence, the number of hours (H_e) over the target limiting temperature T_{upp} during May to September inclusive shall not be more than 3% of occupied hours
- Criterion 2: Daily weighted exceedance (W_e) – considers the overheating severity, the weighted exceedance shall be less than or equal to 6 in any one day (calculation details please refer to CIBSE TM52, 2013).
- Criterion 3: ΔT (equation 7) shall not exceed 4K

MODELLING CONSIDERATIONS

The IESVE model with E-E strategy was used as the base case (Case 1). This base case excludes the overhang shading, ventilation openings are only opened during working hours (the inlets from the shaft and the outlets to the other shafts), night-time ventilation is not considered, and the ceiling structure is the light weight ceiling (ref: Table 1). In comparison with Case 1, the second case (Case 2) includes overhang shading. Progressively, the third case (Case 3) includes the overhang shading and night-time passive ventilation outside the working hours to cool the building fabric. The fourth case (Case 4) used the heavy weight ceiling instead of light weight ceiling compared with Case 3. The progressive changes made from the first case are all expected to help mitigating the indoor operative temperature elevation, therefore Case 4 is expected to be the most effective model among those tested in mitigating indoor heat stress. The current London Heathrow pDSY-1 data was used for the above-mentioned cases. Then the Case 4 model settings were assigned to the C-C strategy model to evaluate the design for four locations (London, Birmingham, Manchester and Edinburgh) in the UK using the CIBSE current pDSY-1 2016 release. This advanced natural ventilation C-C strategy was also evaluated using the using the future projected weather data from London, Birmingham, Manchester and Edinburgh. Lastly, the work explores the effectiveness of each advanced natural ventilation strategies discussed in Figure 1 using the modelling conditions of Case 4 for all four strategies discussed earlier.

RESULTS AND DISCUSSIONS

Development of most effective case

Figure 5 (left diagram) shows the solar gains for Case 1 (the base case) without the overhang shading and Case 2 with the overhang shading for a working week in August using the current London Heathrow pDSY-1 data. From Monday to Friday the solar gain for Case 1 increases but the solar gain remains relatively stable for Case 2. The graph clearly illustrates that the overhang can effectively block the solar gains. When the overhang shading is not present, the peak daily solar gains are higher than the total internal heat gains. Figure 5 (right diagram) shows the weather conditions on these days. Monday is cloudy with relatively high diffuse radiation, Friday has clear sky with the most direct radiation. The overhang shading can block the majority of the direct solar radiation, however, for diffuse radiation its influence is limited, which is why the combined daily solar gains for the shaded case are similar (Figure 5, left). From May to September inclusive the total solar gain to the office space is 4.29MWh for Case 1, the solar gain is 2.79MWh for Case 2 with the overhang shading. The simple 1.0m overhang shading resulted a 35% reduction in solar gain for the office space.

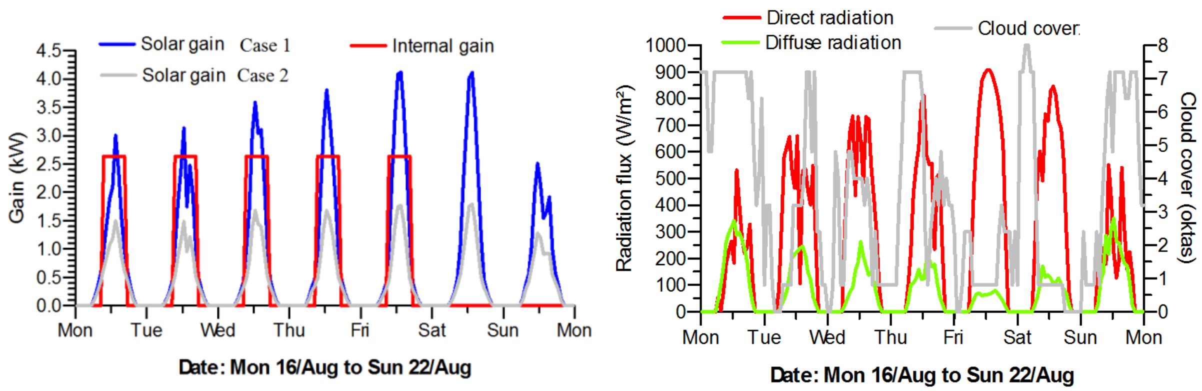

Figure 5: Left: Solar gains, and internal heat gains for Case 1 without shading & Case 2 with shading; Right: corresponding climate conditions (external solar radiation and cloud cover) of the working week.

