Title: Validation of Simulated Thermal Comfort using a Calibrated Building Energy Simulation (BES) model in the context of Building Performance Evaluation & Optimisation

Daniel Coakley	**Edward J. Corry**	**Marcus M. Keane**
Researcher	Researcher	Lecturer & Principal Investigator

Informatics Research Unit for Sustainable Engineering (IRUSE)

National University of Ireland, Galway

ABSTRACT

Building Energy Simulation (BES) models play a significant role in the design and optimisation of buildings. Simulation models may be used to compare the cost-effectiveness of Energy-Conservation Measures (ECMs) in the design stage as well as assessing various performance optimisation measures during the operational stage. Common metrics used to indicate Building Energy Performance include Energy cost, Carbon Dioxide emissions and Indoor Thermal Comfort (Predicted Mean Vote - PMV / Predicted Percentage Dissatisfied - PPD).

Multi-variable optimisation of Building Design and Control often focuses on minimising cost while maximising thermal comfort. This paper focuses on the use of simulated thermal comfort for performance optimisation; particularly the experimental validation of this key building performance index using a calibrated BES model of a case study naturally ventilated building.

INTRODUCTION

One of the primary functions of buildings is to create and maintain a comfortable environment for its occupants. Thermal comfort, or PMV (Predicted Mean Vote) and PPD (Predicted Percentage Dissatisfied) have been used as key metrics for the evaluation of building performance in this context since its introduction in the 1970's (Fanger 1970). With the current increase in adoption of building simulation tools, such as EnergyPlus, for the evaluation and optimisation of buildings at the design stage, it is therefore essential that these tools can accurately represent buildings in terms of both energy consumption and thermal comfort performance.

Thermal Comfort Criteria

Thermal comfort represents an occupant's sense of satisfaction with a zone or space. It is primarily governed by four main environmental factors:

- Air temperature (t_a)
- Relative humidity (h)
- Mean radiant temperature (t_r)
- Air Velocity (v_a)

In addition to the four main environmental factors, two further individual characteristics will also have an effect on the perceived level of thermal comfort.

- Clothing level (*clo*)
- Activity level / metabolic rate

Comfort Scale

Initial studies on thermal comfort and formulation of thermal indices began in the 1920's. The Bedford Scale (Bedford 1936) and subsequent thermal sensation scale (ASHRAE 2004) form the basis for today's subjective/field study comfort studies.

Table 1: Thermal Sensation Scale

Thermal Sensation Scale	**Bedford Scale**
+3 Hot	Much too Warm
+2 Warm	Too warm
+1 Slightly Warm	Comfortably warm
0 Neutral	Comfortable
-1 Slightly cool	Comfortably cool
-2 Cool	Too cool
-3 Cold	Much too cold

While the above scale represents the subjective opinions of the occupants surveyed, PO Fanger also devised a deterministic comfort model to approximate these responses.

Fanger PMV/PPD

P.O. Fanger (Fanger 1970) carried out laboratory experiments in a controlled environment (climate chamber) which attempted to relate environment comfort criteria (air temperature, velocity, humidity) and clothing and activity levels with predicted levels of occupant comfort. This research led to the formulation of the **Predicted Mean Vote** (**PMV**) and the **Predicted Percentage Dissatisfied** (**PPD**). The PMV is essentially an index that predicts the mean value of the votes of a large group of persons on the above 7-point thermal sensation scale (see Table 1).

Deterministically, PMV can be found to be quantified by the following equation which encapsulates all of the environmental and individual characteristics covered in the introduction:

Table 2: Equations for calculating PMV

$$PMV = \left[0{,}303 \cdot \exp(-0{,}036 \cdot M) + 0{,}028 \right] \cdot$$
$$\left\{ \begin{array}{l} (M-W) - 3{,}05 \cdot 10^{-3} \cdot \left[5\,733 - 6{,}99 \cdot (M-W) - p_a \right] - 0{,}42 \cdot \left[(M-W) - 58{,}15 \right] \\ -1{,}7 \cdot 10^{-5} \cdot M \cdot (5\,867 - p_a) - 0{,}0014 \cdot M \cdot (34 - t_a) \\ -3{,}96 \cdot 10^{-8} \cdot f_{cl} \cdot \left[(t_{cl} + 273)^4 - (\bar{t}_r + 273)^4 \right] - f_{cl} \cdot h_c \cdot (t_{cl} - t_a) \end{array} \right\} \quad [1]$$

