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Thermal comfort in UK housing to avoid overheating: lessons from a 'Zero Carbon' case study

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Abstract
In response to the UK Government's commitment to reduce carbon emissions by 80% by 2050 through the Code for Sustainable Homes (CSH), the Sigma Home was designed and constructed by the Stewart Milne Group in 2007. This is the UK's first five star rated home under the Code which is on display at the Building Research Establishment, Innovation Park at Watford. In order to evaluate the actual performance of the house, a co-heating test, thermal comfort survey and window opening behaviour survey were conducted in the Sigma Home. Adaptive thermal comfort behaviours such as the clothing and window adjustments were consistently observed during each occupancy period. The findings suggest we need to avoid the temptation to over-engineer homes, and to design homes and build systems that meet the needs of a mid-range of temperatures, which have fast acting functionality when required, to suit temperature peaks and troughs, out with the mid range levels.

1. Introduction
The UK government is committed to reducing carbon emissions by 80% by 2050 and has now legally enforced the Energy Performance of Buildings Directive which requires that all buildings carry an energy label (Statutory Instrument, 2007). In response to these drivers, the housing market has seen an exponential development of policy culminating in the CSH (2007) and increasingly onerous building regulations in relation to energy performance and carbon emissions for new build housing.

There is an increasing recognition that actual evidence-based building performance, related to occupant behaviour and as-built performance, must inform sustainable housing development, rather than an over reliance on assumed satisfaction surveys, modelling, supply chain rhetoric and estimated design performance. The Stewart Milne Group (SMG) is at the forefront of housing innovation utilising modern methods of construction and is striving to address the highest standards of performance, as outlined in the CSH.

As part of SMG's commitment to sustainable development and the CSH criteria, this research project aimed to fill a gap in their knowledge relating to the strategic impact, practical implementation and effect on their customers of low energy/carbon homes. Their approach was to extend the Sigma research programme, to include post occupancy evaluation (POE) and monitoring of the home. The research focused on the newly developed Sigma Home, as demonstrated at the BRE Innovation Park in Watford, as a pilot study, in order to better understand and tease out key lessons for the future development of the Sigma Home product and to shape and influence policy makers, through a structured research programme.

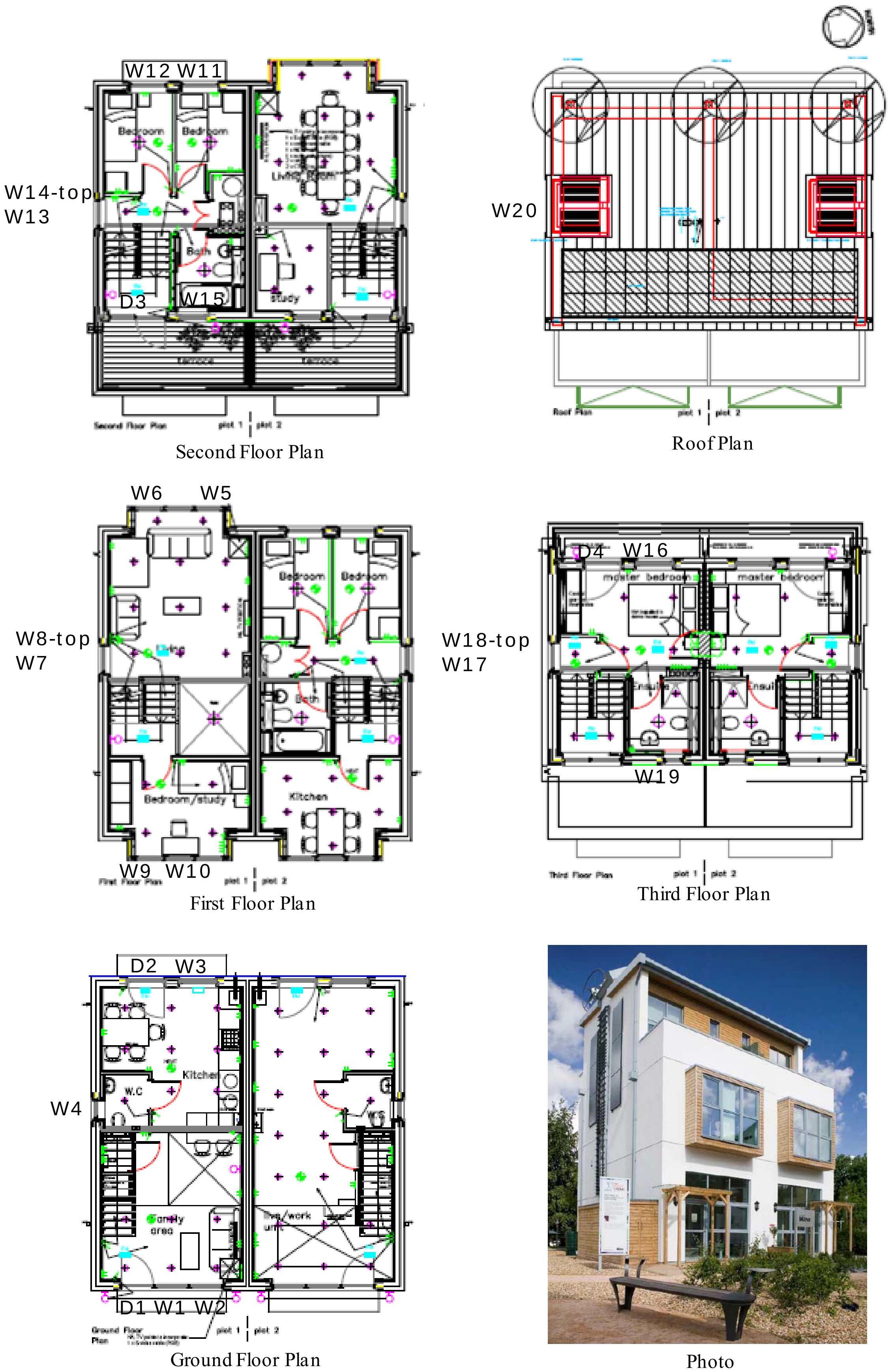

Fig. 1. Plan and view of the Sigma Home.

The study has provided considerable insight into occupants' expectations, perceptions and behaviour in relation to living in an innovative and low energy/carbon home designed to achieve CHS Level 5 standard. This paper focuses on the co-heating test, thermal comfort survey and window opening behaviour, and discusses how the occupants adapted in relation to overheating.

2. Methods

The Sigma Home, a semi-detached prototype dwelling was designed as a contemporary timber frame 3 storey townhouse, arranged over 4 floors to minimise building footprint and maximise living accommodation while making the home affordable (Fig. 1). The home was originally built as a show home, but classified as a test building. This research investigates the overall 'as-built' performance of the plot one.

Co-heating test

In order to establish the actual fabric heat loss co-efficient, a co-heating test was carried out between 6th and 12th March 2008, prior to occupation and while the building was empty (Fig. 2). The amount of heat used to maintain a steady temperature was then calculated and directly equated to the actual heat lost through the fabric. The test was carried out in winter conditions to avoid external temperatures becoming too close to internal temperatures. Major difficulties with the technique included ensuring that nobody entered the building during the test period and taking account of the variations solar gain. This involved completely sealing all openings for the test period. The temperature in the home was set at 27ºC for several days prior to the test itself, due to the relatively warm conditions outside. This enabled a satisfactory temperature difference to be maintained at around 26ºC for the duration of the test. This was not ideal as accuracy begins to fall off when temperatures are above 21ºC indoors, but acceptable under the circumstances.

Fig. 2. Monitoring equipment set up for the co-heating test

Thermal comfort survey

To expand the knowledge of the strategic impact, practical implementation and effect on consumers, of low/zero carbon homes, a post occupancy survey was conducted in the Sigma Home. A family of four (two parents and two children, aged 7 and 12) were recruited for 4 two week occupation periods, from April to December 2008, one in each season of the year. The home was inhabited in very much as normal, with the family carrying out typical daily routines, in an uninterrupted manner. The thermal comfort survey was conducted in the living room using questionnaires which are shown in appendix 1. All members of the family completed the individual thermal comfort sheets provided and 232, 236, 260, and 280 samples were received in Spring, Summer, Autumn and Winter respectively. We physically monitored the air temperature, globe temperature and relative humidity.

Door and window opening behaviour

Contact wireless sensors were used to measure the open or closed status of the external windows and doors of the home (Fig. 3). Due to technical difficulties with these innovative sensors, only two of the four occupancy periods of Autumn and Winter provided accurate data. The labelling of the doors and windows are shown in Fig. 1. There are 4 doors (D1 to D4) and 20 windows (W1 to W20) which are all external openings. All windows are opened manually except W20 which can be opened manually or automatically. The door and window opening behaviour was monitored every minute as a binary data (0=closed, 1=open). Wireless and non-wireless data loggers are placed in four key locations in one home (living room, kitchen, bed room, bathroom and corridor) and two key locations externally to establish temperature and relative humidity levels in the home and outside of it during the four occupancy seasons. The data were collected every minute. These data were analysed for the occupied hours which were identified from the time of thermal comfort voting and the daily activity log sheets completed by the occupants.

