Inter-model comparison of indoor overheating risk prediction for English dwellings

Giorgos Petrou[*1], Anna Mavrogianni[2], Anastasia Mylona[3], Rokia Raslan[2], Gurdane Virk[4] and Michael Davies[2]

1 UCL Energy Institute,
University College London,
Central House, 14 Upper Woburn Place
London WC1H 0NN, United Kingdom
Email: giorgos.petrou.16@ucl.ac.uk

2 UCL Institute for Environmental Design and Engineering
University College London,
Central House, 14 Upper Woburn Place
London WC1H 0NN, United Kingdom

3 CIBSE
222 Balham High Road
London SW12 9BS, United Kingdom

4 Atkins
Euston Tower, 286 Euston Rd, Kings Cross,
London NW1 3AT, United Kingdom

ABSTRACT

According to the 2016 Household Projections report, England's housing stock could reach 28 million households by 2039 with approximately one fifth being new constructions. A significant proportion of these newly built dwellings may face a high risk of overheating as a result of the combined effects of climate change and more stringent building thermal efficiency standards, if not appropriately designed. Reliable methods for predicting indoor overheating risk are required to avoid potentially negative impacts of excess indoor temperature exposure on occupant thermal comfort and wellbeing while simultaneously minimising the use of mechanical ventilation and cooling. Building Energy Simulation (BES) software are widely used in the building construction industry to estimate the overheating risk of new developments. CIBSE's recently released methodology for predicting overheating in new dwellings aims to achieve consistency between existing prediction methods currently applied by building designers and engineers. BES tools are abstract representations of reality and large differences in model outputs are often observed between tools. The level of overheating risk predicted through the CIBSE method may hence depend on the choice of software and its underlying assumptions. Such an effect could directly impact CIBSE's efforts in creating a standardised procedure across the industry. This research project utilised inter-model comparison along with sensitivity analysis to investigate the differences in overheating risk prediction between two commonly used software packages, *EnergyPlus* and *IES VE*. The sensitivity analysis resulted in a total of nine variations of the single-aspect, high-rise flat, simulated in each software. Looking at individual models, there was a general agreement between either software's predictions and the literature's suggestions on the factors that may be driving overheating. Measures such as increased thermal mass, external shading, north-facing direction and cross-ventilation lowered the predicted risk. However, discrepancies between software were observed with only two EnergyPlus models successfully meeting both overheating criteria, compared to all the IES VE models. This work therefore concludes that the choice of BES tool could greatly impact the predicted risk of overheating.

KEYWORDS

Overheating, Simulations, Inter-model Comparison, Sensitivity Analysis, Thermal Comfort

1 INTRODUCTION

Overheating qualitatively describes the condition under which occupants of a dwelling feel uncomfortably hot due to the indoor environment (CIBSE, 2013). Indoor comfort and wellbeing is crucial for human health since people spend most of their time inside buildings (WHO, 2009). Concerns regarding overheating have intensified recently. Along with the projected rise in ambient temperature, climate change is expected to cause an increase in the frequency and severity of extreme heat episodes (Murphy et al., 2009). Such events have been catastrophic in the past, with the 2003 European heatwave leading to an increase in mortality of more than 2,000 in England and Wales (Johnson et al., 2005), and nearly 15,000 in France (Fouillet et al., 2006). An increase in overheating risk may also be an unintended consequence of current building regulations due to the increased levels of thermal insulation and airtightness required (HMG, 2016; Shrubsole et al., 2014).

An important step in mitigating overheating is its accurate and systematic prediction (ZCH, 2015). To encourage the design of thermally comfortable homes, the Chartered Institution of Building Services Engineers (CIBSE) has recently released the Technical Memorandum 59 (TM59), a new methodology for the application of Building Energy Simulation (BES) software to predict the overheating risk in new homes (CIBSE, 2017). Although such software have powerful dynamic modelling capabilities, they are still limited by their core assumptions. Given the exact same inputs, two BES tools may generate different predictions of building energy and thermal performance due to their algorithmic differences (R. Judkoff & Neymark, 1995; Crawley et al., 2008; Raslan, 2010).

