

# The Role of Fabric Performance in the Seasonal Overheating of Dwellings

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## Abstract

Airtightness and thermal conductance of the fabric play a key role in constructing low energy buildings. These two factors might minimise the building's heating demand in winter but contribute to its overheating in summer. This study focused on a building using Insulated Concrete Formwork (ICF), a site-based Modern Methods of Construction (MMC). ICF walls consist of cast in situ concrete poured between two layers of Expanded Polystyrene (EPS) insulation. The walls can achieve very low U-values and high levels of airtightness. The overall aim was to investigate the resilience or vulnerability of the ICF to overheating. A whole building monitoring study was used to empirically investigate the impact of the ICF fabric performance and to validate the accuracy of Building Performance Simulation (BPS) predictions provided by two tools. The results indicate that the building was able to provide a stable internal environment. In addition, both tools were able to predict indoor temperatures in a consistent way. However, the outcome of the analysis highlighted the significance of selecting appropriate data in terms of weather, internal gains and occupant behaviour when assessing overheating and the importance of developing a methodology for model calibration against indoor air temperatures for overheating assessment.

## Introduction

Climate change has been in the focus of scientific research recently. In Europe, the built environment accounts for 40% of the total energy use and 36% of the total CO<sub>2</sub> emissions (Foucquier et al., 2013; McLeod et al., 2013). Residential buildings alone use about 60% of the total energy consumption attributed to the building sector (Foucquier et al., 2013). Governments have set targets to reduce buildings' energy consumption and mitigate environmental impacts by focusing on reduction of fabric heat losses (reduced infiltration, better insulation etc.). Highly insulated, low carbon buildings are sensitive to overheating (Jones et al., 2016; NHBC, 2012). There is strong evidence that a significant portion of domestic housing will overheat, not only in the future, but also under current weather conditions (Committee on Climate Change, 2014).

## Overheating in dwellings

The issue of overheating has received increased attention by both academics and industry. According to Lomas and Porritt (2017), the following factors can have an impact on overheating: Climate change; Urbanisation; Ageing population; Increased energy efficiency of new homes; Modern construction methods leading to dwellings with

less thermal mass; and, Lack of shading devices and shutters for aesthetic reasons.

Predicting overheating is a task which consists of: (1) predicting indoor air temperatures, and (2) selecting temperature thresholds against which the predicted temperatures will be compared (CIBSE, 2013). As far as the first stage is concerned, there are two options: Firstly, to employ either static or adaptive temperature thresholds. For instance, according to CIBSE Guide A (2006) the living areas and bedrooms of a dwelling would be characterised as overheated if more than 1% of the annual occupied hours exceeded an operative temperature of 28°C and 26°C, respectively. Similarly, according to the PassivHaus Planning Package (PHPP) (Hopfe and McLeod, 2015) when an operative temperature equal to 25°C is exceeded, the outcome of the overheating assessment (i.e. the occupied hours that exceed the above threshold) is classified as follows: > 15% as catastrophic; 10-15% as poor; 2-5% as good; and, 0-2% as excellent.

Secondly, adaptive criteria take into account the fact that people have an inherent inclination to adapt to different conditions (e.g. changes in the air temperature) (Nicol and Humphreys, 2002). Hence, the comfort temperature is associated with the prevailing outdoor air temperatures. As far as the second stage is concerned, there are assessment methods like the Standard Assessment Procedure (SAP) (BRE, 2012) and the PHPP tool that employ steady state equations to estimate monthly mean temperatures. Nevertheless, internal temperatures are very sensitive to the ratio of heat gains to losses in homes that fulfil high standards in terms of insulation and airtightness (Dengel and Swainson, 2012). Such a dynamic phenomenon is unlikely to be captured by static calculations. Hence, in order to deal with the overheating issue in more depth and to be able to predict it with more confidence, the employment of a dynamic simulation tool may be necessary (Hopfe and McLeod, 2015). Furthermore, since overheating is an issue that is under investigation in recent years, no knowledge has been acquired yet in relation to the effectiveness of different measures/strategies needed to be adopted in order to tackle it. Hence, dynamic simulations can be employed to bridge this gap (Dengel et al., 2016).

## Performance of ICF

The thermal mass of the fabric can be used to prevent buildings from overheating (Csaky and Kalmar, 2015; Al Sanea et al., 2011). The term 'thermal mass' is used to define all elements in the building fabric that are able to store energy during time of surplus and release this energy back into the space at time of scarcity (Ghattas et al., 2013). The principal benefit of heavyweight (high thermal mass) structures is their ability to dampen fluctuations in

interior conditions when significant fluctuations occur in the outside environment (Al Sanea and Zedan, 2011; Petire, et al., 2001).

The analysis presented in this paper focuses on Insulating Concrete Formwork (ICF), a Modern Method of Construction (MMC) solution provided by the heavyweight construction industry. In recent years, the UK housing industry has shown a trend towards off-site MMC (DCLG, 2008). MMC are mostly lightweight, off-site, innovative technologies of house building. The drivers and barriers to MMC have been analysed in previous work (Pan et al., 2007; Kempton and Syms, 2009) and are outside the scope of this research. Even though ICF is not a lightweight, factory-made construction method, it is a site-based MMC, mainly due to its increased speed of construction. It consists of modular prefabricated Expanded Polystyrene (EPS) hollow blocks assembled on site and cast in-situ concrete. Once the concrete has cured, the insulating formwork remains permanently in place resulting in a typical reinforced concrete wall with continuous internal and external insulation (Chant, 2012).