Figure 6 shows the office operative temperatures (T_{ot}) for a week in August with London Heathrow pDSY-1 weather data. Indoor operative temperature represents a combined thermal parameter from the mean radiant temperature (T_{mrt}) and indoor dry-bulb temperature (T_{dbt}, please note the T_{dbt} on Fig 6 is the ambient dry-bulb temperature from the weather data used) which is the temperature occupants are most sensitive to. For low air movement indoor environment, the operative temperature is the average of the T_{mrt} and the indoor T_{dbt}.

It is evident from Figure 6, reducing solar gain by using shading devices does help in reducing the indoor operative temperature. T_{ot} for Case 2 is consistently (1 to 2°C) lower than Case 1. The temperature difference during weekend is relatively higher (when the office is not occupied). Without night ventilation (Cases 1 & 2), the indoor operative temperatures are relatively high: the heat loss from thermal conduction through building fabric and night-time infiltration can only bring the T_{ot} down by about 3 to 4°C. However, for Case 3 with night-time ventilation, the indoor operative temperature T_{ot} is cooled down by 7 to 8°C compared with its daytime peak; and the daytime peaks are also 2-3°C lower than Case 1 & Case 2. This indicates that the office indoor operative temperature T_{ot} with passive night-time ventilation is cooler than without night ventilation during the working hours.

The ceiling constructions can also have a noticeable influence on the office indoor operative temperature T_{ot} (Figure 6). The difference in temperature was not significant, up to 1°C or so for the days shown in Figure 6, however, when considering the annual effect on the number of hours of elevated temperatures, it is obviously notable (as shown in Figure 7). This indicates that the heavy weight ceiling can prevent a rise in the T_{ot} better than the light weight ceiling during the daytime.

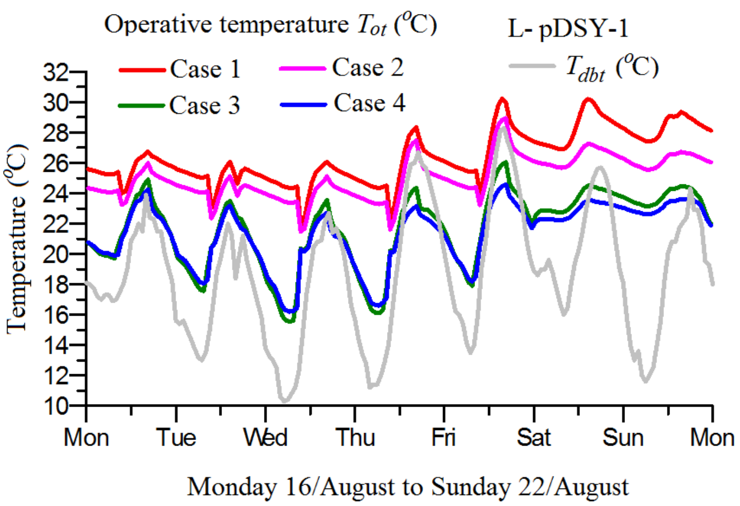

Figure 6: Comparison of operative temperatures T_{ot} for Cases 1 to 4, the outdoor dry bulb temperature T_{dbt} is plotted on the graph for reference.

Figure 7 shows the numbers of hours over temperatures for the Case 1 to 4 discussed in this research. It is evident that the overhang shading, night ventilation and heavy weight construction all helped in mitigating the elevation of the indoor operative temperature. The influence of the heavy weight ceiling is more noticeable in the temperature range of 25 to 26°C, but when the limiting temperature is 28°C or over, the difference becomes less notable between the lightweight and heavyweight ceiling constructions.