EnergyPlus and IES VE are two commonly used BES tools in academic research and the construction industry (EnergyPlus, 2017a; IES VE, 2017a). They have both been validated and verified in the past (EnergyPlus, 2017b; IES VE, 2017b). One of the most commonly used testing procedures is the Building Energy Simulation Test (BESTEST) (R. Judkoff & Neymark, 1995). This is a structured method of comparison between software on progressively more complex models. A set number of models with predefined inputs are simulated in BES tools and a comparison of the results indicates the differences in the simulation engines. This method is now the basis of the ANSI/ASHRAE 140 standard (Ron Judkoff & Neymark, 2006). Although this assessment has aided in the identification and subsequent resolution of many internal errors, no such comparative procedure has focused on overheating. However, an important finding with regards to overheating emerges from the most recently published BESTEST results for IES VE and EnergyPlus: for many of the models tested, the maximum and average temperature predicted by EnergyPlus was greater than for IES VE by more than 1 ºC (EnergyPlus, 2017b; IES VE, 2017b).

This has motivated the work presented in this paper, which aims to establish how the choice of BES tool may impact the overheating assessment. In particular, it aims to quantify and analyse potential discrepancies between EnergyPlus and IES VE for a typical English dwelling archetype. This is achieved by evaluating the overheating risk for both software under different input variations. Through this process, useful conclusions on the implementation of CIBSE's new methodology are drawn, which may also inform and motivate further research in the prediction of overheating risk.

2 LITERATURE REVIEW

CIBSE TM52 suggested three methods for predicting overheating risk (CIBSE, 2013): (i) Building Energy Simulations (BES), (ii) monitoring, (iii) questionnaire surveys. All three methods may be used for existing buildings but only the BES method can be employed to predict the overheating risk in new dwellings. For predominantly naturally ventilated homes, compliance is based on successfully meeting the following two criteria (CIBSE, 2017):

1. The number of hours for which $\Delta T = T_{op} - T_{max}$ is greater or equal to one degree Celsius during the period May to September, inclusive, should not exceed 3% of the occupied hours (hours of exceedance).
2. The bedroom's operative temperature (T_{op}) should not exceed 26ºC for more than 1% of the annual occupied hours (22:00-07:00). This is equivalent to 32 hours in a year.

Operative temperature (T_{op}) is the weighted mean of the room's air and radiant temperature (CIBSE, 2015). T_{max} is the maximum acceptable comfort temperature based on the thermal comfort model presented in (CIBSE, 2013). In the case of vulnerable occupants or predominantly mechanically ventilated dwellings, the criteria are slightly modified (CIBSE, 2013, 2017).

2.1 Overheating

Previous modelling studies are generally in agreement with respect to the determinant factors of building overheating. Hacker et al. (Hacker et al., 2008) established that an increase in thermal mass leads to more stable temperatures and a lower risk of overheating. Mavrogianni et al. (Mavrogianni et al., 2009) identified the dwelling's floor level to be a key factor, with an increase of 50% in the likelihood of heat-related death for the tallest buildings compared to the average in height buildings in London. Taylor et al. (Taylor et al., 2014) demonstrated that the building's orientation is greatly influential on overheating. In a more recent study, Mavrogianni et al. (Mavrogianni et al., 2017) identified internally positioned wall and floor insulation to be positively correlated with high indoor temperatures, while occupant behaviour was recognised as another highly influential factor for overheating. This was also recognised in an empirical validation study of an overheating model by Symonds et al. (Symonds et al., 2017). The importance of natural ventilation as a preventive measure of overheating was discussed by Porritt et al. (Porritt et al., 2012), who identified controlled natural ventilation, especially night-cooling, to be particularly important.

2.2 Sensitivity Analysis and Inter-model comparison

Sensitivity analysis is a valuable method of establishing the effect of inputs on key outputs (Tian, 2013). This method has been employed in the past in the field of overheating to determine some key factors of overheating homes (Mavrogianni et al., 2014; Mavrogianni et al., 2017) or to calibrate BES models (Pereira, Bögl, & Natschläger, 2014). In its simplest form, Local Sensitivity Analysis (LSA) is performed by varying one factor at a time and observing its impact on the output of interest (Tian, 2013). Statistical analysis may then be used to quantify its importance.

Inter-model comparison is a structured way of establishing disagreements between software (Raslan, 2010). The same input is compiled for both software and used to create the closest possible models. Following the simulation, the output is compared and analysed to determine the level of agreement.

3 METHODS & METHODOLOGY

An inter-model comparison was performed in parallel to an LSA to determine differences in predictions for nine variations of the base case (BC), as described in Table 1. For each model, the statistical significance of the difference in the mean operative bedroom temperatures between the two software was assessed using a two-tailed t-test, with the null hypothesis being that temperatures should be similar within a 95% confidence interval.

