SIMULATION EXPERIMENTS WITH BIRMINGHAM ZERO CARBON HOUSE AND OPTIMISATION IN THE CONTEXT OF CLIMATE CHANGE

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ABSTRACT

The Birmingham Zero Carbon House is a Victorian house that has achieved carbon negative performance through retrofit. The house has been extensively simulated in parallel with detailed instrumental monitoring. A dynamic simulation model of the house was first calibrated using measured performance data. The performance of the house was subsequently studied through dynamic simulation in the current and future weather years. Robustness of the building thermal behaviour to climate change was thus analysed and measures for adaptation to climate change were investigated.

INTRODUCTION

Context and aims

The Birmingham Zero Carbon House is a retrofitted Victorian house that has achieved carbon negative performance (Figure 1).

Figure 1 Zero Carbon House: top – street view (top) and garden view (bottom)

The house has been extensively simulated in parallel with detailed instrumental monitoring.

The main features of the Zero Carbon House are:

- High level of thermal insulation reduces heat transfer between inside and outside
- High amount of thermal mass smoothes out temperature fluctuations
- Solar gains from south west reduce space heating demand
- High air tightness and heat recovery ventilation
- Natural daylight
- Solar photovoltaic system generates electricity
- Solar thermal system heats domestic hot water
- Additional heating: Wood burning stove used only in very cold weather
- Energy efficient lighting
- Rainwater harvesting
- Use of locally sourced recycled materials

Our aims are: 1) To calibrate the dynamic simulation model using measured performance data, 2) To study the performance of the house in current weather 3) To investigate the robustness of the building behaviour to climate change using dynamic simulation. 4) To devise a set of design guidelines for robustness and adaptation to climate change.

Investigative approach

Instrumental monitoring of the house was carried out to study the real life performance, collecting data of energy production and consumption as well as indoor thermal conditions. A dynamic simulation model of the house was developed and the calibration of the model was carried out. The calibrated simulation model was subsequently used to study the building performance in different future climates, using probabilistic future weather data for 2030, 2050 and 2080 in a medium carbon emissions scenario. The practical approach taken was to analyse the number of annual occupied hours above a certain internal temperature for the current climate and for the three future climates, using Test Reference Year (TRY) data and Design Summer Year Data (DSY).

Climate change and the built environment

There is an overwhelming scientific consensus that climate change is happening. Well established research is showing that the temperature of the earth's surface has already risen by 0.74 °C since the late 1800s, caused by the increased greenhouse gases in the atmosphere as a consequence of the industrialization of the last century (UNFCCC, 2011a, Met-Office, 2012, DEFRA, 2011, UKCP09, 2010).

The current UK target is to reduce its carbon dioxide emissions by 80% by 2050, that is relative to 1990 emissions, according to the UK's independent climate change committee recommendation (NHBC, 2009).

Domestic buildings are responsible for 28% of the total UK carbon emissions, out of which 73% goes for space and water heating (DCLG, 2006, Boardman et al., 2005).

Across the UK, climate change predictions show an average warming per decade between 0.1 C to 0.3 C for a low emissions scenario and 0.3 C to 0.5 C for a high emissions scenario (Hulme et al., 2002). Summers are expected to be hotter and dryer while winters are expected to be wetter (Jentsch et al., 2008). Climate change is already happening, as evident by the ten hottest years on record in the UK have been since 1990 (DECC, 2009).

UKCP09

Predictions of future weather are uncertain, but projections are crucial to develop adaptation strategies. The UKCP09 are currently the most advanced climate scenarios in the world. They are based on advanced climate modelling, past observations, IPCC (Intergovernmental Panel on Climate Change) emissions scenarios and expert judgement (Iam, 2010, UKCIP, 2010).

Any plausible projection of future climate will rely upon assumptions about future emissions of greenhouse gases and other pollutants; the future climate we experience depends on choices made by governments, societies and individuals about technologies and about lifestyles. The UKCP09 has three scenarios; high emissions, medium emissions and low emissions to represent different possible future states (UKCIP, 2010, Hulme et al., 2002).