$t_{cl} = 35,7 - 0,028 \cdot (M - W) - I_{cl} \cdot \left\{ 3,96 \cdot 10^{-8} \cdot f_{cl} \cdot \left[(t_{cl} + 273)^4 - (\bar{t}_r + 273)^4 \right] + f_{cl} \cdot h_c \cdot (t_{cl} - t_a) \right\}$	[2]
$h_c = \begin{cases} 2,38 \cdot \lvert t_{cl} - t_a \rvert^{0,25} & \text{for} \quad 2,38 \cdot \lvert t_{cl} - t_a \rvert^{0,25} > 12,1 \cdot \sqrt{v_{ar}} \\ 12,1 \cdot \sqrt{v_{ar}} & \text{for} \quad 2,38 \cdot \lvert t_{cl} - t_a \rvert^{0,25} < 12,1 \cdot \sqrt{v_{ar}} \end{cases}$ $f_{cl} = \begin{cases} 1,00 + 1,290\, I_{cl} & \text{for } I_{cl} \leqslant 0,078\ m^2 \cdot K/W \\ 1,05 + 0,645\, I_{cl} & \text{for } I_{cl} > 0,078\ m^2 \cdot K/W \end{cases}$	[3]

Where;

M = metabolic rate (W/m^2);

W = effective mechanical power (W/m^2);

I_{cl} = clothing insulation (m^2 · K/W);

f_{cl} = clothing surface area factor;

t_a = air temperature (°C);

t_r = mean radiant temperature (°C);

v_{ar} = the relative air velocity (m/s);

p_a = water vapour partial pressure (Pa);

h_c = convective heat transfer coefficient [W/(m^2·K)];

t_{cl} = clothing surface temperature (°C)

clo = clothing units, 1 clo = 0.155m^2.ºC/W.

Since PMV predicts the mean of the comfort votes from a large group, another useful measure is the percentage of the total that will be dissatisfied with the thermal environment. (i.e. those that would vote ≥2 or ≤-2 on the thermal sensation scale.

$$PMV = 100 - 95 \cdot \exp\left(-0.03353 \cdot PMV^4 - 0.2179 \cdot PMV^2\right)$$
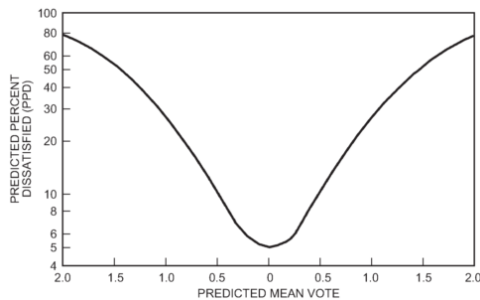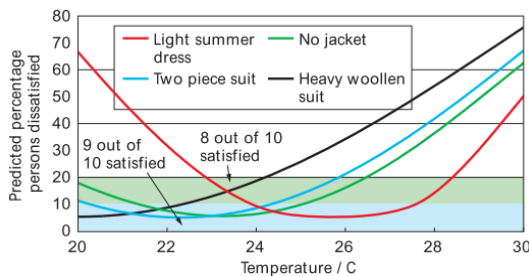

Figure 1: PPD versus PMV

Figure 2: PPD versus Temperature (with Clothing)

CASE STUDY

Our chosen case study is an 80-seater computer lab in a large engineering building. Located on campus at the National University of Ireland, Galway, this provided the most suitable demonstrator in terms of access and data availability. In addition, previous assessments had revealed that computer labs in general had relatively highly levels of occupant dissatisfaction in terms of thermal comfort. The study was carried out during peak operating hours on 13/03/2012 (14:00-18:00)

New Engineering Building

This is a 14,000m^2 four-story engineering faculty building, completed in 2011. The building comprises offices, laboratories, study areas, lecture theatres and computer labs. It is designed to act as a 'living laboratory' and has been fitted with over 4,000 sensors measuring building structural, mechanical, electrical and environmental parameters.