*Figure 1 Prefabricated Expanded Polystyrene (EPS) hollow block of ICF, before the concrete is poured.*

The ICF walling system can provide high levels of airtightness (Petire, et al., 2001) very low U-values and can reduce the existence of thermal bridging. Due to the internal layer of insulation, ICF acts as an insulated panel, acting thermally as a lightweight structure. Research associated with ICF in the UK mainly uses computational analysis (Mantese et al., 2015; Mantese et al., 2016). Previous computational, numerical and field studies conducted elsewhere indicated that in cold climates the thermal capacity of its concrete core shows evidence of heat storage effects, resulting ultimately in reduced energy consumption when compared to a lightweight conventional timber-framed wall with equal levels of insulation (Hart et al., 2014; Armstrong, 2012).

### **Empirical validation of BPS tools**

When trying to assess the energy, environmental and thermal performance of high thermal mass buildings, the

use of reliable dynamic BPS is essential (Davies, 2004). Since all models represent a simplification of reality, it is generally acknowledged that there is a high level of uncertainty and sensitivity associated to current BPS methods and tools (Hopfe and Hensen, 2011). Empirical validation is a common practice to ensure that the results from simulation programs are reliable (Ryan and Sanquist, 2012; Fumo, 2014). To reduce the inaccuracies of BPS, the building models need to be updated when new information becomes available (Monarim and Strachan, 2014).

### **Research aim and objectives**

The analysis presented in this paper focuses on the passive cooling performance of ICF. The aim is to investigate the resilience or vulnerability of ICF to overheating. Whole building monitoring was used to empirically investigate the impact of ICF fabric performance, and to validate the accuracy of two BPS tools predictions when modelling ICF. To the authors' knowledge, this study is one of the first empirical investigations into the impact of ICF fabric performance on overheating in the domestic sector. The objectives are:

- 1 To understand the relationship between ICF fabric performance and propensity of a building to overheat.
- 2 To investigate the impact of occupancy on the dwelling's tendency to overheat, or not; and,
- 3 To empirically evaluate the accuracy of current state-of-the-art BPS tools when modelling ICF, especially their ability to estimate overheating.

### **Methodology**

This study is a computational and empirical evaluation on the passive cooling performance of ICF. Monitoring data were gathered from an ICF low-energy dwelling, designed to achieve near to Passivhaus levels. The case study is a two storey, three-bedroom house of approximately 250m<sup>2</sup>, located in the wider area of Guildford, in a rural settlement called Gomshall. The building envelope uses ICF walls, an insulated foundation raft, a prefabricated concrete hollow-core slab, and prefabricated EPS roof panels. The recorded data included information on the:

- On-site weather data
- Internal air temperatures
- CO<sub>2</sub> levels
- Energy consumption (at the main board)
- Windows opening and closing
- Mechanical Ventilation and Heat Recovery (MVHR) system operation (on summer bypass)

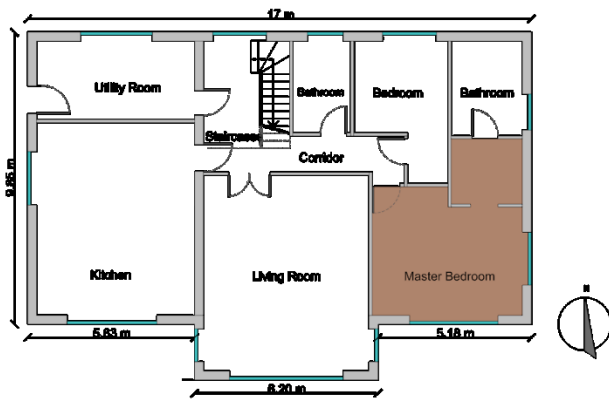


Figure 2 Plan of ground floor

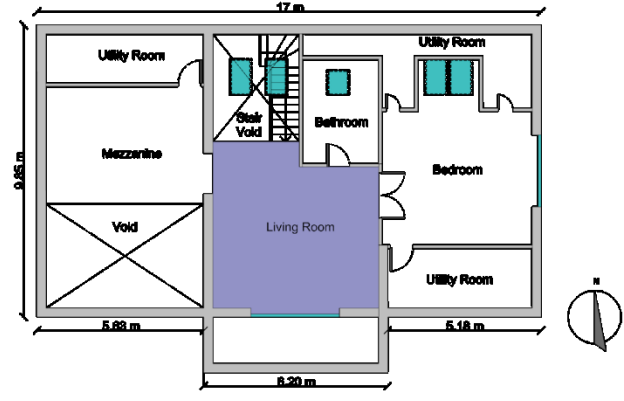


Figure 3 Plan of first floor

Table 1 Thermal properties of materials (data obtained from the contractor)