The UK Climate Projections (UKCP09) provides climate information for the UK up to the end of the century. UKCP09 is the fifth generation of climate change information based on a MET Office designed methodology, reflecting scientists' best understanding of the operation of the climate system (UKCIP, 2010).

UKCP09 attempts to quantify the uncertainties by using probabilistic projections. These uncertainties are caused by; natural climate variability, modelling uncertainty and uncertainty in future emissions (UKCP09, 2010).

Probabilities used in UKCP09 are based on subjective probability (UKCP09, 2010), they are Cumulative Distribution Function (CDF) probabilities in the range 0-100% giving the likelihood of climate change being less than a given value. The data are structured in 5 CDF probability levels of (10%, 33%, 50%, 66% and 90%), all in three emissions scenarios; low, medium and high (UKCIP, 2010, UKCP09, 2010, Exeter, 2011a).

The PROMETHEUS project run by the University of Exeter, provides weather files compatible with many simulation programs. These files are based on the UKCP09, providing data for three future time periods; the 2030s, the 2050s and 2080s, and the 5 CDF probability levels, all in two emissions scenarios (Medium and High) (Exeter, 2011b).

Simulations performed using the different scenarios and probabilities would allow risk-based analysis and adaptation planning, and has been used in different studies (Exeter, 2011a, Kershaw et al., 2011, Capon, 2010). Moreover, similar future weather files have been used in other countries to study the effect of climate change on the built environment (Chan, 2011, Guan, 2011).

Building simulation performed using the different scenarios and probabilities of future weather projections would allow risk-based analysis and adaptation planning, and has been used in different studies (Exeter, 2011a, Kershaw et al., 2011, Capon, 2010, Coley et al., 2011).

METHODOLOGY

Instrumental monitoring

A sophisticated data monitoring system was installed in the case study site, which allows the systematic recording and calculation of detailed information on building and system states such as room and system temperatures, external conditions, energy flows etc (Figure 2). The information gathered allows an evaluation of the thermal conditions in the building for different seasons and conditions of occupancy and use. Additionally, crucial data were obtained of the energy requirements of the case study, energy saving from the zero carbon technologies and from that the carbon emissions of the house.

Figure 2 Instrumentation system in Zero Carbon House

Simulation model

The IES-VE Software is chosen due to its accuracy and versatility as well as the availability of the software license at the University. Furthermore, it is approved for use in compliance checking according to the Part L2 of the Building Regulations for England and Wales and due to that it is commonly used software in the UK by engineering consultants (Murray et al., 2011, Kim et al., 2011). Geometry of the IES simulation model is shown in Figure 3.

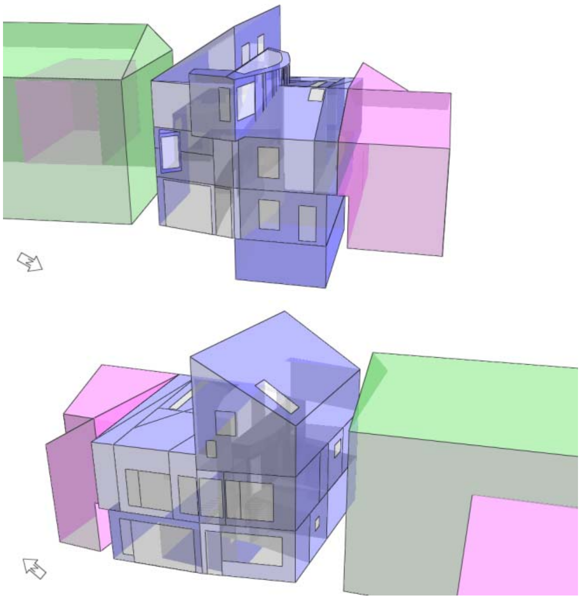

Figure 3 IES simulation model: street view (top) and garden view (bottom)

Energy calibration

Studies show that there are significant discrepancies between actual measured energy consumption of buildings and the simulation results. In a study by Raftery et al. where 121 buildings were modelled the differences between the measured and simulated design consumption ranged between 0.25 and 2.5 times (Raftery et al., 2011).