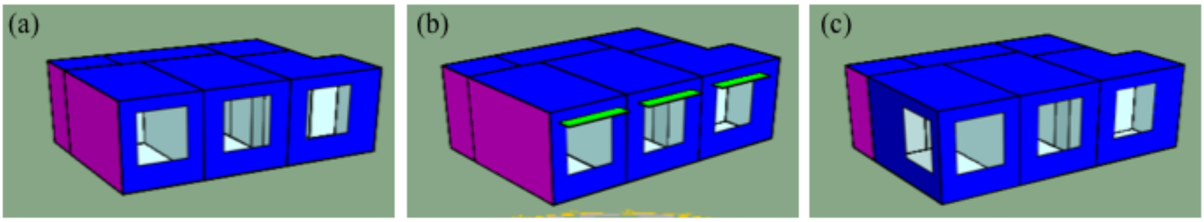

Figure 1: Visualisations of the base case (a), case with external shading (b) and the dual aspect case (c) using the IES VE Model Viewer II.

The base case (Figure 1) dwelling is a naturally ventilated, free-running, single aspect, top-floor flat originally created by Oikonomou et al. (Fig.2, Model VII Oikonomou et al., 2012). The thermal properties of the building's fabric and windows complied with the most recent building regulations for new builds (HMG, 2016). Infiltration rate was kept constant for all models, based on an air permeability of 5.0 $m^3/(h.m^2)$, with an added air exchange of 13 $l.s^{-1}$ for the kitchen and 8 $l.s^{-1}$ for the bathroom (HMG, 2013, 2016). The Design Summer Year 1 CIBSE Weather File was used, with the specified location being the London Weather Centre (CIBSE, 2017). The internal gains for a double bedroom flat with separate living room and kitchen were modelled as instructed in TM59 (CIBSE, 2017). Throughout the day, TM59 requires the opening of windows when the internal temperature of an occupied room exceeds 22 ºC. Although EnergyPlus will model the opening of windows when a threshold is exceeded, it will only do so if the internal temperature is higher than the external. As ventilation was expected to be a critical factor, IES VE was set to operate windows in a similar manner as EnergyPlus. Internal doors were modelled to be open only during the waking hours (08:00-23:00). The bedroom was occupied at all times, while the kitchen and living room were modelled as occupied between 09:00-22:00.

Table 1: A summary of the different variations of the basic model simulated.

Code	**Description**
BC	Floor level: 11.2 m, orientation: south facing, single aspect, top level flat, Lightweight construction: Timber frame, external brick layer and internal plasterboard U-values: Wall – 0.17 W/m^2K, window – 1.28 W/m^2K, floor – 0.18 W/m^2K, roof – 0.13 W/m^2K
G	Ground-Level Flat, floor Level: 0 m, flat of similar temperature above
M	Mid-level flat, floor level: 5.6 m, flats of similar temperature above and below
W	West-facing flat
N	North-facing flat
E	East-facing flat
HW	Heavyweight construction: Concrete blocks, external brick layer, internal dense plaster and carpet
SH	Shading: Overhang external shading, length of 2.2 m and width of 0.5 m over windows
DA	Dual aspect model with a second window included in the bedroom

4 RESULTS

Following the methods described in section 3, the overheating risk was evaluated for all models and is presented in Figure 2. A simple inspection reveals the discrepancy in predictions between the two software, with only two out of the nine models passing both TM59 criteria for EnergyPlus, contrary to the success of every model simulated in IES VE. In general, overheating risk does appear to increase with floor level for both software. Orientation also appears to be a driving factor of overheating in both software, as suggested