1: Opaque Elements						
Element (from Outside to Inside)		Thickness (mm)	Conductivity (W/mK)	Density (kg/m³)	Specific Heat (J/kgK)	U-Value (W/m²K)
ICF Wall	Cement Screed	3	0.8	2100	650	0.113
	Cement Plaster	0.72	0.72	1760	840	
	EPS Insulation	210	0.037	25	1400	
	Cast Concrete	147	2	2300	1000	
	EPS Insulation	108	0.037	25	1400	
	Plasterboard	13	0.21	950	840	
Roof	Slate Tiles	5	1.13	1400	1000	0.115
	Air Gap	25	R=0.15 m²K/W	-	-	
	Rood Decking	25	0.14	530	900	
	EPS Insulation	300	0.037	25	1400	
	Plasterboard	20	0.21	950	840	
Ground Floor*	Stone Bed	300	1.802	2243	837	0.101
	Blinding Layer	50	1.73	2243	837	
	Membrane	5	0.19	1121	1647	
	EPS Insulation	350	0.037	25	1400	
	Concrete Slab	150	2	2300	1000	
	Ceramic Tiles	8	0.8	1700	850	
First Floor	Plasterboard	20	0.21	950	840	1.312
	Air Gap	150	R=0.15 m²K/W	-	-	
	Hollow Core Concrete	250	1.70	2300	840	
	Air Gap	115	R=0.15 m²K/W	-	-	
	Ceramic Tiles	8	0.8	1700	850	
Partitions	Plasterboard	15	0.21	950	840	2.16
	Air Gap	70	R=0.15 m²K/W	-	-	
	Plasterboard	15	0.21	950	840	
2: Transparent Elements						
	Glass U-Value (W/m²K)	Glass g value	Glass Visible Transmittance	Frame Conductance (W/m²K)		
Windows	0.61	0.52	0.67	1.72		
*in the living room and the bedrooms ceramic tiles are replaced with carpet (thickness = 8mm, conductivity = 0.06 W/mK, density = 200 kg/m³and specific heat = 1300 J/kgK)						

To address the three objectives, the research consisted of the following three stages. The first part of the study analysed the monitoring data regarding internal air temperatures for two of the main living areas, the ground floor master bedroom and the first floor living room as shown in Figures 2 and 3. The building was analysed under a transient state in an unoccupied (07/07 to 13/07) and an occupied (24/07 to 30/07) period. The response of the fabric was compared against fluctuations at the

boundary conditions (i.e. ambient temperatures, solar radiation, internal conditions - changes in internal gains and occupancy patterns). The aim was to investigate the effects of the thermal mass in the fabric and to evaluate the resilience or vulnerability of the specific construction method to overheating. Two different weeks within July were analysed and compared, one unoccupied and one occupied (to evaluate the impact of occupancy on the building's tendency to overheat).



Figure 4 South-West view of the building case study

The second part of the analysis was focused on BPS. The recorded data on the actual thermal performance of the ICF case study were compared against the respective design assumption (i.e. weather conditions, internal gains, ventilation rates etc.). Benchmarks regarding the building's operation and occupancy schedules were used from the National Calculation Method<sup>1</sup> (NCM) (i.e. Figures 5 and 6 depict internal gains for the rooms under investigation, while the ventilation rate was equal to 10 l/s/person) along with the Typical Meteorological Year (TMY) climate file from the nearest weather station (Gatwick Airport). The discrepancy between simulation outputs and actual monitoring data was evaluated (to investigate the gap between simulation predictions and reality).

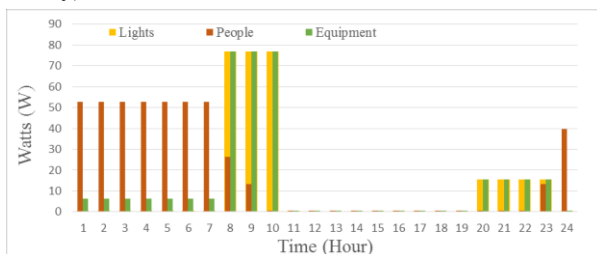


Figure 5 Occupant, lighting and equipment gains from the NCM for the **bedroom in the ground floor**

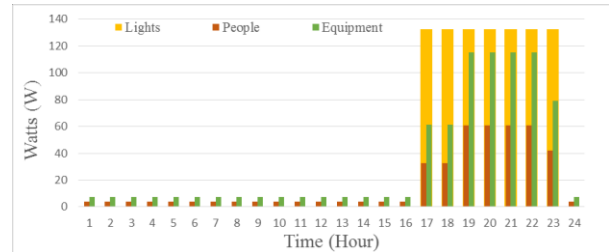


Figure 6 Occupant, lighting and equipment gains from the NCM for the **living room in the first floor**

As far as the creation of the thermal models concerns, two detailed models were constructed in two different research, open-source BPS tools, EnergyPlus<sup>2</sup> and ESP-r<sup>3</sup>. In these tools, each room of the building was modelled as a thermal zone (i.e. the models consist of 16 thermal zones).