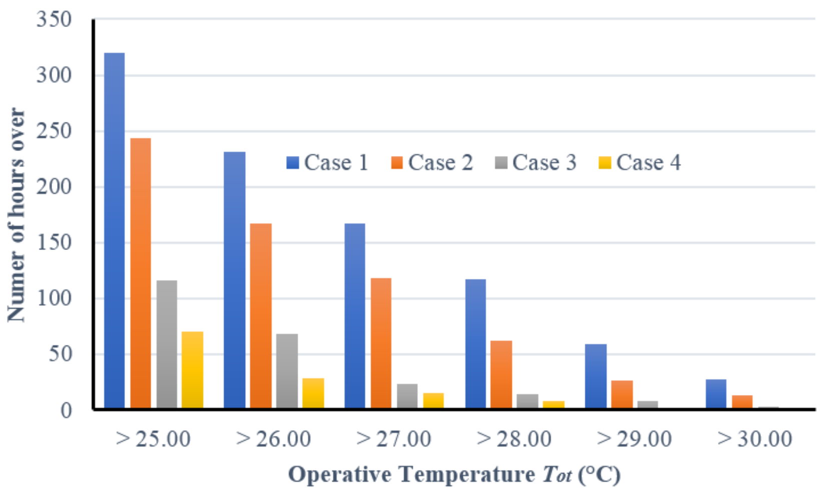

Figure 7: The number of hours over temperatures for Case 1 to 4 for E-E strategy using the current London Heathrow pDSY-1 weather data.

When using the single temperature overheating criterion (number of hours over 28°C) from CIBSE Guide A (2006) to judge overheating, Case 3 with the light weight ceiling resulted 19 hours over 28°C and Case 4 with the heavy weight ceiling has 14 hours over 28°C; with the E-E strategy and night-time ventilation, both Case 3 and Case 4 satisfy the single temperature over heating criterion using the current pDSY-1 at London Heathrow.

Design for different locations in the UK

Case 4 with E-E strategy (with overhang shading, night cooling and a heavy weight ceiling) was further evaluated for four locations in the UK: London, Birmingham, Manchester and

Edinburgh, using CIBSE current release DSY weather data (for London, out of the three stations, only Heathrow weather data were used). Figure 8 shows the predicted number of hours for which the indoor operative temperatures T_{ot} exceeded various values. Using the CIBSE single temperature criterion, overheating is only observed for London but not for any other of the locations examined. The indoor operative temperature T_{ot} was never above 28°C for more than 20 hours in Birmingham, Manchester and Edinburgh. For Birmingham and Manchester, even for 'over 27°C' there were fewer than 10 hours. In Edinburgh, there is no predicted operative temperatures T_{ot} over 25°C using Case 4 developed earlier. In the northern part of the country, smaller ventilation openings may be used without getting the space overheated, for example, 1.0% instead of 1.5% used in this research, and in Edinburgh advanced natural ventilation may not be necessary and simple natural ventilations (i.e. opening windows) can be adequate to maintain interior comfort thermal conditions.