Figure 3: Engineering Building

The building is heavily reliant on natural ventilation for cooling. Mechanically operated window actuators on a south-facing climate façade provide natural conditioning for approximately 90% of time occupied. The area of interest here is a computer lab located on the southeast corner of the building (see Figure 4).

Figure 4: Computer Lab

Space Audit

An audit of the area was carried out as part of this study to gain a better understanding of the space.

Ventilation Strategy
The area is served by a combination of natural and forced mechanical ventilation. Automatically operated window actuators on the SE façade, in conjunction with 6 manually operable windows on the NE façade, provide natural ventilation to the space.

Users have the ability to over-ride the BMS to force open/close the mechanical ventilation system.

HVAC System

The space is also served by a temperature-control air-handling unit (see Figure 5). This AHU does not have a fixed time-schedule, but is enabled to run when the average space temperature exceeds the temperature set-point (22 ºC) by ± 2 ºC. There is also a chilled-beam system designed to provide additional cooling through the overhead concrete slab. Each Active chilled beam control strategy has a PID loop which will modulate the heating/cooling valves to maintain temperature.

The AHU supply air temperature has a floating set point range between a min and max setting (user adjustable) which shall be determined in accordance with outside air temperature (see Figure 5)

The supply temperature shall be achieved by modulating, in sequence, the frost heating control valve, the heating valve, and the cooling valve to achieve the required set point. When a demand for heating exists the frost heating valve will open to meet demand followed by main heating valve. When a demand for cooling exists he CHW valve will open to meet demand. The dew-point is calculated from the space temperature and humidity. The dew-point strategy will override the temperature controls for the air handling unit, so as to maintain the space air dew-point 2ºC below the chilled beam water flow temperature. This means the space dew-point set point shall be a floating set point between 10.5 ºC and 15 ºC.

The average space air quality is monitored by the BMS. In the event that the CO_2 level exceeds the user-adjustable set point of 1500 p.p.m., the supply fan VSD shall be modulated towards its maximum speed, to maintain this set point. If the CO_2 level is below this set point, the fan speed shall return to its normal setting.

Equipment

Apart from occupancy, equipment contribute significantly to space heat gains. The following equipment was surveyed:

Table 3: Equipment Survey

No.	Description	Power [W]
82	Lenovo Thinkvision Monitors	22
82	Thinkcenter i5 PC Tower	320
1	Bizhub C552 MF printer	100 (idle)
1	Networking hub	200
1	Canon A0 Printer	105 (idle)
1	Overhead Projector	80 (idle)
	TOTAL	28.5kW