For this reason, and before investigating the building behaviour under future weather, it was necessary to do the calibration of the model in order to minimise the performance gap that regularly occurs between the simulation model and the actual building.

The energy calibration was carried out using the method reported by Jankovic (2012). Total actual energy consumption was first calculated using the records of when the wood stove was used. The utilisation factor for the fire box in the wood stove was set to 85% and the calorific value of ash wood was used to obtain the actual energy consumption (Table 1, column (1)). Subsequently, the heating temperature setting was varied in the simulation model and the relative error between the actual and simulated total energy consumption was calculated. The heating temperature setting was first decreased from 19.5°C until the relative error changed sign from positive to negative (Table 1, column (2) to (4)). This temperature was subsequently increased and decreased in smaller and smaller steps, depending on the sign of the relative error, thus reducing the relative error (Table 1, column (5) to (8)) until its absolute value was less than 0.2%. The corresponding heating temperature setting of 18.87°C (Table 1, column (9)) was then taken as the representative internal temperature of the house, and was used as the first step in the subsequent temperature calibration, which will be explained in the next section. Earlier work by Jankovic (2012) confirmed carbon negative performance of the house with emissions of -662 kgCO_2 per annum, on the basis of an energy-calibrated IES model.

Temperature calibration

The process of temperature calibration is documented in Table 2, where each row represents a separate calibration step. The measured air permeability was 0.34 m³/h.m² @ 50Pa which would give an infiltration rate of 0.02 ACH with all openings and vents sealed. As buildings never operate under test conditions and as air permeability is likely to change as result of shrinking of building materials, it was justified to use it, expressed as infiltration, as one of independent variables in the calibration process. The heating temperature set point and infiltration rate were changed one at a time. The error between the simulated and monitored temperatures was calculated, whilst checking that the energy calibration was still valid. The temperature error was calculated using the square of differences between the simulated and monitored temperatures, in order to prevent the possibility of the cancelling out between the positive and negative differences. At the end of this process, the calibration set temperature and infiltration rate were obtained, with temperature error of 0.95°C, and relative error between simulated and actual energy consumption of -0.06%, as shown in the last row of Table 2. The temperature error before and after the calibration is shown in Figure 4.

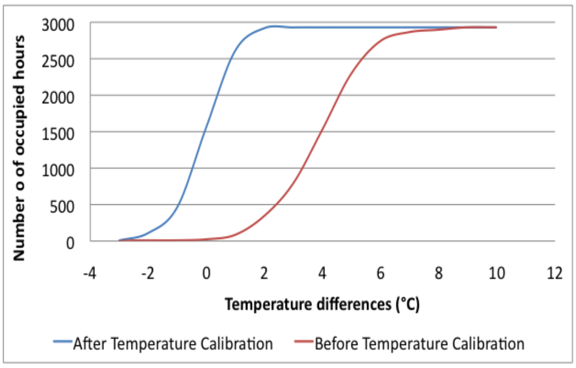

Figure 4: Cumulative frequency of occurrence of errors before and after temperature calibration

Table 1 Calibration of the simulation model for heating energy demand

	Actual Energy (MWh)	Simulated Energy (MWh) Ti =							
		19.50 ◦C	19.00 ◦C	18.20 ◦C	18.50 ◦C	18.80 ◦C	18.90 ◦C	18.85 ◦C	18.87 ◦C
Date	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Jan 01-31	0.507	0.721	0.664	0.576	0.608	0.641	0.653	0.647	0.649
Feb 01-28	0.457	0.297	0.258	0.198	0.220	0.242	0.250	0.246	0.248
Mar 01-31	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Apr 01-30	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
May 01-31	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Jun 01-30	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Jul 01-31	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Aug 01-31	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Sep 01-30	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Oct 01-31	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Nov 01-30	0.203	0.384	0.327	0.246	0.275	0.306	0.317	0.311	0.313
Dec 01-30	0.609	0.634	0.577	0.489	0.521	0.555	0.566	0.560	0.562
Summed total	1.776	2.036	1.826	1.508	1.624	1.744	1.785	1.764	1.773
Relative Error		14.65%	2.80%	-15.08%	8.55%	-1.01%	0.48%	-0.65%	-0.17%