Fig. 3. Wireless contact sensor on external door opening

3. Results and discussions

3.1 Co-heating test

The indoor temperatures were almost constant during the co-heating test and the mean value is 26.7°C (Figure1 and Table 1). Results showed that indoor temperatures are well maintained in the tested period. The mean indoor and outdoor temperature difference (Δt) is 19.0 K which is well above than the minimum requirement of the co-heating test: 15 K (Lowe *et al.* 2007).

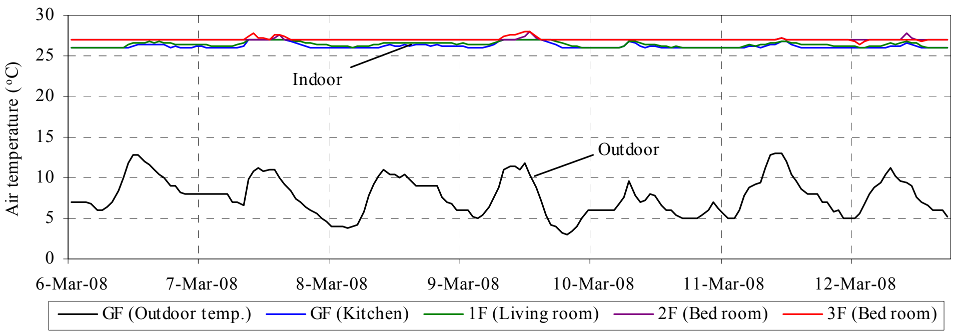

Fig. 4. Indoor and outdoor air temperature variation for 7 days.

Table 1. Average indoor and outdoor air temperature for 7 days.

Description	Air temperature (°C)
GF (Kitchen)	26.2
1F (Living room)	26.4
2F (Bed room)	27.0
3F (Bed room)	27.0
Average (Indoor)	26.7
GF (Outdoor air temperature)	7.7
Indoor and outdoor temperature differences (K)	19.0

All data were measured at 1-minute interval. Indoor air temperatures were measured at 1 m from the floor level and outdoor air temperature was measured about 2 m from the ground level.

Prediction of the ventilation heat loss

The ventilation rates V_n (air change rate per hour) were estimated using a variant of the 1/20 rule-of –thumb (Lowe *et al.* 2007):

$V_n=0.85q_{50}/20$ (1)

where 0.85 is the shelter factor by assuming the two sides sheltered. q_{50} is the air permeability of the house which were measured before: 2.72 $m^3/(h.m^2)$ @ 50 Pa and after: 4.80 $m^3/(h.m^2)$ @ 50 Pa the co-heating test. Two values are quite different because the first value was measured about 6 months before the co-heating test and the second value was measured at the end of the co-heating test, after some sealant had been removed accidentally. The predicted ventilation heat loss C_v (W/K) were calculated using the following equation.

$C_v=0.33V_nV$ (2)

where, 0.33 is the specific heat of air (W/m^3K). V is the volume of the house (326.25 m^3).

Corrections of the solar gain

The hourly power consumption was corrected for the solar gain. As suggested by Wingfield *et al.* (2006), multiple regression method is used for correction. The results are shown in the Table 2.

$P_r=a\Delta t+bS+c$ (3)

P_r=total hourly real power consumption (W)

Δt =hourly mean indoor and outdoor temperature differences (K)

S=hourly mean solar radiation (W/m^2)

a & b = regression coefficients

c=constant

$P_c=P_r-bS$ (4)

P_c=Corrected hourly power consumption (W)

Table 2. Multiple regression analysis to correct the solar gain.

Equation	n	r	S.E.		*p-value*	
			Δt	Solar (S)	Δt	Solar (S)
$Pr=41.5\Delta t-5.5S+1928.3$	169	0.50	11.8	0.2	$p=0.001$	$p=0.005$

n: number observations, r= correlation coefficient, S.E. (Standard Error) and p-value are shown for each regression coefficient. (To consider the variation of the solar radiation, hourly mean data is used for multiple regression analysis. We also checked by the day and night mean or daily mean value but all the regression coefficients are not statistically significant due to the small variation in measured data.)

Table 3. Predicted and actual heat loss of the Sigma Home.

Variable (W/K)	Co-heating test	
	Before	After
Predicted fabric heat loss (C_f)	60.96	60.96
Predicted thermal bridging (H_{TB})	19.93	19.93
Predicted ventilation heat loss (Cv)	12.45	21.96
Total predicted heat loss coefficient ($C_f+H_{TB}+Cv$)	93.34	102.85
a. Total mean predicted heat loss coefficient	98	
Mean heat loss coefficient of the measured data	142	
b. Mean heat loss coefficient of the corrected data	144	
Differences (a-b)	46	

The thermal bridging calculation is based on accredited construction details by using a global Y-value from SAP (2005). Further investigation of all fabric detailing would be required for a more realistic prediction.

Predicted and actual heat loss

The predicted and actual heat loss coefficient is shown in Table 3 and Fig. 5. The fabric heat loss coefficient and thermal bridging were predicted by using SAP (2005). The ventilation heat loss and corrected heat loss coefficient were calculated by using equations (2) and (4) respectively. The actual heat loss coefficient is 144 W/K which is higher than the predicted value of 96 W/K.

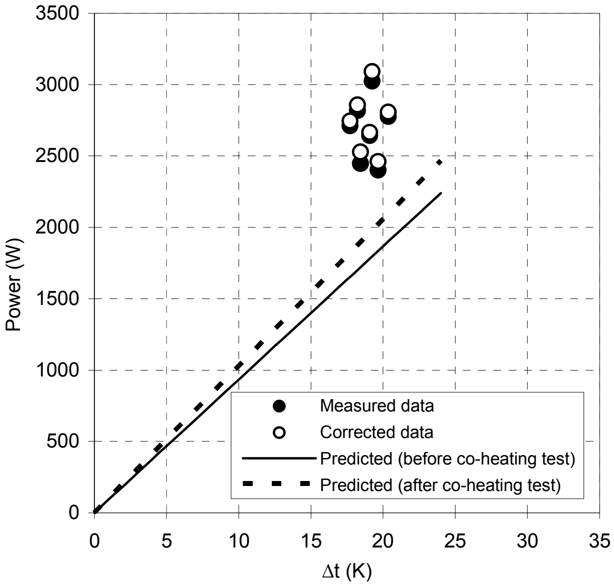

Fig. 5. Relation between the power and Δt.

The use of thermal imaging during the test period identified significant air leakage around the window frames and under the skirting boards as well as several cold bridges at complex junction points (Stevenson and Rijal, 2008). The Co-heating test and thermal imaging clearly revealed the 'as- built' performance of the fabric, following construction. The findings indicate the as built, heat loss parameter was approximately 50% worse than the predicted design stage assessment. This clearly has implications for predicted thermal comfort conditions as designed for and suggests that predicted modelling will be inaccurate until construction techniques are improved.

3.2 Thermal comfort surveys

Thermal comfort votes

In just under half of the responses the occupants feel 'comfortably warm' with a relatively even distribution of feelings ranging between 'too warm' and 'too cool' (Fig. 6, Appendix 1). Even though some of responses are 'too warm' in Summer, most of responses are in the centre three categories (comfortably cool, comfortably neither warm nor cool and comfortably warm) which are taken as a comfort zone with a drift towards feeling 'comfortably cool'. The feeling changes in the Autumn and Spring with a drift towards feeling 'comfortably warm'. The results indicate that the occupants are generally very satisfied with the thermal condition of the house in all seasons.

Thermal preference votes

The occupants generally preferred the temperature to remain as it was, with well over half the samples in this category, across all four seasons (Fig. 7, Appendix 1). There is an improvement from Summer to Winter, with the occupants feeling that the temperature was just right, for more of the time in the Winter. There is good agreement with the feelings of comfort experienced and the preference for temperature in all four seasons (Fig. 8). This means that the results are reliable in terms of relating comfort to temperature.