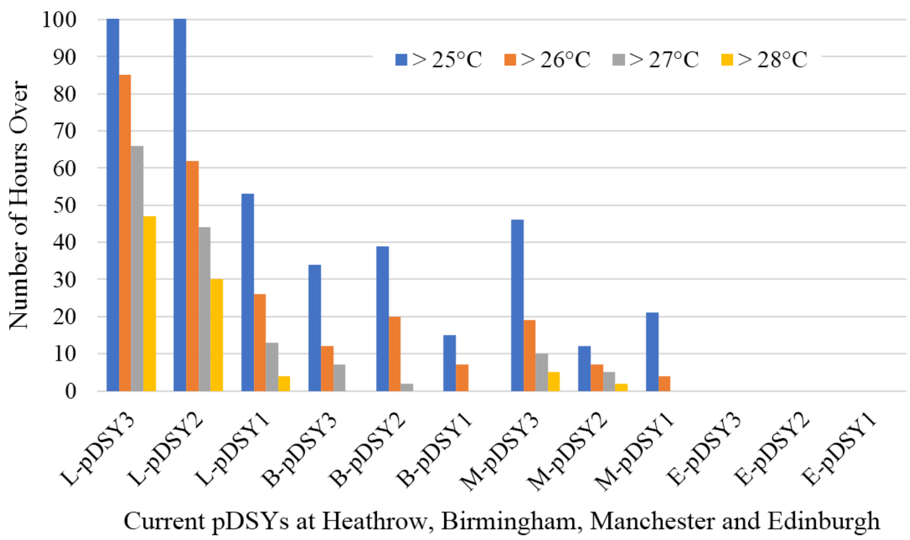

Figure 8: The predicted number of hours over temperatures for Case 4 with E-E strategy at four locations in the UK: CIBSE current pDSYs weather data 2016 release were used

Future performance of ANV

Using the single temperature criterion from CIBSE Guide A (2006), Case 4 with E-E strategy was further examined using the future projected weather data for London, Birmingham, Manchester and Edinburgh. The future weather data of the years 2020, 2050 and 2080 were used (CIBSE weather data 2016 release, see Methodology section).

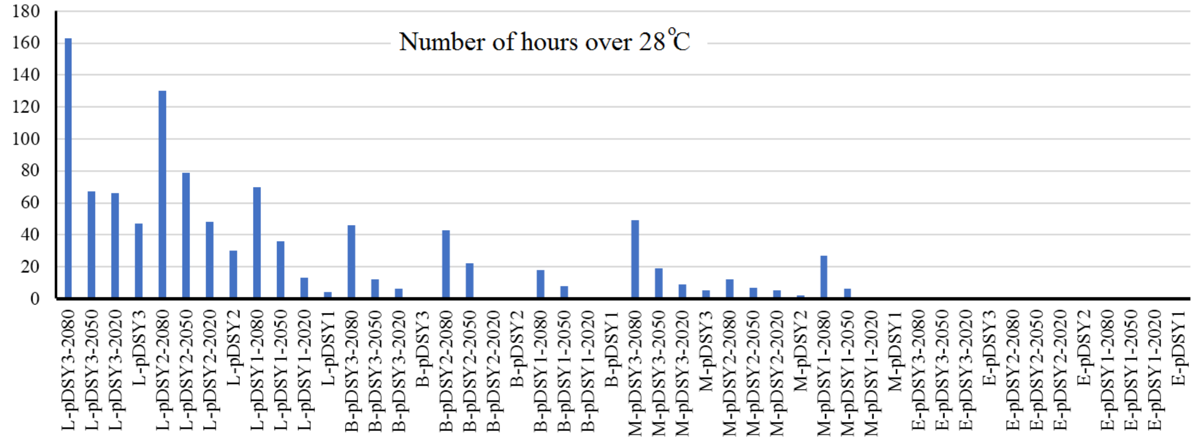

Figure 9: The predicted number of hours the internal operative temperature over 28°C using the current and future DSYs for London, Birmingham, Manchester and Edinburgh.

Figure 9 shows the number of hours over 28°C with all three probabilistic pDSYs at 4 geographic locations in the UK. In Edinburgh, the design will not have overheating concern in the future using this criterion. While for Manchester and Birmingham, only after 2050 will overheating concern become an issue. For London Heathrow climate, the overheating concern is imminent. The Case 4 design only meets the criterion with the ‘moderate warm summer’ – the pDSY-1, while for pDSY-2 & pDSY-3, the design will be judged as overheating even at the current weather condition; and with the future scenarios, London Heathrow will be overheated if no mitigation measures are put in place.