Lighting

The area is served by 80 x T12 fluorescent light fixtures, each consuming approximately 40W, giving a total lighting power consumption of 3.2kW
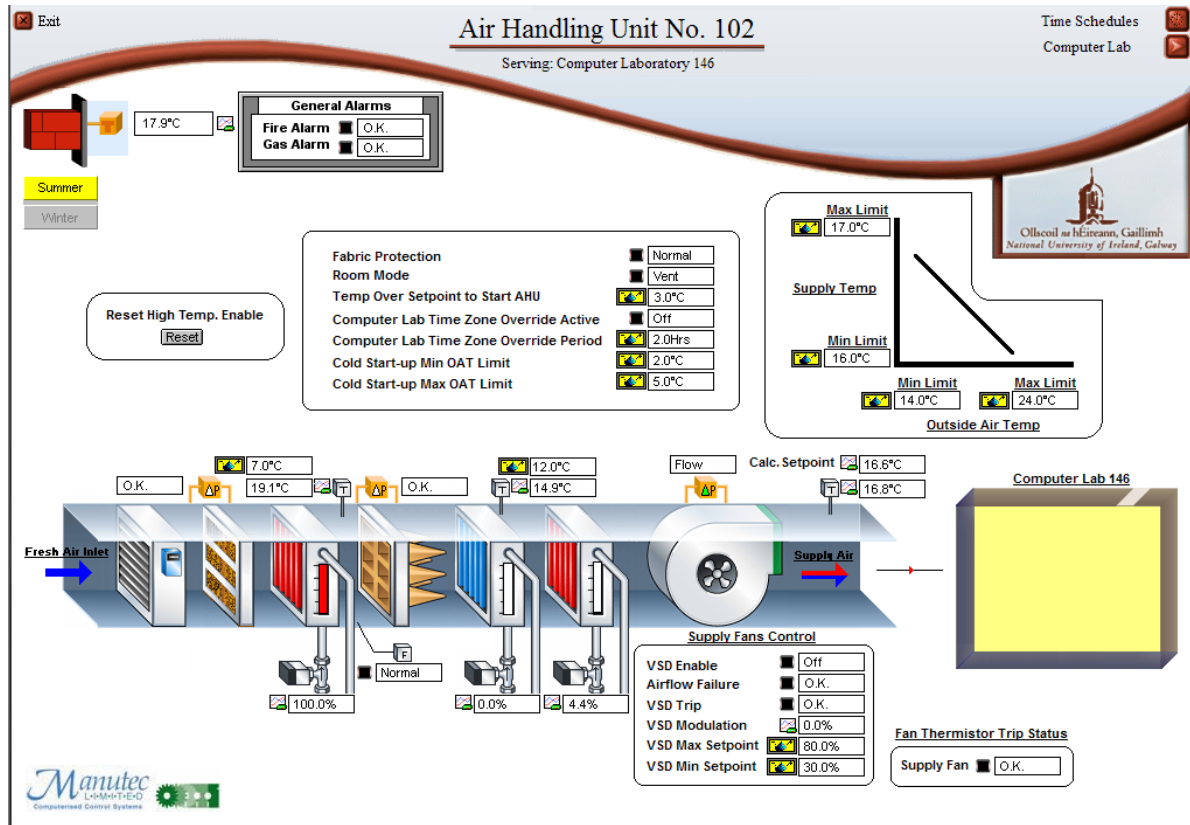
Figure 5: Air-handling Unit serving computer lab G146

METHODOLOGY

The following section will be broken down into three main sections:

1. Measurement-based PMV
2. Survey-based PMV
3. Simulation-based PMV

1. Measurement-based PMV

In order to validate simulation outputs, a quantitative assessment of each simulated zone was carried out. This study was conducted using a combination of thermal comfort metering equipment, handheld Temp/RH meters and building management system (BMS) instrumentation.

The following section describes how each measurement was taken and presents a summary of the findings. Table 8 presents a summary of the overall results.

Weather Data

It has been shown that perceptions of thermal comfort are dependent not only on indoor micro-climate, but also on outside meteorological parameters (Auliciems 1969). In addition, detailed weather data is required to accurately model building operation. For this purpose, a weather station was installed on campus measuring:

- Dry-bulb temperature ($\pm 0.5°C$);
- Relative humidity ($\pm 2\%$);
- Barometric pressure ($\pm 50Pa$);
- Wind speed [$\pm 0.1 ms^{-1}$ ($0.3 - 10 ms^{-1}$); $\pm 1\%$ ($10 - 55 ms^{-1}$); $\pm 2\%$ ($> 55 ms^{-1}$)];
- Wind speed -3s gust [($\pm 0.1 ms^{-1}$ ($0.3 - 10 ms^{-1}$); $\pm 1\%$ ($10 - 55 ms^{-1}$); $\pm 2\%$ ($> 55 ms^{-1}$)];
- Wind direction [$\pm 2\%$ ($> 5 ms^{-1}$)];
- Global solar irradiance ($< 5\%$);
- Diffuse solar radiation ($< 15\%$);
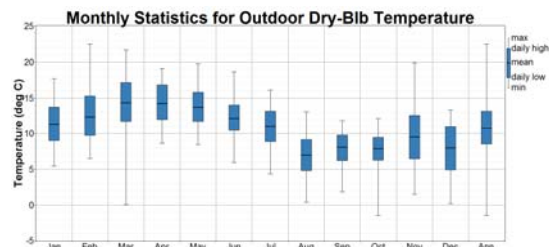- Barometric pressure ($\pm 50Pa$);

Figure 6: Outdoor Dry-bulb temperature, 2012

Galway has a typical maritime temperate climate, with average temperatures ranging from 5.9 °C (43 °F) in January to around 15.9 °C (61 °F) in July.