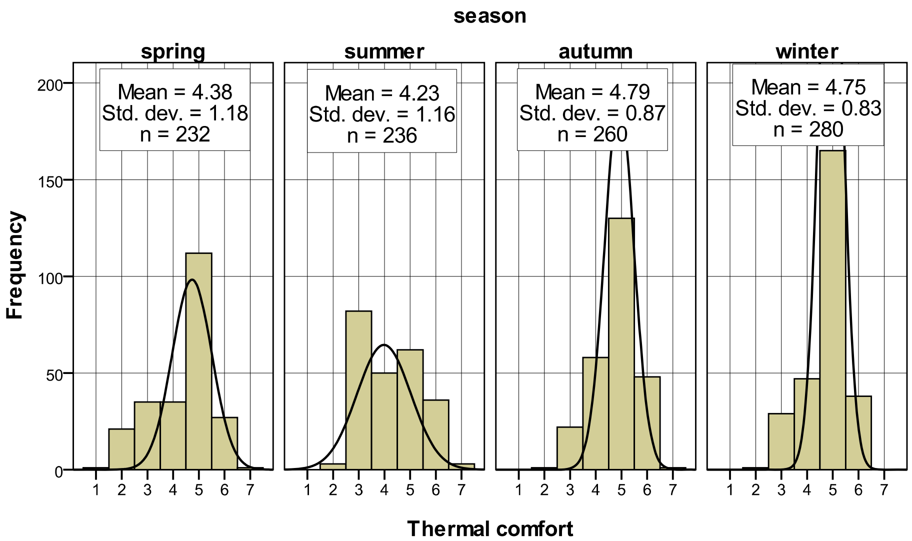

Fig. 6. Distribution of thermal comfort votes

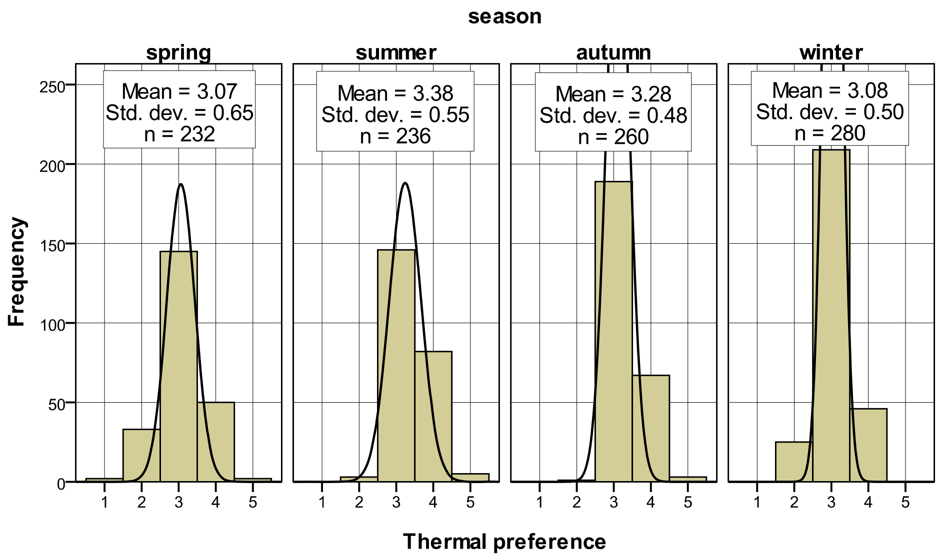

Fig. 7. Distribution of thermal preference votes

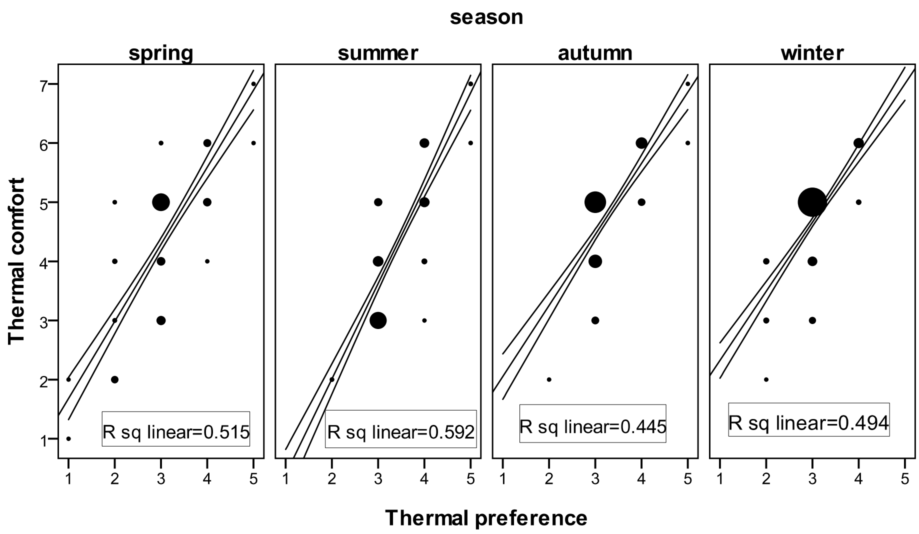

Fig. 8. Relation between the thermal comfort and thermal preference (The size of 'circle' represents the number of votes.)

Overall comfort

In Fig. 9, most of the samples are in the 'comfortable' columns (scales 4, 5 & 6). Less than 10% of the samples showed 'Slightly uncomfortable' (scale 3) and no major discomfort was experienced in any season. There is a slight increase in overall comfort for the Summer period, which may be due to the family feeling they had more control over the conditions, with the use of the adjusted Mechanical Ventilation with Heat Recovery (MHVR) supplemented by the opening of windows, although this is speculative at this stage of the research. This feeling increased in the Autumn and Winter period with a significantly increased number of samples registering greater overall comfort. The comfort condition of each member of the family is generally higher, than the seasonal averages, apart from the son (Fig. 10, Appendix 1). In terms of overall comfort, the home was very successful, with the family feeling increasingly comfortable over the duration of the four occupancy periods.