Table 2 Calibration of the simulation model for internal temperatures

Step	Model Modifications	Infiltration Rate (ACH)	Heating Set Point	Temperature Average difference (°C)	Heating Relative Error
0	Model after energy calibration	0.020	18.87	4.11	-0.17%
1	Heating set point	0.020	16.00	3.34	-40.16%
2	Infiltration rate	0.050	16.00	3.16	-30.52%
3	Infiltration rate	0.100	16.00	2.89	-17.48%
4	Infiltration rate	0.200	16.00	2.47	2.48%
5	Natural ventilation at 20°C (summer)	0.200	16.00	1.71	2.48%
6	Add existing trees during summer	0.200	16.00	1.20	2.48%
7	Heating set point	0.200	15.80	0.96	-1.39%
8	Heating set point	0.200	15.50	0.93	-7.38%
9	Infiltration rate	0.220	15.50	0.93	-3.23%
10	Infiltration rate	0.240	15.50	0.96	0.96%
11	Infiltration rate	**0.235**	**15.50**	**0.95**	**-0.06%**

Table 3 Overheating analysis for base case model

Number of occupied hours temperatures >28° in living area							
Emission Scenario	Birmingham TRY	TRY Birmingham			DSY Birmingham		
		2030 TRY	2050 TRY	2080 TRY	2030 DSY	2050 DSY	2080 DSY
Medium Emissions Scenario	0	16	37	102	99	95	184
Percentage of Occupied Hours		0.8%	1.9%	5.1%	5.0%	4.8%	9.2%
High Emissions Scenario	0	16	56	228	78	90	232
Percentage of Occupied Hours		0.8%	2.8%	11.4%	3.9%	4.5%	11.6%

Table 4 Mitigation of overheating with shading

Number of occupied hours temperatures >28° in living area				
Shading Strategy	Birmingham TRY	DSY High Emissions Birmingham		
		2030 DSY	2050 DSY	2080 DSY
Base Case Model	0	78	90	232
Brise-Soleil 120cm	0	70	89	220
Decrease		-10.26%	-1.11%	-5.17%
Louvers (April-Sep)	0	50	82	176
Decrease		-35.90%	-8.89%	-24.14%

Table 5 Mitigation of overheating with free cooling

Number of occupied hours temperatures >28° in living area				
Free Cooling Strategy	Birmingham TRY	DSY High Emissions Birmingham		
		2030 DSY	2050 DSY	2080 DSY
Base Case Model	0	78	90	228
Free Cooling 1ach	0	34	62	183
Decrease	-	-56.41%	-31.11%	-19.74%
Free Cooling 3ach	0	31	53	147
Decrease	-	-60.26%	-41.11%	-35.53%
Free Cooling 5ach	0	31	50	112
Decrease	-	-60.26%	-44.44%	-50.88%

Table 6 Mitigation of overheating with shading and free cooling combined

Number of occupied hours temperatures >28° in living area				
	Birmingham TRY	DSY High Emissions Birmingham		
		2030 DSY	2050 DSY	2080 DSY
Base Case Model	0	78	90	232
Percentage of Total Occupied Hours	-	3.90%	4.50%	11.60%
Free Cooling 5ach + Louvers	0	20	43	95
Percentage of Total Occupied Hours	-	1.00%	2.15%	4.75%
Decrease	-	-74.36%	-52.22%	-59.05%

A question can be asked whether the resultant heating set temperature in Table 2 might indicate a possibility of the occupants' thermal discomfort. However, there are two points to bear in mind. Firstly, the simultaneous use of two parameters in the error minimisation effectively creates a two-dimensional error function, which could be described as a rugged landscape with hills and valleys, and therefore having local minima as well as a global minimum. The result of the minimisation in Table 2 could represent a local rather than a global minimum, however a further investigation of the minimisation function was outside of the scope of this paper. Secondly, a detailed thermal comfort study carried out by Jankovic (2012) found that Predicted Percentage of Dissatisfied (PPD) was 6.87% in winter and 5.17% in summer, hence quite close to thermal neutrality as defined in ASHRAE 55-2004 of PPD=5% for predicted mean vote of PMV=0.