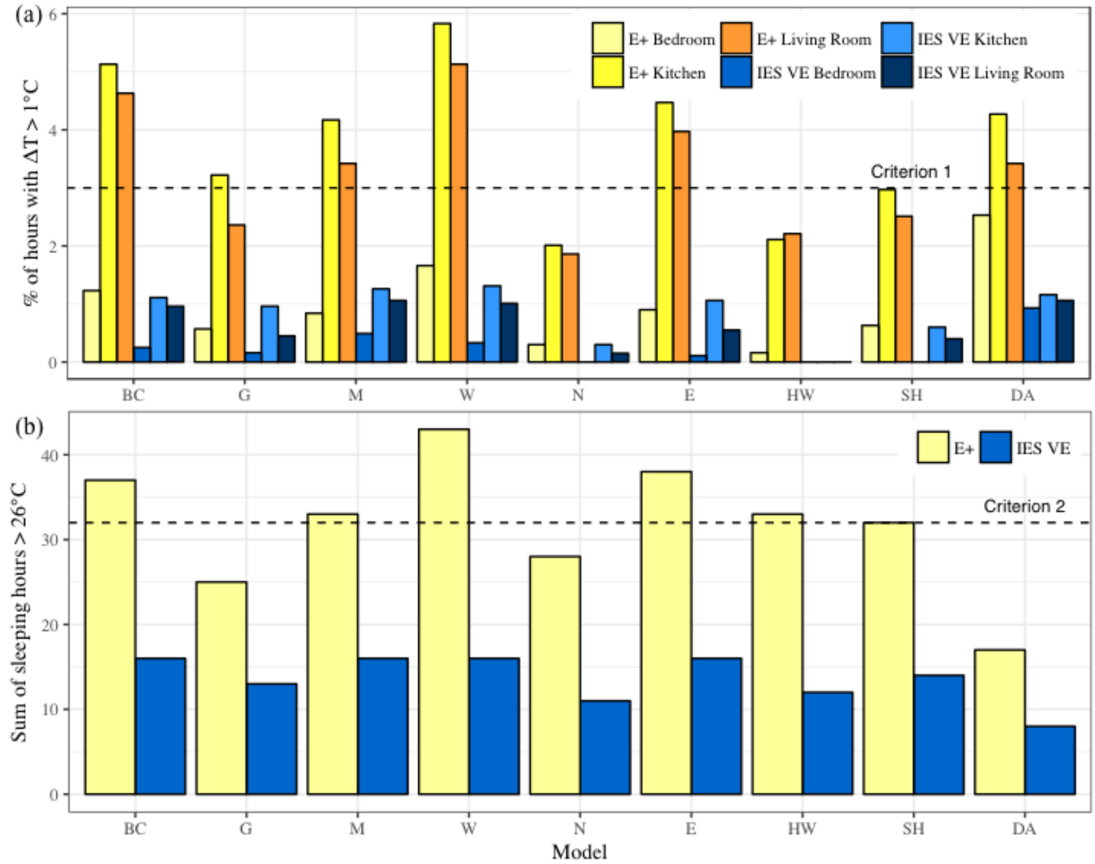

Figure 2: Parts (a) and (b) display the results of criterion 1 and 2 for all models, respectively. A high overheating risk is suggested for any model that surpasses either criterion line.

by the literature. North-facing flats succeed in meeting both criteria, with this model having the lowest risk of overheating for EnergyPlus. On the contrary, the west-facing flats appear to be the most prone to overheating between all other choices modelled. The increase of thermal mass resulted in the decrease of overheating risk for both software, with EnergyPlus passing the first criterion but failing the second. The equivalent model in IES VE recorded no hours above the T_{max} and successfully reduced the hours recorded for criterion 2. External shading played an important role in overheating for both software, especially for criterion 1. Its inclusion has led to the approximate halving of all hours of exceedance for either software, with the bedroom in IES VE recording no temperatures above T_{max}. As could be expected, its effectiveness diminishes for criterion 2. The increased solar gains in the dual-aspect flat increased the hours of exceedance in the bedroom by more than two times in EnergyPlus and more than three times in IES VE. However, the hours of exceedance in all other rooms and the hours recorded for criterion 2 have decreased. This may be attributed to the increased ventilation and cooling rate associated with cross-ventilation.

Figure 3 illustrates the distribution of operative temperatures for each model iteration in both softwares. The median temperatures predicted by EnergyPlus are in all cases greater than those in IES VE. Similar changes in the distributions of either software can be noticed for every model iteration. Another important observation is that overall and for individual cases, there is a greater spread in indoor temperatures for EnergyPlus models, suggesting greater fluctuations in temperature. The mean Interquartile Range (IQR) is 2.23 ± 0.06 ºC for EnergyPlus and 1.58 ± 0.05 ºC for IES VE. For both software, the North-facing model iteration shows the smallest IQR with the heavyweight iteration following closely. In EnergyPlus, the greatest IQR is seen in the basic case while for IES-VE it is the dual aspect