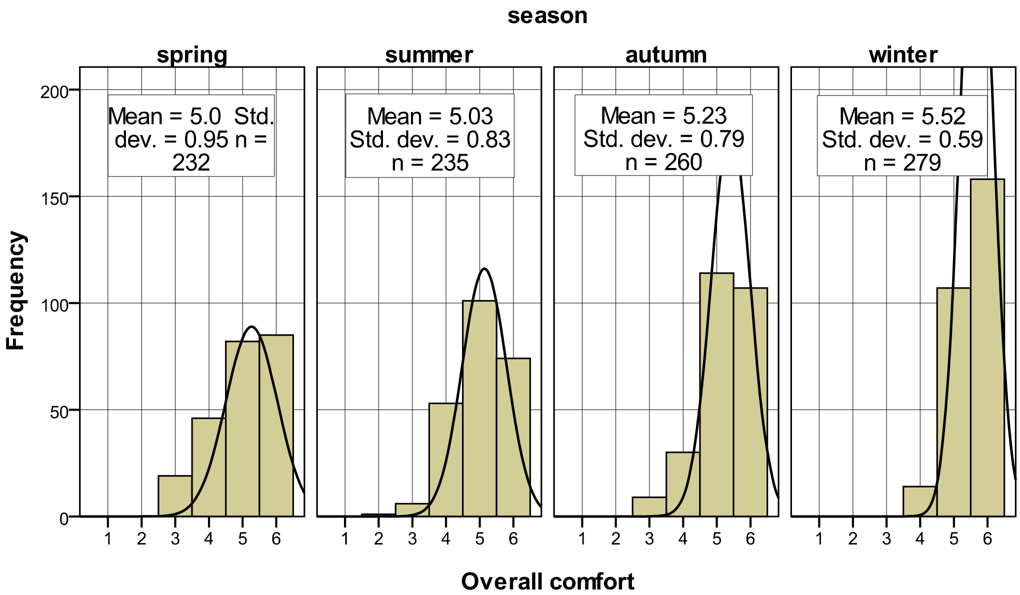

Fig. 9. Distribution of overall comfort

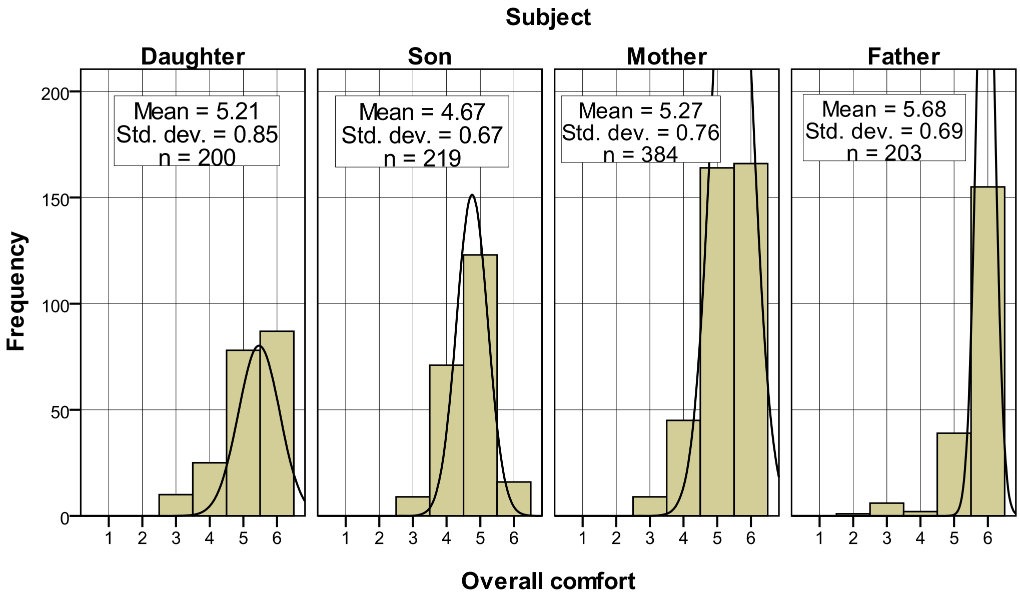

Fig. 10. Distribution of overall comfort for each subject

Layers of clothing

Generally the family only wore one or two layers of clothing in the home (Fig. 11). This indicates that they had adapted to the generally warm conditions in the home, with average temperature ranging between 20.5-23.4 ºC at the time of voting. The family generally wore more layers of clothing in the Spring period than the Autumn period (Fig. 11). This was because they were used to wearing less layers of clothing in the Summer period (Fig. 11) and thus even when temperatures were relatively cooler externally, they still wore mainly only one layer of clothing, in the Autumn. The correlation coefficient of the layers of clothing and outdoor temperature is -0.26 (n=233, p=0.001) in Summer and -0.15 (n=233, p=0.017) in Winter which support the hypothesis. The family also wore more layers of clothing in Winter in response to the cooler temperatures outside and inside. They adjusted layers of clothing according to the varying outdoor air temperature from season to season.

Outdoor air temperature

Fig. 12 shows that the mean outdoor air temperature in Summer is 13.7K higher than in Winter. The thermal comfort data was collected and related to the outdoor temperature in all four seasonal periods. The mean outdoor temperature for the Autumn period is half way between the Spring and Summer mean temperatures, while the Winter temperature is lower.

Indoor air temperature

The overall indoor temperature in Summer is higher than in Spring (Fig. 13).The family experienced the greatest temperature range within the home in the Summer, when they recorded their perceptions. The average overall indoor temperature for Autumn is slightly lower than for the Summer but higher than the Spring and Winter temperature. Paradoxically, the family felt 'comfortably cool' in the Summer but 'comfortably warm' in the Autumn and Winter, even though the average temperature inside, was slightly lower during these periods.

Indoor relative humidity

The indoor relative humidity was generally within the comfort zone of 40 to 60% but is an average of 10% lower for the Autumn period (Fig. 14). This would explain why the family felt things were drying more quickly, but does not explain why they felt the air was 'less dry' in the Autumn, when the opposite is the case. The relative humidity is slightly low in Winter possibly due to the greater use of central heating.

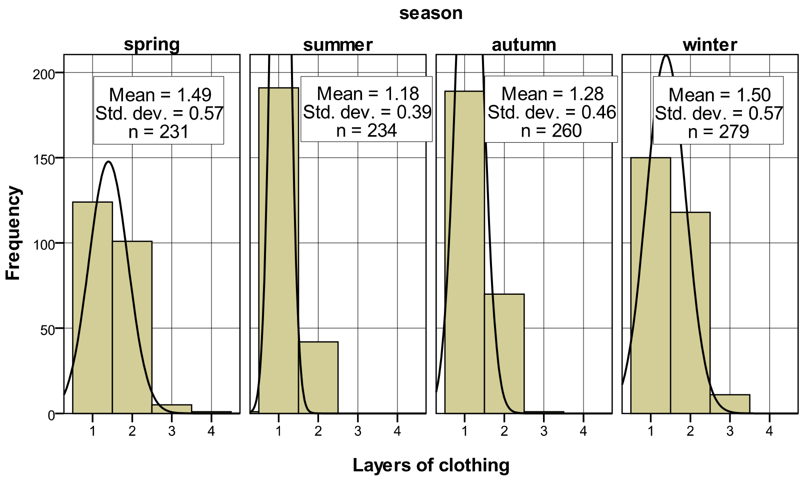

Fig. 11. Distribution of layers of clothing

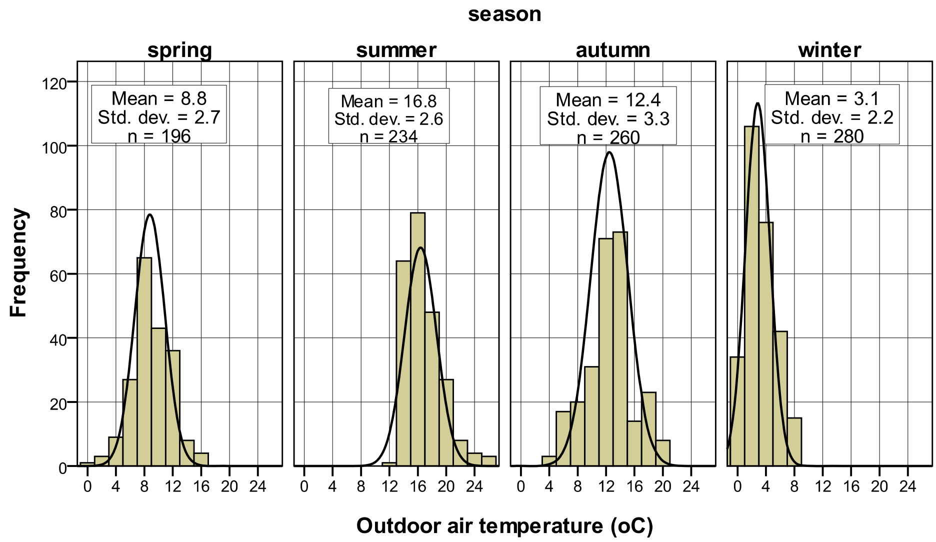

Fig. 12. Distribution of the outdoor air temperature at the times of voting

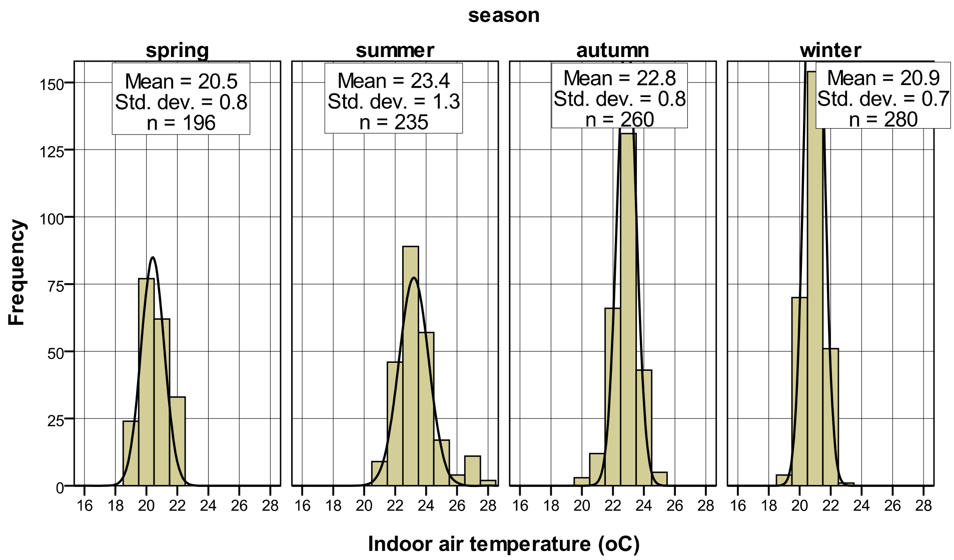

Fig. 13. Distribution of the indoor air temperature at the times of voting

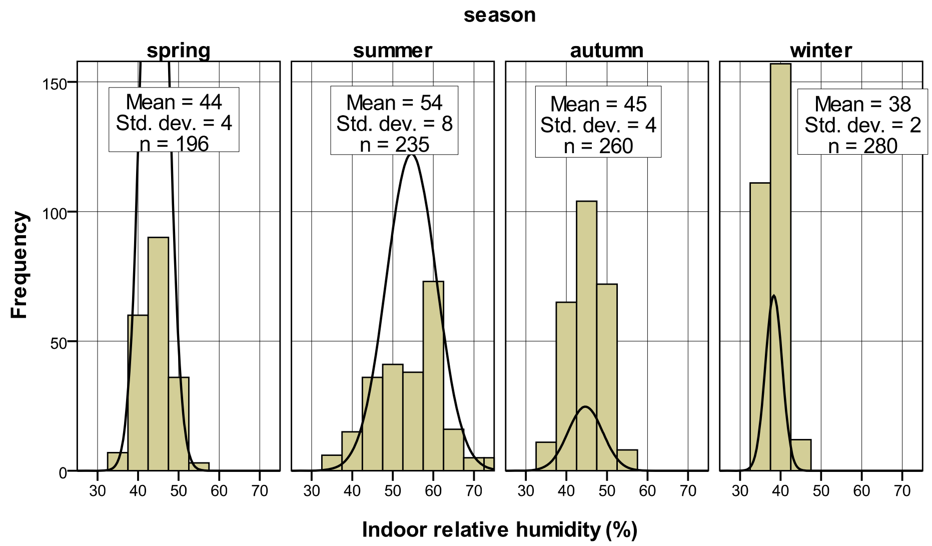

Fig. 14. Distribution of the indoor relative humidity at the times of voting in living room.