Table 3 shows the likely thermal performance of Case 4 using the adaptive thermal comfort criteria. The examined period is from May to September inclusive. Criteria 1 is to assess the overheating occurrence – the hours of exceedance H_e during May to September inclusive shall not be more than 3% of occupied hours. In all four geographic locations when considering both current and future pDSY weather data, the design failed to meet the Criteria 1 for three weather conditions: L-pDSY2-20520, L-pDSY2-2080, L-pDSY3-2080. Criteria 2 assesses the overheating severity by counting the daily weighted exceedance, it is more stringent as there are 8 weather years the design failed to meet this Criteria 2. For ‘a moderate warm summer’, Case 4 design will fail Criteria 2 towards 2080 (L-pDSY1-2080); for “a more intense single warm spell’ weathers, Criteria 2 was failed for both current and future weather conditions; and for weather years which have ‘a long period of persistent warmth”, the three future projected weather years failed to meet Criteria 2 criterion but the current L-pDSY3 weather passes. The Criteria 3 also assesses the overheating severity, but its target on the maximum indoor and outdoor temperature difference is a much more relaxed criterion among the three criteria of the adaptive thermal comfort approach. With both current and future DSY weather data at the four locations considered in this research using Case 4 model, none failed to meet this criterion. Using the adaptive thermal comfort overheating criteria, only when two out of the three criteria failures to be met then the design is judged as overheating. In Table 3, those three weather years that failed criteria 1 and 2 are L-pDSY2-20520, L-pDSY2-2080, L-pDSY3-2080.

The single temperature criterion (2nd column of Table 3) is included for reference only (although it was calculated over a year, this parameter remained the same when it is calculated from May to September, indicating there is no number of hours over 20°C outside these months for Case 4). This single temperature overheating criterion is broadly consistent with the adaptive thermal comfort approach in assessing overheating, for example, those cases that failed to meet the adaptive thermal comfort overheating criteria has large ‘number of hours over 28°C’, such as L-pDSY3-2080 with 163 hours (while the target is only 20 hours). The Case 4 design failed to meet the single temperature criterion for all the weather years listed in Table 3. However, using the adaptive thermal comfort overheating criteria, only three of these weather years, the design failed. It is evident that the adaptive thermal comfort approach overheating criteria do provide a more relaxed approach in guiding natural ventilation design in practice, it is relatively easier to meet these criteria than the single temperature criterion.

Where NV or ANV strategies fail to meet the indoor thermal comfort criteria, other solutions may be suggested to mitigate the potential overheating in buildings. Examples of such design are the design of Judson College Library in the United States (Lomas et al 2007) and the design of the Science and Technology Museum Building in South China (Ji et al 2009). For both cases, a hybrid design with both natural ventilation and mechanical cooling was used. The passive ANV approach is used during the mid-seasons where the outdoor climate condition allows the ANV system to maintain the indoor thermal comfort, while during the hot seasons, operating the mechanical cooling system to combat the hottest conditions.

Table 3: Examining the likely overheating using current and future weather data for Case 4 (light shaded rows failed to meet the CIBSE TM52 (2013) *adaptive overheating criteria for Category II requirement from BS EN 15251 (2007)).*

Weather years	>28(°C), target < 20 hours	Occupied days (%)	Criteria 1 target < 3%	Criteria 2 target < 6 deg. hours	Criteria 3 target <4K	Failed Criteria
L-pDSY3-2080	163	71.2	6.2	15	3	1 & 2
L-pDSY3-2050	67	71.2	2.4	8	2	2
L-pDSY3-2020	66	71.2	2.3	8	2	2
L-pDSY3	47	71.2	0.8	4	1	-
L-pDSY2-2080	130	71.2	4.9	24	4	1 & 2
L-pDSY2-2050	79	71.2	3.3	17	3	1 & 2
L-pDSY2-2020	48	71.2	2.3	13	3	2
L-pDSY2	30	71.2	1.4	8	2	2
L-pDSY1-2080	70	71.2	1.5	9	2	2
L-pDSY1-2050	36	71.2	0.8	4	1	-
L-pDSY1-2020	13	71.2	0.1	1	1	-
B-pDSY3-2080	46	71.2	0.7	3	1	-
B-pDSY2-2080	43	71.2	0.2	1	1	-
B-pDSY1-2080	18	71.2	0.2	1	1	-
M-pDSY3-2080	49	71.2	1	4	1	-

M-pDSY3-2050	19	71.2	0.2	2	1	-
M-pDSY2-2080	12	71.2	0.7	10	2	2
M-pDSY2-2050	7	71.2	0.5	4	1	-
other years*	-	71.2	0	0	0	-

*other years are those years all three criteria show 0 values, overheating is unlikely to happen, L, B, M here means London (Heathrow), Birmingham & Manchester. E (Edinburgh) is not included as the calculated values for the three criteria for all the weather years from Edinburgh are 0.