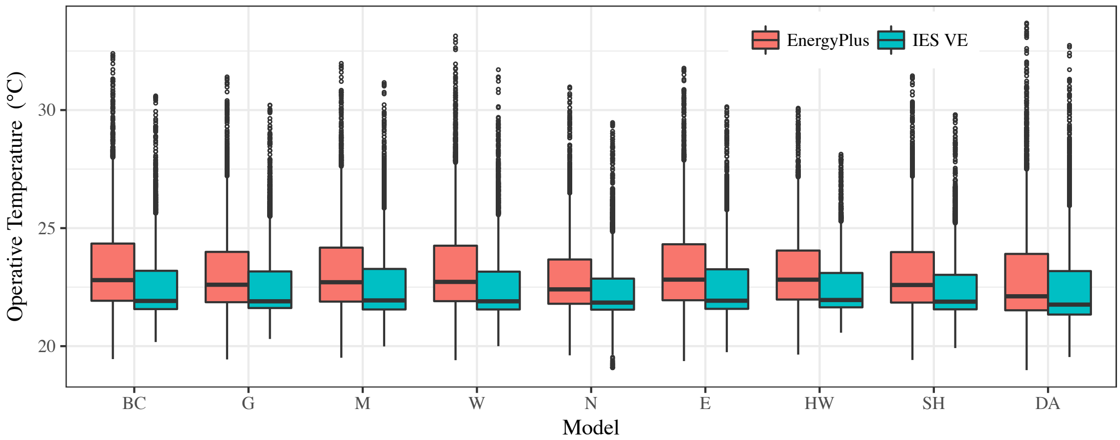

Figure 3: Box Plot of hourly averaged bedroom operative temperatures for the whole period of interest. The points above the upper whisker suggest a significant degree of positive skewness.

flat. Statistically significant differences in the mean bedroom temperature between the two software were found at the 5% significance level for all nine model iterations.

Operative temperature time series graphs allow the better understanding of the behaviour of certain model iterations during the warmest 15 days of the weather file (Figure 4). The rate of change of indoor temperatures appear similar between software. For the base case, the mean temperature difference between the two software is 1.16 ± 0.02 ºC. Contrasting the base case with the dual aspect models demonstrates a clear increase in the peak bedrooms temperature of the dual aspect flats on most days. Similarly, there is a decrease in the minimum temperatures reached. Both software predicted temperatures above 32 ºC, with EnergyPlus predicting a maximum temperature of 33.7 ºC. This was more than 4 ºC above the day's estimated T_{max}. On the same day, temperatures above 33 ºC persisted for five consecutive hours in EnergyPlus. The maximum temperature predicted by IES VE was 32.7 ºC. Furthermore, it may also be noted that the software are now in closer agreement, with a mean temperature difference of 0.79 ± 0.02 ºC. This may possibly be attributed to similar effects of cross-ventilation on the indoor temperatures of either software. Looking at the heavyweight construction, the increase in thermal mass parameter has resulted in smaller temperature fluctuations for both software. Comparing the base case with the heavyweight iteration for each software shows that the increase in thermal mass had a more significant effect in IES VE than EnergyPlus, with the mean temperature difference increasing to 1.25 ± 0.02 ºC.

5 DISCUSSION

The findings presented above suggest that the choice of BES tool is critical to the estimation of overheating risk, with the software disagreeing on the predicted risk of overheating in seven out of the nine cases. Due to the non-linear interaction of the many factors influencing the internal environment of the modelled flats, it is currently unclear why this level of disagreement exists. However, a few generic suggestions could be made with the way natural ventilation is modelled in each software being possibly crucial. EnergyPlus calculates the wind pressure coefficients depending on the building's geometry and location while IES VE has stored coefficients which depend on the opening's height and exposure (EnergyPlus, 2015; IES VE, 2015). The levels of agreement for this factor seem to depend on the existence of single-sided or cross ventilation, as seen in Figure 4. From the same figure, it can be suggested that the modelling of thermal mass could also be an important factor for the observed differences. Other possible causes may include the simulation of solar and conductive gains.