Prediction of comfort temperature

The indoor air temperature and globe temperature are well related (Fig. 15) and thus the indoor air temperature (T_i) has been used to calculate the predicted comfort temperature (T_c) by using Griffiths' method (Griffiths, 1990, Nicol *et al.*, 1994, Rijal *et al.* 2008).

$T_c = T_i + (4 – C) / a*$ (5)

Where C is thermal comfort vote and a* is the assumed value of regression coefficient. The choice of an appropriate value for the gradient is difficult. We have assumed a gradient of 0.5 votes/K (Nicol *et al.*, 1999, Rijal *et al.*, 2008).

Fig. 16 shows that the predicted comfort temperature for people living in the Sigma Home in Summer is higher than in Spring and then lower for the Autumn and Winter again.

The actual indoor air temperature in Autumn and Winter was a degree and a half higher than predicted, *indicating that the house may have been running at a temperature higher than necessary due to incidental heat gains* and an inability to effectively control the heating temperatures. The family still felt 'comfortably warm' rather than 'neither warm nor cool', although it is not clear whether they are in fact choosing to be 'comfortably warm' rather than 'neither warm nor cool'. Ideally, the comfort temperatures should stay within two degrees either side of the mean comfort temperature for any day, as people can generally tolerate a four degree daily variation within the home as a 'comfort zone'. Further analysis is required for the daily variation of the comfort temperature. What is apparent is that people will tolerate quite a high degree of variation in each season and that they are comfortable at different temperatures related to the seasonal temperature. Heating and ventilation controls need to be adjusted each year to recognise this variation and tolerance threshold. This could be done as part of the maintenance programme and user induction.

The comfort temperature was then related to the outdoor air temperature (Fig. 17). Due to the seasonal adaptation, the comfort temperature is lowest in Winter, middle in Spring and Autumn and highest in Summer. This finding is similar to the finding of Humphreys (1975). The following equations are obtained from the regression analysis.

T_c=0.22T_{out}+18.6 (n=969 (all), r=0.53, p<0.001) (6)

T_c=0.32T_{out}+17.2 (n=491 ($T_{out}\geq$10°C), r=0.40, p<0.001) (7)

When outdoor air temperature (T_{out}) is greater than 10 °C, the regression coefficient is close to the CEN standard (CEN, 2007).

When we assume the equal sensitivity for each family, the comfort temperature of the adults is about 2 K higher than for the children (Fig. 18). This could be related to the higher number of layers of clothing worn by the children (Table 4). The regression coefficient is also close to the overall data (see equation 6).

Adaptive comfort behaviour was consistently observed during each occupancy. This relates to the individuals comfort perception and threshold. Generally the occupants recognised the seasonal changes and the varying hot or cold outdoor temperatures and adapted their behaviour and perceptions accordingly. This was particularly evident in their daily routines, and clothing adjustment. This is adverse to the design concept for consistent and regulated cooling and heating functionality within the home. However the homes flexibility and variety of heating and cooling systems, met with a high degree of acceptance by the family. They felt they could respond to the thermal comfort conditions in the home, when they wanted to. The key findings of the thermal comfort survey are that there was a small seasonal variation in the indoor air temperature, which tracked the larger seasonal variation, in outdoor air temperature and that the family were comfortable with this. This demonstrates people's ability to adjust to seasonal temperatures and proves the theory of Adaptive Thermal Comfort. An energy saving could be made, by seasonally adjusting the indoor temperature of the home to reflect the predicted comfort temperature.

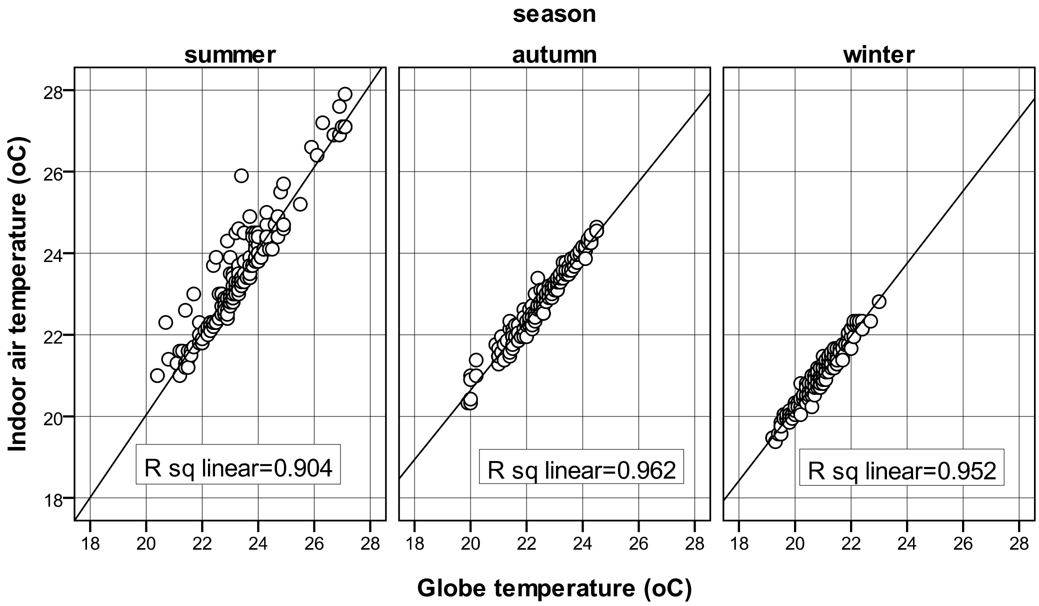

Fig. 15. Relation between the indoor air temperature and globe temperature

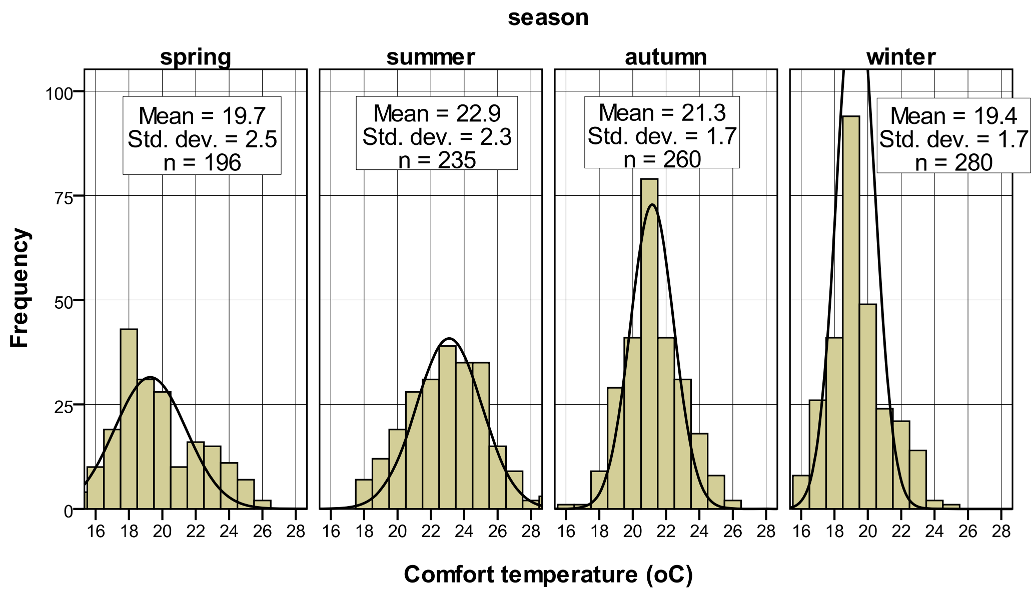

Fig. 16. Distribution of the predicted comfort temperature

Table 4 Number of layers of clothing for each subject.

Subject	Number of observations	Mean	Standard Deviation
Daughter	200	1.5	0.5
Son	217	1.4	0.6
Mother	384	1.3	0.5
Father	203	1.3	0.5
All	1,004	1.4	0.5

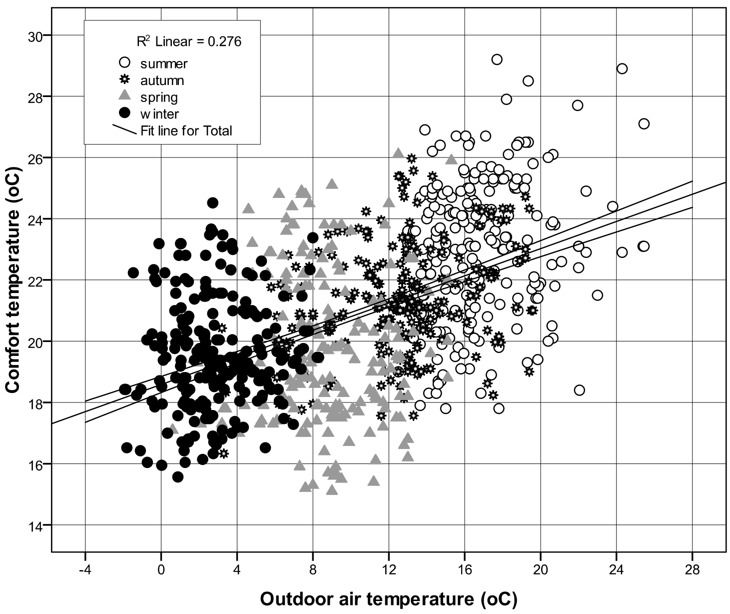

Fig. 17. Relation between the comfort temperature and outdoor air temperature.