Operative Temperature (t_{op})

In order to account for room temperature gradient, air temperature (t_a) readings were taken locally at each work station, using a hand-held thermometer. Radiant temperature (t_r) was recorded at a single location, using the thermal comfort meter shown below.

Figure 7: QuestTemp 36 Thermal Comfort Meter

An operative temperature was then calculated to combine the effect of mean and radiant air temperature as follows (CIBSE 2006):
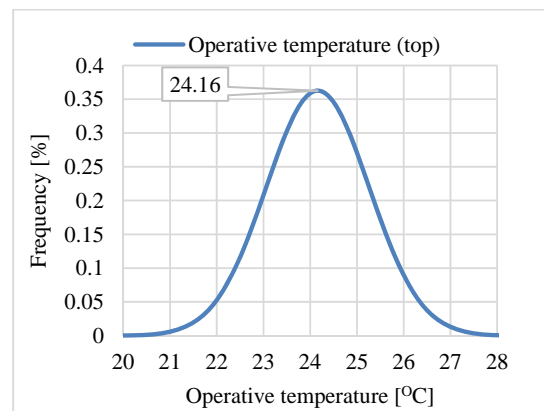
$$t_o = 1\,/2\ t_a + 1\,/2\ t_r$$

Figure 8: Operative temperature frequency distribution

As indicated above, the typical operative temperature for the surveyed space is 24.1 ± 1.1 ºC. This is relatively high compared to other spaces within the building and can be explained by the fact that this space contains high levels of equipment and occupants (Refer Table 3).

Relative Humidity (RH)

Relative humidity was recorded using the thermal comfort meter above, and validated against readings from the building management system. The average value of 31.78 ± 5.04% is slightly low and may cause discomfort in some individuals – resulting in a feeling of dryness or respiratory irritation. Recommended levels for occupied spaces are generally between 40 and 70% (CIBSE 2006b).

Velocity of Air, (v_a)

Air velocity readings were taken at a central point in the study space, using the QuestTemp 36 thermal comfort meter. Surveyed room conditions revealed a value of 0.229 ± 0.096%. It was not possible to survey conditions at each local workspace due to the fact that only one meter was available. However, it is unlikely that air velocity would have a significant impact on this study as values are generally well within comfort ranges (0.1-0.3m/s). (CIBSE 2006b).

2. Survey-based PMV

An online survey was used to assess individual parameters related to thermal comfort. This survey was based on the original ASHRAE indoor comfort survey and adapted to include addition questions relating to occupant adaptability, activity and food intake.

Comfort Vote

Occupant comfort was assessed by means of an online survey of Comfort Vote (CV). The CV is measured on a 7-point scale (see Table 1) as defined by American and international standards. (ASHRAE 2003; International Standards Organisation (ISO) 2005).The average surveyed CV is 0.82 ± 0.89 (see Figure 9).
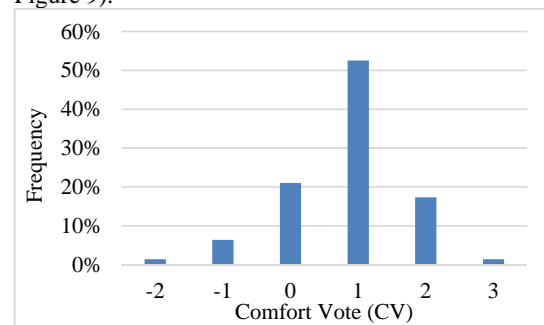

Figure 9: Comfort Vote Freq. Distribution

A standard deviation of 0.89 is similar to that shown by previous studies (McCartney and Fergus Nicol 2002; Kuchen and Fisch 2008) and lends to the hypothesis of McIntyre (1978) which states that the minimum standard deviation possible in field studies is ±1. By using the ASHRAE 7-point scale, we can make a direct comparison between surveyed CV and Predicted Mean Vote (PMV).
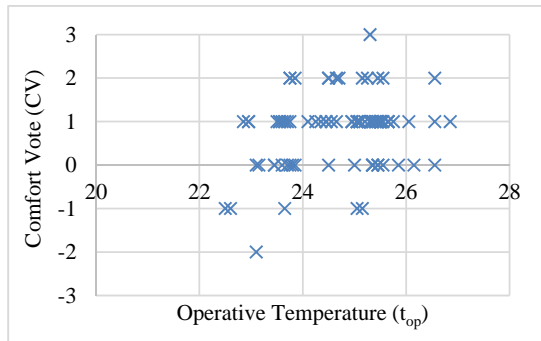
Figure 10: Regression analysis and dispersion of Comfort Vote (CV) versus operative temperature (t_{op}).