SIMULATION EXPERIMENTS

Overheating analysis

Using the results of the calibrated simulation model, overheating analysis was first carried out for the current climate conditions.

The overheating was considered to be occurring when the internal air temperature exceeded 28^{o}C in living spaces according to the CIBSE guide A (2006). The results of this initial overheating analysis for the Typical Reference Year (TRY) and Design Summer Year (DSY) are shown in Table 3, with no overheating in the current climate. Overheating occurs when applying future weather files, increasing steadily under TRY future climate predictions of 50th percentile, thus reaching almost 102% of the initial value in 2080 under the medium emissions scenario, 228% of the initial value under the high emissions scenario in the same year. The overheating appears to be worse under the DSY 50th percentile predictions, reaching 184% of the initial overheating hours under the medium emissions scenario in 2080, and almost 232% of the initial value under the high emissions scenario in the same year.

Mitigating overheating

As overheating predicted in this way appears to be significant, the question is whether it could be mitigated with relatively simple measures such as shading and/or free cooling. The analysis of mitigation of overheating was carried out for DSY climate files under the high emissions, being the worst case scenario.

Two types of shading devices were introduced into the simulation model, applied to the south-west facade. Brise-soleil shading of 120 cm, and external louvers for the summer months. Results of mitigation of overheating with shading are shown in Table 4. The most significant reduction is in the year 2030, between 10% (120 cm brise-soleil) and 35% (louvers). The effect of shading is diminishing through the future climate years, so that the reduction of overheating is between 1% (120 cm brise-soleil) and 24% (louvers).

As the results of mitigation of overheating with shading devices was not entirely satisfactory, still leaving significant overheating in the building, the effect of free cooling was subsequently investigated.

Free cooling is a term that refers to cooling with external air, at the time when its temperature is lower than the inside temperature, whilst the inside temperature is approaching the overheating temperature. This is typically achieved using mechanical ventilation heat recovery (MVHR) systems in a bypass mode so that colder incoming air does not exchange heat with warmer exhaust air. As the simulated building already has the MVHR system, this type of cooling was considered to be realistic.

Firstly, a free cooling profile was created in the simulation model, so as to operate the mechanical ventilation under the following conditions:

1) external air temperature is lower than internal air temperature, and
2) internal air temperature is greater than 26 ^{o}C

The somewhat lower temperature trigger for starting the free cooling of 26 ^{o}C was chosen in an attempt to prevent the overheating in advance, rather than to deal with overheating when it has already started to occur.

Secondly, three air change rates for free cooling were set in the internal conditions template: 1, 3 and 5 air changes per hour (ACH).

Similarly as in the case with shading, the most significant reduction of overheating through free cooling was achieved in the year 2030 , with 56% decrease from the initial overheating hours under 1 ACH, and 60% decrease under 5 ACH (Table 5). Unlike solar shading, free cooling provided significant reduction of overheating through the future climate years, achieving 19% reduction of the total overheating hours at 1 ACH in 2080, and 50% reduction at 5 ACH in the same year (Table 5).

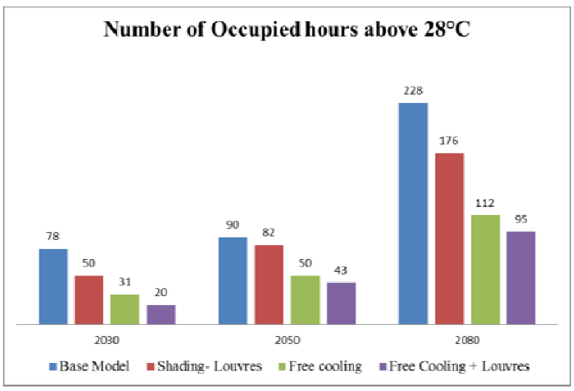

Figure 5 Reduction of overheating through mitigation

However, even with this significant reduction, the overheating was still occurring in the building. A question was then raised whether the combined effect of shading and free cooling could lead to more significant reduction of overheating. The results of the combined analysis are shown in Table 6. The combined effect of these two measures reduces the number of overheating hours to 20 in the year 2030 representing the reduction of almost 74.3%. In 2080, the reduction is just over 59%, making the total number of overheating hours of 95. The effects of the mitigation measures are summarised in Figure 5.