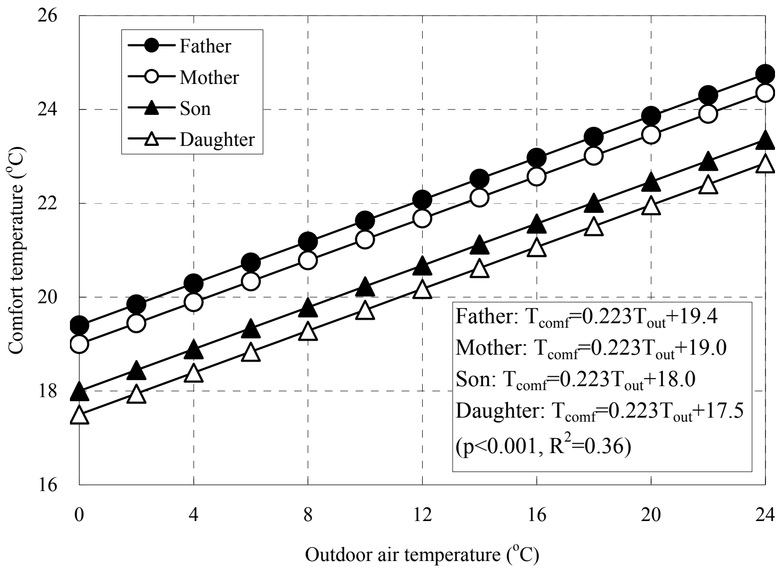

Fig. 18. Relation between the comfort and outdoor air temperatures for each subject.

3.3 Door and Window opening behaviour

A key aspect of building performance is the relationship between occupants' attempts to provide their own comfort conditions and the means provided for them to do this, set against any automated building performance controls. It is well known that occupants' desire to open windows can often confound attempts to save energy in housing, through the use of MHVR systems (Macintosh and Steemers, 2005). A key aim of this study was to establish how the family was ventilating the Sigma Home, using the windows and doors and what relationship this had with their perceptions of thermal comfort, as well as the use of the MVHR and heating systems. This might begin to provide the means for predicting the window behaviour for future housing design, given certain comfort conditions.

Proportion of door and window opening in Autumn

The proportion of door opening is almost zero over the Autumn period and there is no correlation with outdoor air temperature (Table 5). The proportion of window opening varies significantly. Half of the windows (10 out of 20) were either never or rarely opened during the occupied hours. *W3, W5, W9, W11, W16, W19 and W20 are used as the main windows to control the indoor environment in each room*. In effect, only one window was being opened for each room. The correlation coefficients of these windows with outdoor air temperature are high except for the W19 and W20. The correlation coefficient of indoor air temperature and window opening were not consistent (some are negative and some are positive). This could be because the indoor air temperature variation is small (Fig. 19) compared with outdoor temperature (Fig. 20). The weak relationship between the window opening and indoor temperature maybe equally be because the windows are being used to control indoor temperature, which creates a feed-back relationship.

What is clear from the above findings is that only a very small number of windows are actually being used to ventilate/control the home by the occupants. *This in turn could mean that cost savings could be made by reducing the number of openable windows considerably* and 'tuning' the openable windows according to the occupant behaviour.

Table 5. Mean door and window opening, and correlation coefficient with outdoor air temperature in Autumn.

Space	Door & window	Number of observations	Mean	Correlation coefficient	*P-value*
Kitchen (GF)	D1	13,349	0.01	0.09	*p<0.001*
	D2	8,462	0.00	0.04	*p<0.001*
Balcony (2F)	D3	13,348	0.00	0.02	*p=0.008*
Balcony (3F)	D4	13,349	0.00	0.02	*p=0.005*
Kitchen (GF)	W1	13,332	0.06	0.48	*p<0.001*
	W2	13,349	0.01	0.21	*p<0.001*
	W3	**13,349**	**0.16**	**0.43**	***p<0.001***
Toilet (GF)	W4	13,349	0.00	0.01	*p=0.123*
Living (1F)	**W5**	**13,349**	**0.10**	**0.53**	***p<0.001***
	W6	13,329	0.01	0.03	*p<0.001*
	W7	13,349	0.00	-	-
	W8	13,349	0.00	0.06	*p<0.001*
Bed room (1F)	**W9**	**13,346**	**0.04**	**0.34**	***p<0.001***
	W10	13,349	0.02	0.20	*p<0.001*
Bed room (2F)	**W11**	**13,349**	**0.17**	**0.42**	***p<0.001***
	W12	12,413	0.11	0.42	*p<0.001*
	W13	13,349	0.00	0.00	*p=0.669*
	W14	13,349	0.00	0.01	*p=0.545*
Bed room (3F)	W15	11,522	0.00	0.01	*p=0.436*
	W16	**13,349**	**0.20**	**0.49**	***p<0.001***
	W17	13,349	0.00	-0.01	*p=0.551*
	W18	13,259	0.00	0.05	*p<0.001*
Shower room (3F)	**W19**	**13,349**	**0.43**	**0.11**	***p<0.001***
Roof	**W20**	**13,324**	**0.83**	**0.17**	***p<0.001***

P-value: Significant level (2-tailed) of the correlation coefficient, Mean = average proportion of door or window opening (e.g. 0.83 = 83% of the monitored time), Note: Windows highlighted in **bold** are main ones used by occupants.

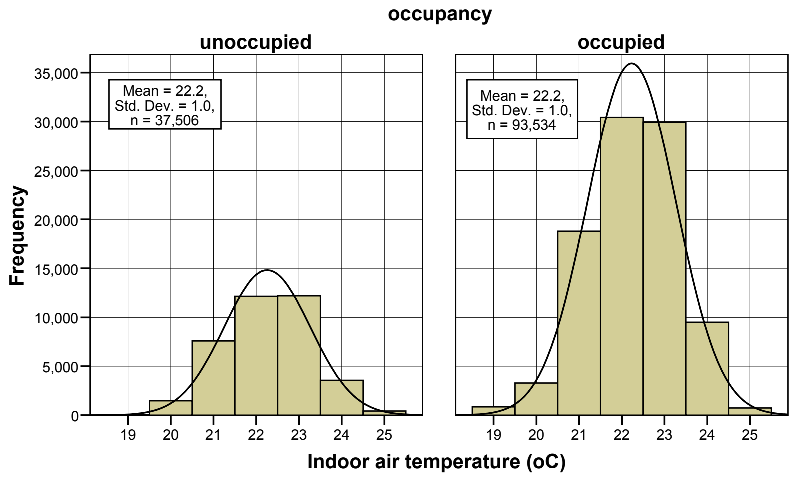

Fig. 19. Indoor air temperature in the kitchen, living room, bed rooms (1F, 2F & 3F) and shower room in Autumn.

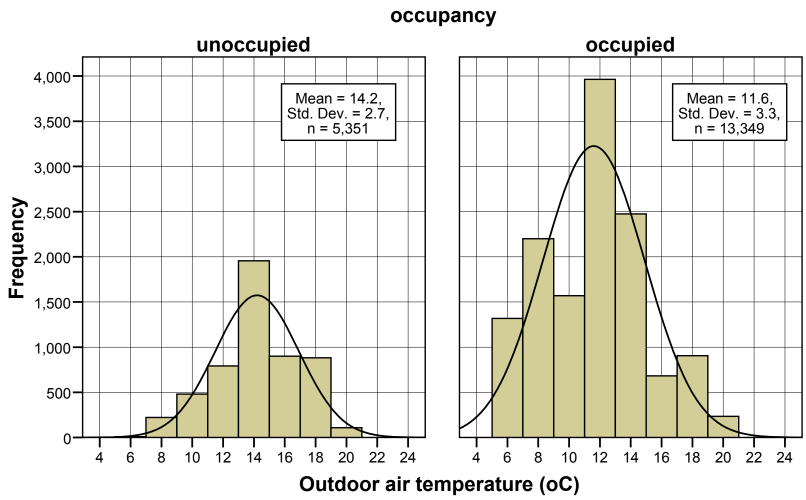

Fig. 20. Outdoor air temperature in Autumn.