Infiltration rates were predicted utilising data from the leakage test that was conducted; according to this test, the effective leakage area (ELA) @ 4 Pa was found to be equal to 0.39 cm<sup>2</sup>/m<sup>2</sup>. This was used as an input to the simulations by multiplying this value with the exposed area of each thermal zone.

The third and final stage of the analysis was the empirical validation of the simulation results provided by the two BPS tools. Information from the monitoring study was used as input in the post-occupancy simulation models. Outputs for the absolute air temperatures were compared with recorded data. The aim was to evaluate the discrepancy between the two BPS tools and the gap between simulation predictions and reality.

Occupancy schedules were derived from the CO<sub>2</sub> levels recorded at room level. Then, occupant gains were estimated based on the information that the building was occupied by two persons and obtaining values for the metabolic rates from the NCM (e.g. 90 and 110 W/person for the bedroom and the living room respectively). Gains from lights and equipment were estimated based on the derived occupancy schedules and measurements of electrical consumption at building level. Finally, ventilation rates (Table 2) were predicted based on information provided by the occupants regarding the operation of the MVHR unit.

<sup>1</sup> NCM is a procedure for demonstrating compliance with Building Regulations. Available at <http://www.uk-nem.org.uk/> [last visited: 12/12/16]

<sup>2</sup> EnergyPlus<sup>TM</sup> is a whole building energy simulation program developed in the Department of Energy (DOE) in USA. Available at: <https://energyplus.net/> [last visited: 12/12/16]

<sup>3</sup> ESP-r is a whole building energy simulation program developed at Department of Mechanical Engineering at

the University of Strathclyde in UK. Available at: <http://www.esru.strath.ac.uk/Programs/ESP-r.htm> [last visited: 12/12/16]

<sup>4</sup> The RMSE is a measure of the difference between two sets of values; lower values indicate better agreement between these two sets

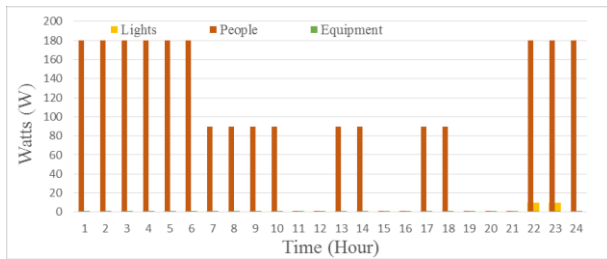


Figure 7 Internal gains obtained from the monitored data for the **bedroom in the ground floor**

It is important to recall that this study focuses on the ability of BPS tools to predict indoor air temperatures irrespective of the temperature thresholds chosen for the overheating assessment. Therefore, no specific overheating criteria were considered.

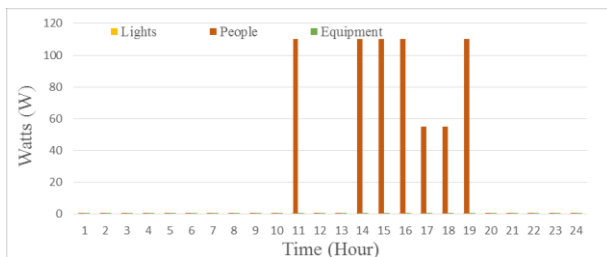


Figure 8 Internal gains obtained from the monitored data for the **living room in the first floor**

Table 2 Ventilation rates for both rooms under investigation

	Schedule	Flow/Zone (l/s)
Unoccupied week	00:00–24:00	1.58
Occupied week	00:00-06:30	8.32
	06:30-11:30	48.58
	11:30-13:30	73.61
	13:30-21:00	48.58
	21:00-24:00	8.32

Finally, to date, there is no standard methodology available regarding how to calibrate a model in terms of indoor air temperatures. The International Performance Measurement and Verification Protocol (IPMVP) (U.S. Department of Energy, 2002) and the ASHRAE Guideline 14 (ASHRAE, 2002) provide some criteria for determining whether a model is calibrated but these are applicable only in the case that energy use is assessed. Nevertheless, since the Root Mean Squared Error (RMSE<sup>4</sup>) is employed as a means to measure the declination between actual data and simulations, this statistical measure will be used in this study as well.

## Results

### Indoor air temperature predictions utilising typical weather data and inputs from NCM

Comparing recorded air temperatures with predictions made by EnergyPlus and ESP-r utilising typical weather data and inputs from the NCM for the bedroom on the ground floor illustrates the significance of choosing appropriate data for weather, internal gains and ventilation rates as shown in Figure 9. From this graph, two observations can be made. Firstly, that the air temperatures predicted by the two BPS tools are much higher than the recorded air temperatures. More specifically, the average monitored daily temperature ranges from 22.9°C to 24.6°C while the average temperature predicted by EnergyPlus and ESP-r ranges from 35.1°C to 36.6°C. Secondly, that the diurnal temperature profile arising from the monitored data is much more stable than those predicted by the two BPS tools as stated previously. Daily fluctuations between the highest and lowest temperatures range from 0.8°C to 2.1°C for the recorded data, while for the data from EnergyPlus and ESP-r the fluctuations range from 2.8°C to 5.1°C and 2.4°C to 6.1°C respectively. As far as the inter-model comparison is concerned, there is good agreement between the two tools with a RMSE equal to 0.66°C.