The ANV effectiveness in space conditioning

With the same modelling conditions (1.0 m overhang shading, night ventilation, heavy weight ceiling construction, and the London Heathrow pDSY-1 a moderate warm weather), the effectiveness of the four ANV strategies was evaluated by using number of hours over various temperatures. The simulation results showed that the two Centre-in strategies (C-C & C-E) performed better than Edge-in strategies (E-C & E-E), as shown in Figure 10 (left diagram). The number of hours over 26°C or higher, all four strategies performed similarly. With lower temperatures such as 24°C, 25°C etc, the difference becomes obvious.

For the Centre-in strategies, the incoming air will flow through an under-floor plenum, the extended flow path increased the interaction between incoming air and the constructions, longer airflow path will also increase flow resistance. These factors will influence the volume flow and the temperature of the air entering the offices. This kind of plenum has been adopted with success, i.e. the Braunstone Health Centre (Cook & Short, 2005). In principle, the plenum adds extra thermal mass which can help smoothing the temperature swings of the incoming fresh air. The temperature of the air in the plenum tends to be reduced to some extent compared with outdoor air temperature, this is evidenced in Figure 10 (right diagram). However, the extra airflow resistance from the plenum can decrease the amount of airflow. The true nature of such system warrants further investigation in terms of its cooling potentials to the office spaces. For the cases considered in this research, the plenum does help mitigating the indoor operative temperature elevation.

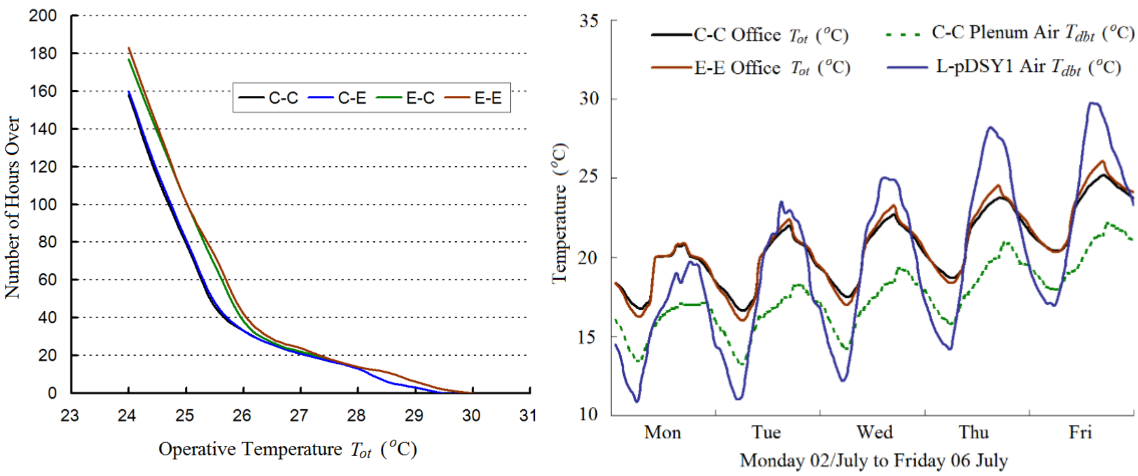

Figure 10: Left: the predicted number of hours over operative temperatures for all four ANV strategies; Right: office operative temperatures for E-E and C-C strategies and the plenum air temperatures.