Prediction of window opening in Autumn

This section explains the method for predicting the proportion of window opening to the change in temperature in the home. This is useful for understanding how the control windows identified above will generally be used.

The data for the window opening are provided in binary form. For binary data whose probability varies with a stimulus (in this case temperature) a useful statistical method is logistic regression (Nicol and Humphreys, 2004). Logistic regression equations describing the proportion of windows open are shown in the Table 6. The statistical package SPSS Version 17 was used for calculation. The relationship is governed by the logit relationship:

$$\mathrm{logit}(p)=\log\{p/(1-p)\}=bT+c \qquad (8)$$

$$p=e^{(bT+c)}/\{1+e^{(bT+c)}\} \qquad (9)$$

p is the probability that the window is open, T the temperature (outdoor), b the regression coefficient for T and c is the constant in the regression equation. All the regression coefficient in Table 6 are statistically highly significant (p<0.001). However, the coefficient of determination (R^2) of W19 and W20 is significantly low.

The results in Fig. 21 show that the proportion of W3, W5, W11 and W16 opening are similar for a given outdoor temperature. The proportion of W9 opening is lowest, indicating that W3 (kitchen), W5 (upper living room area), W11 (middle bedroom) are the windows which will be mainly used to control internal temperature variation by the occupants. The proportion of W19 and W20 opening is significantly higher in comparison with other windows. The reason could be that W20 opens automatically based on temperature-setting to avoid overheating. W19 may have an important role in avoiding the moisture build up in the shower room. The mean relative humidity of the shower room in the occupied hours was highest (53%) in comparison with other rooms. However, most of the relative humidity in the whole house is within the comfort zone (40 to 60%) in the occupied or unoccupied hours (Fig. 22).

A key issue with W20 top vent window over the stairwell, being open for so much time (83% of the monitored time) is that it is letting out warm air that the MVHR system cannot deal with during occupancy. This suggests that the house could be prone to overheating, purely due to internal gains without the skylight window being open. When this data is triangulated with the interview findings (which are to be covered in another paper), it is apparent that there is still a large amount of uncontrolled incidental heat gain in the home coming from: oven, lights, plasma TV (excessive), computers, showers, hot water pipes etc. Given that the average outdoor temperature for the Autumn period was not particularly hot, this is an issue that must be fully considered within the design of future low-carbon dwellings and is highlighted in the designer's guide (EST, 2005). This concern with the future overheating in low-energy housing is also reflected in research from Denmark (Marsh *et al.*, 2010).

Table 6. Logistic regression analysis of the selected windows for each room in occupied hour in Autumn

Space	Window	Number of observations	Equation	Coefficient of determination (R^2)
Kitchen (GF)	W3	13,349	logit=0.419T_{out}-7.06	0.18
Living (1F)	W5	13,349	logit=0.842T_{out}-14.15	0.28
Bed room (1F)	W9	13,346	logit=0.726T_{out}-14.00	0.12
Bed room (2F)	W11	13,349	logit=0.405T_{out}-6.82	0.17
Bed room (3F)	W16	13,349	logit=0.471T_{out}-7.40	0.23
Shower room (3F)	W19	13,349	logit=0.069T_{out}-1.08	0.01
Roof	W20	13,324	logit=0.143T_{out}-0.01	0.03

T_{out}: Outdoor air temperature, R^2: Cox & Snell R square, Note: All regression coefficients are significant ($p<0.001$)

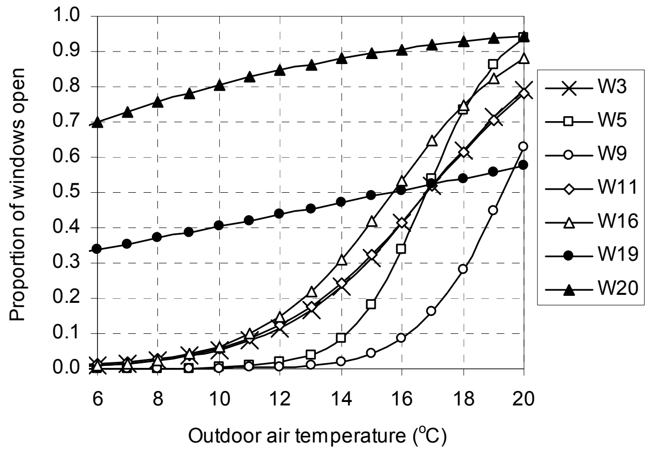

Fig. 21. Proportion of window opening as a function of outdoor air temperature in occupied in Autumn.

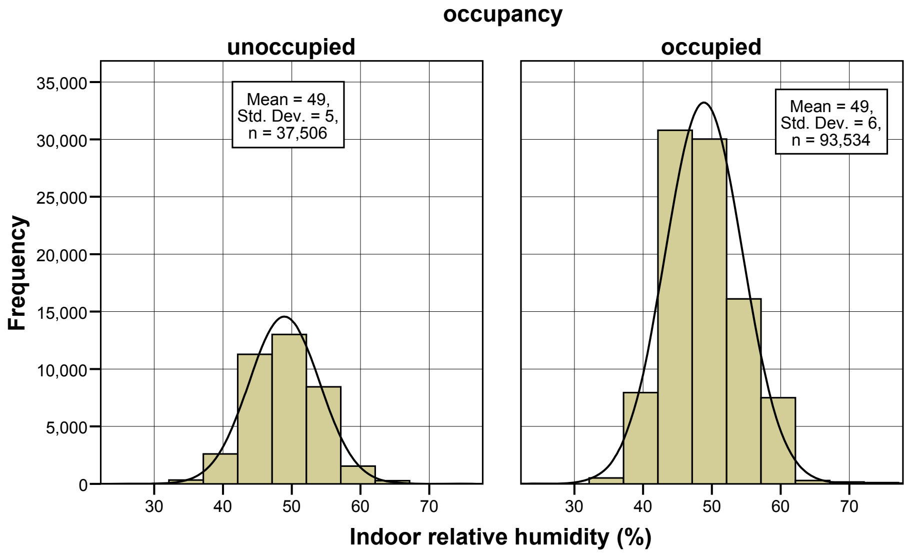

Fig. 22. Indoor relative humidity in the kitchen, living room, bed rooms (1F, 2F & 3F) and shower room in Autumn.

Door and window opening in Winter

The mean proportion of door and window opening is zero in Winter (Stevenson and Rijal, 2009). Similar behaviour was found in the UK and Pakistan office buildings (Rijal *et al.* 2007 and 2008). Thus, the analysis of correlation and prediction are not possible for Winter. However, we have analyzed the Standard Deviation (SD) of door and window opening for further analysis. Most of the SD in the occupied hours are higher than in the unoccupied hours (Stevenson and Rijal, 2009). This means that occupants primarily opened the doors and windows to control the indoor environment during the occupied hours. Because of low outdoor air temperature (Fig. 23), they might be being opened only for short period of time to avoid the cold air and to save the heat in the home at the time of occupancy. This needs further research to prevent unnecessary heat loss, whilst retaining a flexible outlook as to why the users may wish to open windows. There may be a gender element associated with window opening that deserves further investigation.

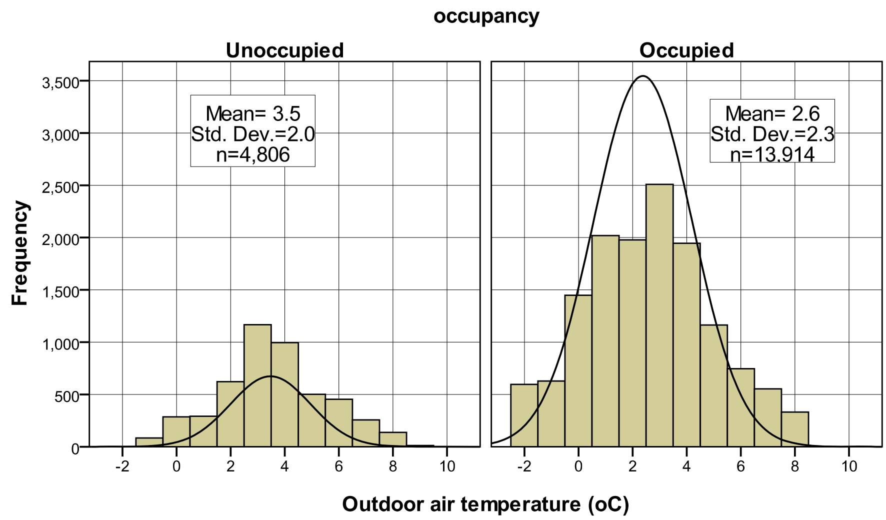

Fig. 23. Outdoor air temperature in the unoccupied and occupied hours in Winter.