The temperature predictions for the living room on the first floor are similar (Figure 10). The average monitored daily temperature ranges from 24.0°C to 25.1°C while the average temperature predicted by EnergyPlus and ESP-r ranges from 35.8°C to 37.8°C and 36.3°C to 38.1°C respectively. Similarly, daily differences between the highest and lowest temperatures range from 1.0°C to 2.4°C for the recorded data, while for the data from Energy Plus and ESP-r the differences range from 1.6°C to 6.2°C and 2.1°C to 7.0°C respectively. Again, the agreement between the predictions of the two tools is high with a RMSE equal to 0.62°C.

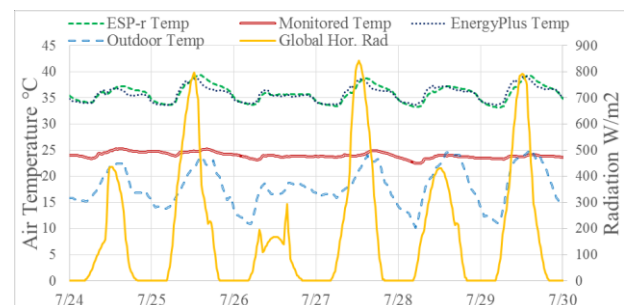


Figure 9 Outdoor Air Temperature, Global horizontal Radiation, and Air Temperatures predicted by EnergyPlus and ESP-r for the **occupied bedroom in the ground floor** between 24/07 to 30/07



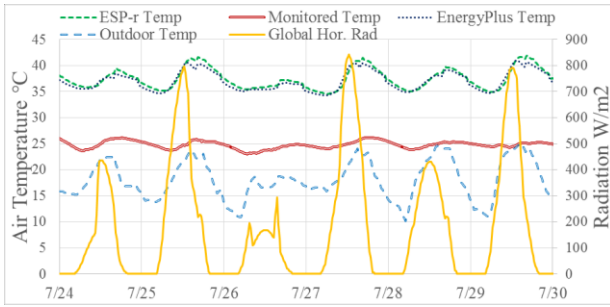


Figure 10 Outdoor Air Temperature, Global horizontal Radiation, and Air Temperatures predicted by EnergyPlus and ESP-r for the **occupied living room in the first floor** between 24/07 to 30/07

#### Indoor air temperature predictions utilising monitored data for the unoccupied week

Indoor air temperatures estimated by EnergyPlus and ESP-r were compared against actual temperatures in the bedroom in the ground floor and the living room in the first floor. The simulations were conducted utilising monitored weather data and internal gains. The analysis period was from the 07/07 to 13/07, a period that the building was unoccupied. This resulted in the removal of a great amount of uncertainty associated with occupants' varying behaviour (e.g. in terms of opening/closing windows and internal heat gains in rooms).

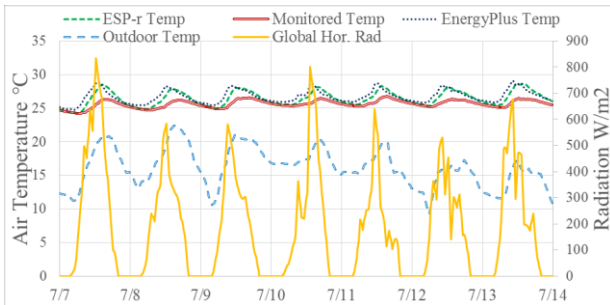


Figure 11 Outdoor Air Temperature, Global horizontal Radiation, and Air Temperatures predicted by EnergyPlus and ESP-r for the **unoccupied bedroom in the ground floor** between 07/07 to 13/07

From the graph in Figure 11, it is apparent that both BPS tools predict indoor temperatures in a consistent way. In addition, both tools seem to overestimate peak temperatures while a time lag is also observed indicating that solar gains are not accounted for realistically. More specifically, daily fluctuations between highest and lowest temperatures range from 24.2°C to 26.8°C for the recorded data, while for the data from EnergyPlus and ESP-r the fluctuations range from 24.8°C to 29°C and 24.2°C to 28.6°C respectively. The RMSE is equal to 1.04°C for the ESP-r, 1.34°C for the EnergyPlus and for the inter-model comparison is equal to 0.62°C. When the sum of hours exceeding 26°C and 28°C is considered, a significant difference is observed between the predictions and actual measurements as Figure 12 indicates.

The analysis for the living room indicates similar findings. The RMSE is approximately equal to 1.0°C

(1.0°C for the ESP-r and 1.11°C for the EnergyPlus) while the error associated with the inter-model comparison is less than 1.0°C (0.67°C). As shown in Figure 13, a time lag and an overestimation of peak temperatures is observed here too.

When examining actual hours of exceedance of the temperature thresholds considered, it is apparent that the difference between monitored temperatures and predictions is substantial as Figure 14 suggests.