Discussions on accuracy of model predictions

The results and observations discussed earlier are based on the numerical calculations of the building models used in this manuscript. Many of the findings are based on the predication of the indoor parameters such as temperature. How accurate such predictions can be in practice is often prone to query and scrutiny. Without physical measurements to validate such predictions it is always difficult to make an unbiased judgement.

Dynamic thermal model validations have always been a challenging subject as it is difficult to represent the complexity of boundary conditions in an open environment, i.e. a building, on site, exposed to the natural environment. Instead, the typical approach was to use benchmark cases to verify the consistency of such models. Such approaches include the benchmarking settings from CIBSE TM33 (2006) and ASHRAE140 (2011). IESVE went through the verification process in accordance with ASHRAE 140, published a report to illustrate the performance of this dynamic simulation tool (IESVE report 2004). The report shows that IES is consistent with other well known dynamic thermal modelling tools.

IESVE has been extensively used in modelling dynamic thermal responses of buildings and there has been attempts in terms of model validation (Strachan et al 2015, Ji et al 2019a). Discrepancies do often exist, however, for comparative studies (i.e., this research), IESVE has been consistent (Ji et al 2019b). The typical use of this tool without validation is the compliance calculation for school buildings by following the Building Bulletin 101 guidance document, where the modelling outputs are used without validation (Ji et al 2018).

CONCLUSIONS

In this paper, dynamic thermal simulation tools were used to evaluate the thermal performances of advanced natural ventilation (ANV). Four different ANV strategies were integrated in to a hypothetical design. The effective modelling case was developed using the Edge-in/Edge-out strategy with the current Heathrow pDSY-1 weather data. This effective model with Edge-in/Edge-out strategy was then used to examine the risk of overheating in four cities across the UK: London, Birmingham, Manchester and Edinburgh under the current and future climates of the UK:. The context of the paper focused on how architecture design alterations can influence building thermal performances, and in the UK the ANV design practices have been viewed as a way towards a more sustainable architecture engineering in the future.

The evidence from the model predictions confirm that the use of overhang shading, night time cooling and heavyweight ceilings can mitigate the elevation of indoor operative temperatures in the summer, which is consistent with what is expected in existing design practices. Overall, shading and night time cooling had greater potential to reduce the internal operative temperatures than the structure thermal mass - the heavy weight ceiling. The heavy weight ceiling had a relatively large influence when office operative temperatures are around 25°C to 26°C. From this research it is evident that the given design with advanced natural ventilation can adapt to the future climate conditions in the northern part of the UK. With the current climate conditions, the design will pass both CIBSE single temperature overheating criterion and the adaptive overheating criteria. However, with the future projected weather data and the single temperature criterion, the design is mostly not able to maintain thermal comfort in London, and overheating is also evident in Manchester and Birmingham towards 2080. In Edinburgh, no overheating concern is predicted by the end of the century is observed, so decreasing the ventilation openings may still be able to maintain thermal comfort in the north due to cooler summer in the region. The adaptive thermal comfort overheating criteria are more relaxed as only three examined weather years in London out of 36 future weather years evaluated (L-pDSY2-20520, L-pDSY2-2080, L-pDSY3-2080), the design does not meet those criteria. For Edinburgh and some weather years of Birmingham and Manchester, all three criteria have zero value so there is no concern for overheating under such conditions judged by the adaptive overheating criteria.

Closer examination of the four ANV strategies indicate that the Centre-in strategies do perform better than the Edge-in strategies due to the extended thermal structure for Centre-in strategies. The outdoor air temperature can be pre-cooled by the plenum structure and ventilation routes before entering the office space, which does have a positive influence in lowering the indoor operative temperatures.

The research clearly illustrates the huge differences of overheating assessments using different overheating criteria. With the adaptive thermal comfort approach, where occupants are expected to adapt to the ever-changing climate conditions, the existing design will meet the adaptive overheating criteria for long period of time in the future, this is particularly true for the northern part of the UK. However, overheating in naturally ventilated buildings will become a concern in southern part of the UK such as in London, therefore, a hybrid approach becomes necessary in the foreseeable future.

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