4. Conclusions

The field investigation of the co-heating test, thermal comfort survey and window opening behaviour conducted in the Sigma Home reveals a number of clear lessons for the future development of 'zero carbon' housing:

1. The gap between the modelled and actual heat loss coefficient means that builders will have to focus more on the external fabric of homes, significantly improve construction techniques and avoid overly complex junctions if they are to meet the heat loss parameter requirement of CSH5 and 6,
2. Occupants will tend to adjust their personal thermal comfort levels according to the varying outdoor temperature from season to season. This is adverse to the design concept for consistent and regulated cooling and heating functionality within the home which is advanced by manufacturers and suggests that domestic control systems need to be developed to be more responsive to seasonal comfort levels.
3. The average predicted comfort temperature for the occupancy was over a degree lower than the actual temperature recorded, indicating that the home was always slightly warmer, than it need be. Seasonal adjustment of the indoor temperature settings to reflect the predicted comfort temperature should be factored into the delivery and maintenance of 'zero carbon' housing control systems. Further work needs to be carried out to develop the 'potential discomfort index' for housing in order to facilitate this (Nicol *et al.*, 2009).
4. MVHR systems are not designed to cope with overheating and given the propensity for new housing to overheat, greater emphasis on natural ventilation strategies for preventing overheating is required in policy making.
5. The passive solar stack and automatic window at the top of the house proved key to preventing peak day overheating. This automatically responded to the overheating spikes at peak summertime day temperatures, particularly when the occupants were returning to the home following work. Passive solar stack ventilation provides effective mitigation of overheating without compromising security and is likely to be common place in future 'zero carbon' homes and will need more development.
6. Greater understanding of the usage pattern of window openings is important for optimising cost in 'zero carbon' homes. This allows a reduction of non-critical openings in windows, whilst retaining user acceptance and the buildings comfort level.

In conclusion, the Sigma home learning has provided a valuable insight into user expectations, perceptions and behaviour, correlated to the actual performance of a low carbon prototype home. It has demonstrated the need for a full understanding of any new products, systems or processes, before bringing them to market. This area is of fundamental importance in relation to the success, or otherwise, of low carbon housing, for mainstream production. The findings suggests that there should be some 'occupant-testing' of all housing prototypes, as well as completed developments, prior to full occupation and in parallel with, effective 'as-built' post- completion review processes. This research has already impacted on the wider sector and helped to shape and inform, key stakeholders and policy maker's decisions. As a direct result, SMG have completely revised their approach and are now leading a consortium of national housing developers, manufacturers and researchers in a pioneering £6.5 million demonstration project to develop improved fabric solutions for new housing, partly funded by the UK government, called AIMC4 (TSB, 2009). The project recognises the need to address the energy demand related to fabric performance before addressing the renewable energy supply side for 'zero carbon' homes, as highlighted by the findings in this paper. This new project specifically includes the evaluation methods discussed in this paper.

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References

CEN (2007), EN 15251: Indoor Environmental Input Parameters for Design and Assessment of Energy Performance of Buildings Addressing Indoor Air Quality, Thermal Environment, Lighting and Acoustics, Comite´ Europe´en de Normalisation, Brussels.

CHS (2007), Code For Sustainable Homes, Technical Guide, Department for Communities and Local Government, London.

CIBSE (2006), CIBSE Guide A, 7th edition, CIBSE, London, chapter 1.2.2, Thermal comfort: annotated definitions of main thermal parameters, Chartered Institution of Building Services Engineers.

EST (2005), Energy efficiency best practice in housing: Reducing overheating – A designer's guide, Energy Saving Trust.

Griffiths I.D. (1990), Thermal comfort in buildings with passive solar features: Field studies, Report to the Commission of the European Communities, EN3S-090, UK.

Humphreys M.A. (1975), Field studies of thermal comfort compared and applied, Department of the Environment: Building Research Establishment, CP 76/75 (Reissued in: *J. Inst. Heat. & Vent. Eng. 44*, pp. 5-27, 1976).

Lowe R.J., Wingfield J., Bell M., Bell J.M. (2007), Evidence for heat losses via party wall cavities in masonry construction, *Building Services Engineering Research Technology 28 (2)*, 161-181.

Macintosh A., Steemers K. (2005), Ventilation strategies for urban housing: lessons from a PoE case study. *Building Research & Information 33(1)*, pp. 17-31.

Marsh R., Larsen, V. G., Kragh M. (2010), Housing and energy in Denmark: past, present, and future challenges, *Building Research & Information, 38 (1)*, 92 -106

Nicol J.F., Raja I.A., Allaudin A., Jamy G.N. (1999), Climatic variations in comfortable temperatures: the Pakistan projects, *Energy and Buildings 30 (3)*, 261-279.

Nicol F., Jamy G.N., Sykes O., Humphreys M., Roaf S., Hancock M. (1994), A survey of thermal comfort in Pakistan toward new indoor temperature standards,

Nicol J.F., Hacker J., Spires B., Davies H. (2009), Suggestion for new approach to overheating diagnostics, *Building Research & Information, 37(4)*, 348-357.

Nicol J.F., Humphreys M.A. (2004), A stochastic approach to thermal comfort – Occupant behavior and energy use in buildings, *ASHRAE Transactions 110 (2)*, 554-568.

Rijal H.B., Tuohy P., Humphreys M.A., Nicol J.F., Samuel A., Raja I.A., Clarke J. (2008), Development of adaptive algorithms for the operation of windows, fans and doors to predict thermal comfort and energy use in Pakistani buildings, *ASHRAE transactions 114 (2)*, pp. 555-573.

Rijal H.B., Tuohy P., Humphreys M.A., Nicol J.F., Samuel A., Clarke J. (2007), Using results from field surveys to predict the effect of open windows on thermal comfort and energy use in buildings, *Energy & Buildings 39 (7)*, pp. 823-836.

SAP (2005), The government's Standard Assessment Procedure for energy rating of dwellings, BRE, Garston, Watford, UK.

Statutory Instrument (2007), No. 991, The Energy Performance of Buildings (Certificates and Inspections) (England and Wales) Regulations 2007.

Stevenson F., Rijal H.B. (2008), The Sigma Home: towards an authentic evaluation of a prototype building, *Proceedings of the 25th Conference on Passive and Low Energy Architecture*, Dublin, 22-24 October.

Stevenson F., Rijal H.B. (2009), Post-occupancy evaluation of the Stewart Milne Group's Sigma® House, Stewart Milne Group (Final report).

TSB (2009), Press release 24th November 2009: Taking aim – unique partnerships targets construction of sustainable homes, Technology Strategy Board (available at: http://www.innovateuk.org/_assets/pdf/press_releases/pressreleaseaimc4final24nov09.pdf – accessed 15.01.2010)

Wingfield J., Bell M., Bell J., Lowe B. (2006), Evaluating the impact of an enhanced energy performance standard on load-bearing masonry construction – Interim Report Number 5 – Post construction testing and envelope performance, PII Project CI 39/3/663, Leeds Metropolitan University.

Appendix 1

Thermal comfort study in the 'living room' of the Sigma Home

Loggers are set up in the living room that will record temperatures. We are interested in matching these automatically recorded temperatures with how you feel at different times of the day over the two week periods of time that you are occupying the home. For each day it would be very helpful if you could record how you feel 4 times in the morning, 4 times in the afternoon and 4 times in the evening.

- Ideally, your recordings on the attached form should be spaced about an hour apart.
- Please provide the recording for your normal lifestyle (not just after heavy exercise and heavy work.)
- If you forget, do not try to remember how you felt, just start again at the next convenient time.
- Please give the time to the nearest minute using the twenty four hour clock (e.g. 10:08, 16:00).
- This survey is intended for adults but children can be included if they understand the scale properly and are willing to provide records.

How to use thermal comfort scales

If you are attending to other things you may not be aware of your thermal sensation.
So, take a moment to 'listen' to your body.
How are you feeling?
Now choose one sensation that corresponds to your feeling.
Tick the box.

Date:

Time period→	6:00-9:00		9:00-12:00		12:00-15:00		15:00-18:00		18:00-21:00		21:00-24:00	
Actual recorded time→												

1. Temperature
How do you feel at this time?

7. Much too warm												
6. Too warm												
5. Comfortably warm												
4. Comfortably neither warm nor cool												
3. Comfortably cool												
2. Too cool												
1. Much too cool												

I would prefer to be:

5. Much cooler												
4. A bit cooler												
3. No change												
2. A bit warmer												
1. Much warmer												

2. Overall comfort
At this time, how would you rate your overall comfort?
(considering temperature, air movement, humidity, lighting, noise and air quality)

6. Very comfortable												
5. Moderately comfortable												
4. Slightly comfortable												
3. Slightly uncomfortable												
2. Moderately uncomfortable												
1. Very uncomfortable												

3. Activity level
What have you been doing in the last hour? (tick any that apply)

Sitting - passive												
Sitting - active												
Standing - relaxed												
Standing - working												
Walking - indoors												
Walking - outdoors												

4. How many layers of clothing on your upper body?

Number of layers												