#### Indoor air temperature predictions utilising monitored data for the occupied week

Figure 15 displays estimates from the BPS tools, as well as measured air temperatures for the period between 24/07- 30/07 for the bedroom on the ground floor. What is interesting in the graph is that the occupants have no influence on the results. The RMSE is less than 1.0°C (0.99°C for the ESP-r and 0.94°C for the EnergyPlus) while as far as the inter-model comparison concerns, the

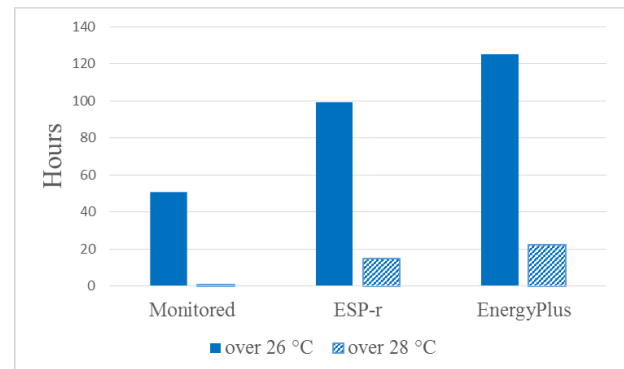


Figure 12 Sum of total hours exceeding 26°C and 28°C for the **unoccupied bedroom in the ground floor** between 07/07 to 13/07

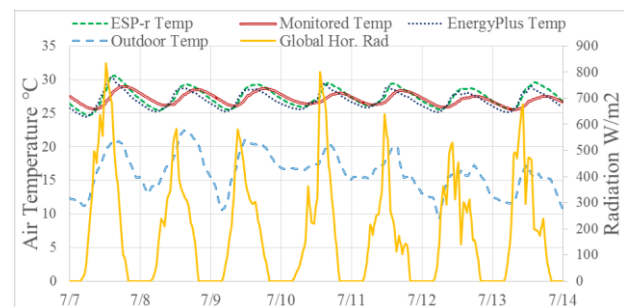


Figure 13 Outdoor Air Temperature, Global horizontal Radiation, and Air Temperatures predicted by EnergyPlus and ESP-r for the **unoccupied living room in the first floor** between 07/07 to 13/07

respective error is equal to 0.82°C. As in the previous analyses, spikes are observed too. However, the trend observed in the previous graphs (i.e. the BPS tools overestimate systematically air temperatures) is not evident in this graph, implying that the inconsistency between recorded data and estimates cannot be attributed solely to the way solar gains are taken into account. For this analysis, no difference is observed in relation to the sum of hours exceeding 26°C and 28°C. The installed sensors did not record temperatures greater than the above

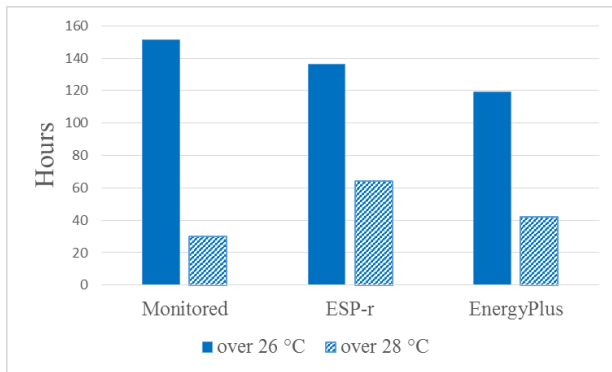


Figure 14 Sum of total hours exceeding 26°C and 28°C for the **unoccupied living room in the first floor**

thresholds, which is depicted by both tools.

The analysis for the living room in the first floor suggests a greater inconsistency between measurements and predictions than the analysis for the bedroom. The RMSE is equal to 2.21°C for the ESP-r and 1.31°C for the EnergyPlus. At the same time, the declination between the two tools is larger as well (1.26°C).

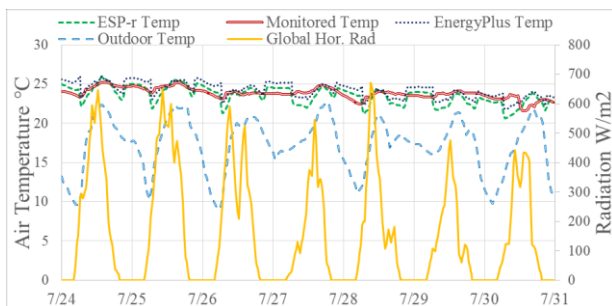


Figure 15 Outdoor Air Temperature, Global horizontal Radiation, and Air Temperatures predicted by EnergyPlus and ESP-r for the **occupied bedroom in the ground floor** between 24/07 to 30/07

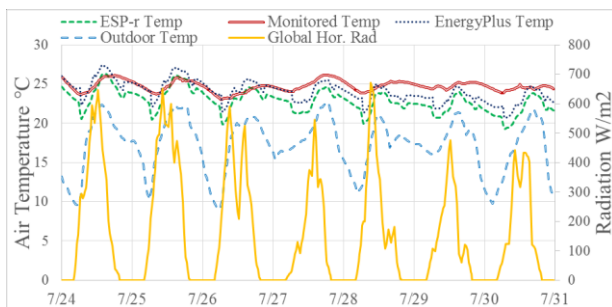


Figure 16 Outdoor Air Temperature, Global horizontal Radiation, and Air Temperatures predicted by EnergyPlus and ESP-r for the **occupied living room in the first floor** between 24/07 to 30/07

From the graph in Figure 16, it is apparent that for the majority of the analysis period both tools underestimate air temperatures (with the exception of EnergyPlus for short time periods which predict higher temperatures than the measured values). Finally, the sum of the total hours exceeding 26°C was less than 10 hours, something that was depicted by both tools while both measured and

predicted temperatures never exceeded 28°C as shown in figure 17.