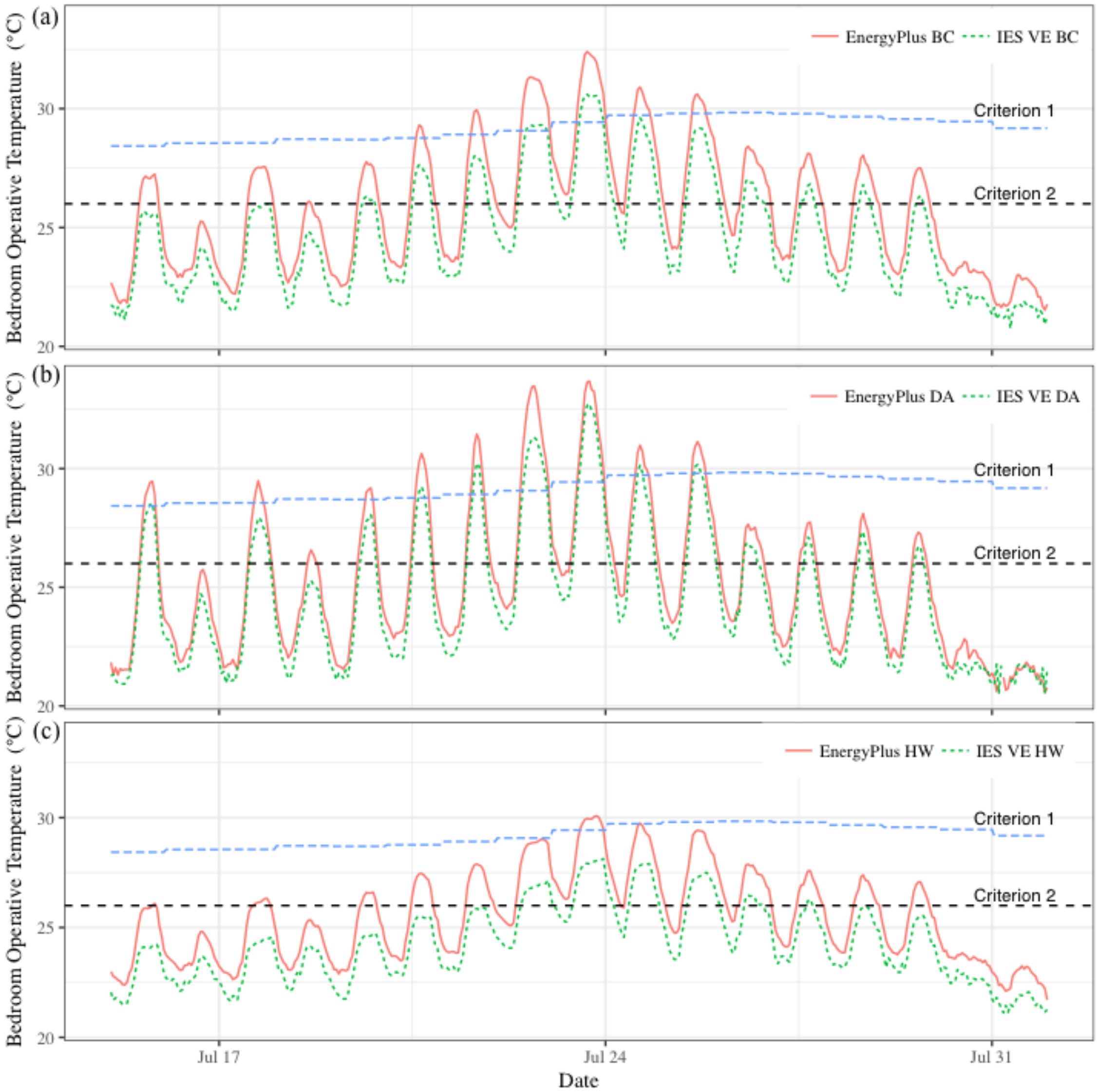

Figure 4: A comparison between the hourly estimated bedroom operative temperatures of the base case (a), the dual aspect flat (b) and the heavyweight construction flat (c). The bedroom operative temperature range was set to be equal for all three parts.

The sensitivity analysis results are in agreement with the findings of existing literature with regards to the inputs identified to be important for overheating. Features such as high thermal mass, north-facing orientation, external shading and secondary window in a single zone may all significantly help reduce the overheating risk. However, care should be taken when applying such measures and evaluating risks based only on the two suggested criteria. Dual-aspect flats with a S-W orientation have resulted in a significant increase in indoor temperatures of bedrooms during the day and decrease during the night. This is due to the additional solar gains dominating the increased cooling from cross-ventilation during the day. However, the model benefits from the addition of the secondary window overnight. Although single-aspect flats are expected to be at a higher risk of overheating due to the reduced ventilation cooling (ZCH, 2015), this research recommends that S-E or S-W facing dual aspect flats should also be tested if present in the building being investigated. Another possible concern that arises involves heavyweight constructions that may not be sufficiently ventilated, as shown by the predicted high overnight indoor temperatures.