DISCUSSION

Dynamic simulations were carried out for the thermally calibrated model. The UKCP09 probabilistic future weather files for Birmingham were used to look at the effect of global warming on the internal environment and possible mitigation measures.

The calibrated model was tested using medium and high emissions scenarios of 50th percentile, Both TRY & DSY weather files showed a great increase of overheating, which was related to the number of occupied hours over the CIBSE comfort threshold temperatures of 28^{o}C in living spaces.

The overheating increase of up to 228% indicated the need of future proofing buildings in the context of climate change, in order to maintain thermal comfort as well as a carbon negative performance. Several methods were used in order to mitigate overheating: external shading; free cooling; and a combination of shading and free cooling.

The first mitigation method applied to the model was external shading elements to reduce solar gains. The brise-soleil showed the capacity of reducing temperatures in the near but not in the far future extreme weather, noting that in this model the façade is south-west facing, and the hot western sun will still penetrate the living room with the brise-soleil.

Adding louvers in the period between April-September when solar radiation exceeded 200 W/m² showed higher reductions. This would have a less visual effect on the façade than the brise-soleil.

The free-cooling using the existing MVHR has proved the ability to achieve more comfortable internal conditions, especially when combined with the louvers. Nevertheless, the two mitigation methods combined do not reduce the percentage of overheating hours below the CIBSE recommended 1%, bearing in mind that weather files used are representing the 50th percentile worst-case scenario.

A new Technical Memorandum addressing adaptive thermal comfort is being formed by CIBSE, due to the limited data for outdoor running mean temperatures greater then 25 ^{o} C. Research shows that when outdoor temperatures exceeds 25 ^{o} C then the upper limit indoor operative temperature for healthy adults would be 31 ^{o} C (Porritt et al, 2012). Therefore, thermal comfort thresholds will rise with the rising temperatures, taking into account the human adaptation.

Mitigation methods need to be part of the retrofit decision-making process, in order to eliminate further costs in the future and also to help maintain a low energy performance. With the current focus on heating demands, we need to be aware of the highly possible cooling demands as shown in the dynamic simulation results.

CONCLUSION

This paper described the results of simulation analysis of the Birmingham Zero Carbon House, a 170 years old Victorian residence that has achieved zero carbon performance through retrofit. An IES simulation model of the house was calibrated for total energy consumption and internal temperature, so that the relative error between actual and simulated energy consumption was less than 0.1% and the temperature error was less than 1C. Subsequently, the model was used for the analysis of overheating under the current climate, and under climate predictions for 2030, 2050, and 2080.

The results of this paper show that overheating arising from climate change can be effectively but not fully mitigated using relatively simple measures, such as shading and free cooling. The combination of these two measures achieves the best results.

These results should not be generalised, as they correspond to a specific case of the Birmingham Zero Carbon House, which has high level of thermal insulation and thermal mass. The future climate data used for this analysis are probabilistic, which further restricts a generalisation.

However, the results show a clear pattern of reduction of overheating hours, demonstrating that our homes would be able to provide comfortable shelters under increasingly difficult conditions resulting from the climate change. Therefore, it is advisable to prepare homes gradually for adaptation to climate change. The two examples of shading and free cooling given in this paper are not the only low energy and low emissions measures that are capable of mitigating the effects of climate change. Evaporative cooling, absorption cooling and others would be equally suitable, but these were outside of the scope of the current paper. However, they are on the agenda of our research team and will be investigated in the near future.

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