### Analysis of the fabric response to fluctuations in the boundary conditions

From the monitoring results, it can be seen that the indoor air temperatures in both rooms under investigation (i.e. ground floor master bedroom and first floor living room) are relatively stable. For the occupied week, the diurnal temperature variation is between 2.5°C for the master bedroom (Figure 9) and 3.2°C for the living room (Figure 10), while the ambient air temperature fluctuation is up to 15°C. For the unoccupied week, the diurnal temperatures fluctuation is in the range of 2.5°C in the bedroom (Figure 11) and in the range of maximum 5°C for the first-floor living room (Figure 13), while the ambient air temperature fluctuates up to 12°C. These findings show that the fabric of the building is able to dampen internal air temperature swings, providing a stable internal environment. This is partly attributed to the thermal mass of the fabric and the space (i.e. ICF walls, concrete slab and internal furnishing), but also to the ventilation regime (continuous mechanical ventilation, operating in conjunction with the thermal mass). Moreover, it is interesting to notice that when comparing the two weeks (occupied and unoccupied), the effect of the occupants show minimal impact on the internal air temperature swings. In both weeks, the internal air temperatures, although stable, are significantly higher than the ambient air temperatures. Nonetheless, for the occupied week, when we are mostly concerned about overheating, indoor temperatures remain below 26°C for both spaces under investigation. Finally, in the unoccupied week, the first floor living room shows a slightly increased air temperatures and higher diurnal temperature variation in comparison to the ground floor bedroom (Figures 11 and 13).

## Discussion

### Thermal Performance of ICF

The findings of the analysis regarding the thermal response of the fabric to changes in boundary conditions indicate that the thermal mass of the structure is able to dampen diurnal indoor temperature variations. The monitoring results confirm the findings of previous studies (Csaky and Kalmar, 2015; Al-Sanea et al., 2011; Petire et al., 2001) showing that the fabric with increased levels of thermal mass results in a relatively stable internal environment. For the occupied period, internal air temperatures were below 26°C. The internal temperatures were found to be relatively higher for the unoccupied week, yet the diurnal temperature swings were again significantly reduced in comparison to the ambient temperature fluctuations. This is attributed to the thermal mass of the fabric, the added thermal mass due to furniture but also on the operation of the mechanical ventilation system. The latter was operating with constant airflow rates, even during the unoccupied week, purging the excess heat from the thermal mass, avoiding a possible heat build-up.

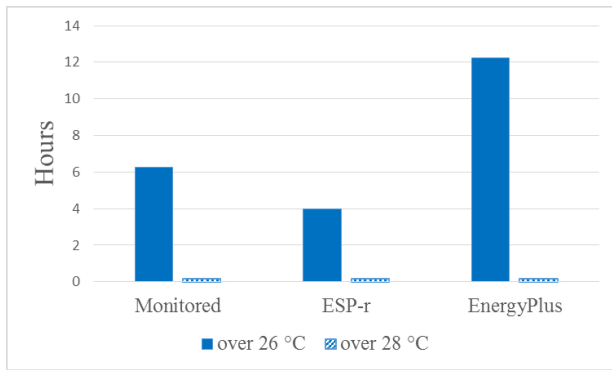


Figure 17 Sum of total hours exceeding 26°C and 28°C for the **occupied living room in the first floor** between 24/07 to 30/07

### Impact of Selection of Input Data in Simulation Results

In the analysis of indoor air temperatures, when utilising typical weather data and inputs from the NCM, the findings confirmed the results of previous studies (De Wilde, 2014; Coakley et al., 2014; Fumo, 2014); the selection of appropriate input data has a significant impact on the accuracy of the simulations. More specifically, Figures 5-8 show that the internal gains predicted by the NCM database are higher than the actual ones (with the exception of occupant gains where the NCM underestimates them). In addition, it was observed that the differences between the two data sets regarding ventilation rates had a more profound impact on the results. The actual ventilation rates (Table 2) were much higher than those from the NCM (for instance, for the living room according to the NCM the living room has  $\frac{1}{2}$  of an occupant during the evening, resulting in 5.5 l/s).

The simulation data provided by both BPS tools showed very good agreement. However, they both predicted significantly higher internal air temperatures, greater diurnal temperature variations, and also severe overheating. The analysis highlighted the significance of calibration, and it showed the importance of updating post occupancy simulation models with real input data, if available.