This work has also demonstrated the levels of uncertainty that are involved in the prediction of overheating risk. Overall, the choice of BES tool appears to be a determinant factor in the overall prediction of overheating risk, which may depend on software default hardcoded assumptions that are not always transparent. In addition, a modeller may choose from a number of options the way certain physical processes will be simulated within the software, directly influencing the end prediction. Finally, the parameters which describe the dwelling along with its occupation pattern should be known and inputted accurately in order to minimise external errors (Imam, Coley, & Walker, 2017). As the prediction of overheating risk involves absolute limits, it may be the case that a combination of all these errors could lead to the passing or failing of the criteria. This indicates that modellers should not consider the criteria as simply a binary indicator where every successful result is of equal merit. Taking into account the uncertainties involved in building overheating modelling, a more nuanced approach towards the interpretation of overheating risk predictions and mitigation actions may need to be adopted by building modellers and designers.

5.1 Limitations and Future Work

This work identified appreciable differences in the prediction of overheating between IES VE and EnergyPlus and offered preliminary interpretations of their causes. As part of ongoing work, a more thorough investigation of algorithmic differences between the software examined will identify the source of these discrepancies. However, empirical validation is needed in order to determine which software's predictions are closer to reality. In addition, although the local sensitivity analysis performed in this paper allowed for the direct comparison of the software, this work was limited by not investigating the interaction of inputs. For this purpose, future work will involve global sensitivity analysis techniques.

It should be highlighted that this work did not aim to establish the effectiveness of the suggested criteria in predicting thermally uncomfortable environments in dwellings. Such endeavour would be of great interest and importance but was out of the scope of this research.

6 CONCLUSIONS

This work aimed to quantify the differences in the prediction of overheating risk between two commonly used software, IES VE and EnergyPlus. Modelling inputs identified in the literature as being key overheating factors were varied. An inter-model comparison procedure was run in parallel with local sensitivity analysis, generating nine models within each software. When analysed using the CIBSE TM59 criteria, the results suggested a significant discrepancy between the two software for all models. EnergyPlus predicted a failure in one or both of the criteria in seven model iterations out of nine, while IES VE predicted passing the criteria for all models. Within each software, the factors expected to increase the risk of overheating agreed to a satisfactory level with the literature. Further work is required to determine the exact causes for the observed differences and to establish a truth standard by empirically validating either software's prediction.

7 ACKNOWLEDGEMENTS

This research was made possible by support from the EPSRC Centre for Doctoral Training in Energy Demand (LoLo), grant numbers EP/L01517X/1 and EP/H009612/1 and the Chartered Institution of Building Services Engineers. We would also like to thank Ms Eleni Oikonomou for providing the characteristics for a base case model.

8 REFERENCES

CIBSE. (2013). *The limits of thermal comfort: avoiding overheating in European buildings,TM52: 2013*. London: Chartered Institution of Building Services Engineers.

CIBSE. (2015). *Guide A, Environmental Design*. London: Chartered Institute of Building Services Engineers.

CIBSE. (2017). *Design methodology for the assessment of overheating risk in homes, TM59: 2017*. London: Chartered Institution of Building Services Engineers.

Crawley, D. B., Hand, J. W., Kummert, M., & Griffith, B. T. (2008). Contrasting the capabilities of building energy performance simulation programs. *Building and Environment*, *43*(4), 661–673.

EnergyPlus. (2015). *EnergyPlus Engineering Reference Guide*.

EnergyPlus. (2017a). EnergyPlus. Retrieved 22 May 2017, from https://energyplus.net

EnergyPlus. (2017b). Testing and Validation. Retrieved 22 May 2017, from https://energyplus.net/testing

Fouillet, A., Rey, G., Laurent, F., Pavillon, G., Bellec, S., Guihenneuc-Jouyaux, C., … Hémon, D. (2006). Excess mortality related to the August 2003 heat wave in France. *International Archives of Occupational and Environmental Health*, *80*(1), 16–24.

Hacker, J. N., Saulles, T. P. D., Minson, A. J., & Holmes, M. J. (2008). Embodied and operational carbon dioxide emissions from housing: A case study on the effects of thermal mass and climate change. *Energy and Buildings*, *40*(3), 375–384.

HMG. (2013). *The Building Regulations 2010 incorporating 2010 and 2013 amendments - Approved Document F1 Means of Ventilation*. London: NBS.