### Empirical Validation of BPS Tools

The empirical validation of the BPS predictions showed that there was an overall good agreement between the simulation results provided by the two BPS tools, but also between simulation predictions and reality. Both tools showed a tendency to overestimate peak temperatures in both rooms during the unoccupied period. This may also be a result of the optical properties assigned to the windows. Both tools require inputs such as transmittance and reflectance for each window layer, data that were not available. Such properties were assumed for both BPS models based on the description of the window (in terms of number of layers and presence of coatings) and ensuring that the overall properties of the windows (U-values and g-values) match those provided by the manufacturer. However, it is not certain that solar gains were modeled accurately since different combinations of

optical properties can result in the same overall provided U-values and g-values. The most significant inconsistencies were observed in the simulation of indoor air temperatures in the first floor living room. Both BPS tools predicted temperatures below those recorded. This may be due to the fact that the living room is in contact with the staircases where no physical boundary exists. However, in terms of modelling this zone a boundary had to be introduced: in this case a single layer of glazing was chosen, with a very large U-value in order to allow solar gains from the windows located in the staircases to enter the living room. Nevertheless, this highlights the importance that zoning can have. It would be interesting to investigate further the inconsistency, or otherwise, if a more sophisticated method (i.e. CFD analysis) was employed for the simulation of the inter-zonal air movement. A slight time lag was observed in the simulation results. This implies that the way the two tools calculate the availability of solar radiation is different. Moreover, a time lag on the peak internal temperatures was also observed between simulation predictions and actual recorded data. The inconsistency was observed when the peak internal temperature occurs. Both tools predicted peak internal temperatures a few hours earlier than in reality. This indicates that solar gains are not accounted for realistically in the simulation. Part of the aforementioned time lag is also attributed to the thermal mass in the fabric and the internal space. A limitation of both simulation models is that they did not include internal mass due to furniture. Previous studies have shown that the furniture could have a significant influence on the distribution of energy received by room and the surfaces temperature (Hand, 2016; Soelami and Ballinger, 1992).

The general observation is that although there was a good consistency between the simulation predictions of both BPS tools and between simulation and reality, when estimating hours of exceedance of the temperatures thresholds, a significant divergence was observed. The latter raises concerns on the ability of simulation tools to accurately estimate number of hours that indoor air temperatures exceed a certain threshold.

In the comparison between the occupied and the unoccupied periods, the uncertainty introduced by the occupants had an insignificant influence on the simulation results. During the calibration of the post-occupancy simulation models, the most considerable sensitivity was observed on the simulation of the mechanical ventilation regime. This can be attributed to the fact that infiltration rates for each room were estimated utilising the ELA as determined in the building leakage test. However, during the test the MVHR unit was not in operation. Under actual conditions, when the MVHR unit is on, the infiltration rates may be different (Ng, Emmerich and Persily, 2014). Finally, significant sensitivity was also observed on the specification of the pre-conditioning period.



## Research Limitations

Although monitored data were available for windows operation, these were not utilised for two reasons. First, the set of data was incomplete and second, other critical information such as opening factors were not available. Taking into account the parameters needed to be included in a BPS tool for modelling windows operation (e.g. pressure coefficients of exterior surfaces, operation schedule of interior doors etc.) it was decided to omit them due to the high amount of uncertainty introduced in the thermal models. In addition, the interaction between the MVHR unit and the airtightness of the building was not considered. For this reason, the ventilation flow rate was used as a variable in the calibration process.

## Conclusions

This study set out to investigate whether an ICF building can buffer temperature changes and hence reduce the likelihood of overheating. This study was also designed to investigate the contribution of occupant behaviour in overheating. Although the current research draws on data from a single case study, the findings suggest that an ICF building can help moderate temperature changes; the diurnal temperature profile for both rooms considered was more stable than the respective outdoor profile. Furthermore, the analysis from the occupied period showed that occupants did not increase the propensity of the home to overheat at all. However, no wider conclusions can be drawn, given that the results come from one single case study and the period of analysis is quite short. Also, this analysis has shown through simulations the significance of selecting appropriate data when assessing overheating. Utilising inputs from the NCM database resulted in a large discrepancy between simulation predictions and actual for the indoor temperatures. Nevertheless, both software tools were able to predict indoor temperatures in a consistent way when an inter-model comparison was performed and after inputs from the NCM were replaced with actual data, the respective gap was reduced substantially. Finally, a discrepancy was observed in relation to the ability of the BPS tools to predict indoor temperatures depending on the criterion used for assessing their adequacy. More specifically, although the RMSE was relatively low for most simulations (around 1.0°C), there was a great discrepancy between recorded data and predictions when hours of exceedance of specific temperature thresholds were considered. This highlights the importance of developing a methodology with specific criteria for calibrating a thermal model for overheating assessment.

## Future Work

Future work will focus on investigating the impact of various design interventions such as different types and sizes of shading devices, different types of glazing etc. in this case study. The impact of these measures on the indoor environment will be assessed with both models (i.e. the model utilising input data from the NCM and the model utilising monitored data).

## Acknowledgement

The authors gratefully acknowledge the Engineering and Physical Sciences Research Council UK (EPSRC), the Centre for Innovative and Collaborative Engineering (CICE) at Loughborough University, Aggregate Industries UK Ltd, the Building Research Establishment (BRE), and Mr Ronny and Ms Barbara Karlsson for their support.

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