HMG. (2016). *Conservation of fuel and power in new dwellings. Building Regulations Approved Document L1A*. London: NBS.

IES VE. (2015). MacroFlo Calculation Methods. Retrieved 22 May 2017, from http://www.iesve.com/downloads/help/Thermal/Reference/MacroFloCalculationMethods.pdf

IES VE. (2017a). IES VE. Retrieved 22 May 2017, from https://www.iesve.com

IES VE. (2017b). Software Validation. Retrieved 22 May 2017, from https://www.iesve.com/software/software-validation

Imam, S., Coley, D. A., & Walker, I. (2017). The building performance gap: Are modellers literate? *Building Services Engineering Research and Technology*, *38*(3), 351–375.

Johnson, H., Kovats, R. S., McGregor, G., Stedman, J., Gibbs, M., & Walton, H. (2005). The impact of the 2003 heat wave on daily mortality in England and Wales and the use of rapid weekly mortality estimates. *Euro Surveill*, *10*(7), 168–171.

Judkoff, R., & Neymark, J. (1995). *International Energy Agency building energy simulation test (BESTEST) and diagnostic method*.

Judkoff, R., & Neymark, J. (2006). Model validation and testing: The methodological foundation of ASHRAE Standard 140. In *Transactions-American Society of Heating Refrigerating and Air Conditioning Engineers* (Vol. 112, p. 367). ASHRAE; 1999.

Mavrogianni, A., Davies, M., Chalabi, Z., Wilkinson, P., Kolokotroni, M., & Milner, J. (2009). Space heating demand and heatwave vulnerability: London domestic stock. *Building Research & Information*, *37*(5–6), 583–597.

Mavrogianni, A., Davies, M., Taylor, J., Chalabi, Z., Biddulph, P., Oikonomou, E., … Jones, B. (2014). The impact of occupancy patterns, occupant-controlled ventilation and shading on indoor overheating risk in domestic environments. *Building and Environment*, *78*, 183–198.

Mavrogianni, A., Pathan, A., Oikonomou, E., Biddulph, P., Symonds, P., & Davies, M. (2017). Inhabitant actions and summer overheating risk in London dwellings. *Building Research & Information*, *45*(1–2), 119–142.

Murphy, J., Sexton, D., Jenkins, G., Boorman, P., Booth, B., Brown, K., … Kendon, E. (2009). *UKCP09 Climate change projections*. Exeter: Met Office Hadley Centre.

Oikonomou, E., Davies, M., Mavrogianni, A., Biddulph, P., Wilkinson, P., & Kolokotroni, M. (2012). Modelling the relative importance of the urban heat island and the thermal quality of dwellings for overheating in London. *Building and Environment*, *57*, 223–238.

Pereira, W., Bögl, A., & Natschläger, T. (2014). Sensitivity Analysis and Validation of an EnergyPlus Model of a House in Upper Austria. *Energy Procedia*, *62*, 472–481.

Porritt, S. M., Cropper, P. C., Shao, L., & Goodier, C. I. (2012). Ranking of interventions to reduce dwelling overheating during heat waves. *Energy and Buildings*, *55*, 16–27.

Raslan, R. (2010). *Performance Based Regulations: The Viability of the Modelling Approach as a Methodology for Building Energy Compliance Demonstration*. University College London.

Shrubsole, C., Macmillan, A., Davies, M., & May, N. (2014). 100 Unintended consequences of policies to improve the energy efficiency of the UK housing stock. *Indoor and Built Environment*, *23*(3), 340–352.

Symonds, P., Taylor, J., Mavrogianni, A., Davies, M., Shrubsole, C., Hamilton, I., & Chalabi, Z. (2017). Overheating in English dwellings: comparing modelled and monitored large-scale datasets. *Building Research & Information*, *45*(1–2), 195–208.

Taylor, J., Davies, M., Mavrogianni, A., Chalabi, Z., Biddulph, P., Oikonomou, E., … Jones, B. (2014). The relative importance of input weather data for indoor overheating risk assessment in dwellings. *Building and Environment*, *76*, 81–91.

Tian, W. (2013). A review of sensitivity analysis methods in building energy analysis. *Renewable and Sustainable Energy Reviews*, *20*, 411–419.

WHO. (2009). *Improving public health responses to extreme weather/heat-waves - EuroHEAT*. World Health Organisation (WHO).

ZCH. (2015). *Overheating in homes, The big picture, Full Report*. Zero Carbon Housing.