Despite the relatively low spread of operative temperature (t_{op}), we can still see a definite correlation between CV and t_{op} as indicated in Figure 10. We also examined whether discrepancies existed between male and female responses. The average female (16.9%) comfort vote was 0.43 ± 1.12, while male (83.1%) comfort vote was 0.90 ± 0.81. While a discrepancy does exist, this may be explained by the fact that we have a much smaller female sample size. Further studies would be required to confirm statistical significance of this result.

Clothing Insulation

The level of clothing insulation is of vital importance when calculating predicted mean vote (PMV). This affects the rate at which heat is transferred between the human body and the surrounding environment. Clothing insulation is generally measured in units of clo (1 clo = $0.155 m^2.^oC/W$). Values for this parameter are made available for typical clothing ensembles, or can be calculated by summing individual items of clothing (ASHRAE 2004). Occupant were asked to calculate this value and submit their sum-totals as part of the online survey. The average value for clothing insulation is 0.86 ± 0.26, which is typical for this climate and time of year. The difference between clothing for men (0.86) and women (0.85) is negligible.

Figure 11: Sample FLIR thermal imaging photograph

As part of this study, we also investigated the rigour of the thermal insulation calculation. Using Equation [2], we calculated the clothing surface temperature for each individual participant, using their provided clothing insulation (clo) and metabolic rate (met). Their actual clothing surface temperature was then accurately measured using a FLIR thermal imaging camera. A summary of the data collected is presented in Table 4. Interestingly, the calculation methodology provided surface temperatures to a high degree of accuracy (±5.4%). In general, we found that the value had been under-estimated. This was likely due to an error in choosing the correct metabolic rate, as we will show in the following section (Metabolic Rate).

Table 4: Summary of clothing insulation and measured clothing surface temperatures

clo Value	No.	CV	$T_{cl,meas}$	$T_{cl,calc}$	Error
<0.5	12	0.67	30.517	29.45	4.56%
0.5-0.6	16	0.56	30.544	29.05	5.05%
0.6-0.7	22	0.77	29.609	28.77	5.11%
0.7-0.8	48	0.77	29.115	28.41	4.80%
0.8-0.9	50	0.84	28.904	28.06	6.42%
0.9-1	22	0.82	29.073	28.21	4.25%
1-1.1	19	1.00	28.763	27.52	4.78%
1.1-1.2	9	1.11	27.456	27.30	7.21%
1.2-1.3	6	1.00	28.467	27.34	5.92%
1.3-1.4	7	0.86	27.414	26.98	6.27%
1.4-1.5	2	1.00	29.950	26.81	10.41%
>1.5	6	1.00	26.617	26.85	5.32%
Total	219	0.82	29.062	28.19	5.39%

Food Intake

The intake of food has been shown to cause an increase in metabolic rate (i.e. the rate at which the human body generates heat) by up to 15% immediately after consumption (Fanger 1970). Therefore, participants were asked whether they had consumed and food/drink within the past hour. They were also asked to provide details where possible. We found that almost 75% of those surveyed had consumed food/drink within the past hour (see Table 5). There is a definite discrepancy between those who did not consume any food/drink (0.71) and those that did (0.83-0.96), in particular those that consumed a hot drink. The difference can be accounted for by the increase in metabolic rate instigated by the intake of food and drink, as well as the increased sense of warmth accompanied by the consumption of hot drinks such as tea or coffee.

Table 5: Food intake summary

Food Intake	No.	Percent	PMV
None of these	55	25.11%	0.71
Cold Drink Combos	93	42.47%	0.83
Hot Drink Combos	25	11.42%	0.96
Meal Combos	46	21.00%	0.87
Grand Total	219	100.00%	0.82

Metabolic Rate / Activity level

The metabolic rate (met) defines the rate at which the human body produce heat through internal processing of calories from food. It is a product primarily of activity and food intake as well as, to a lesser degree, age and fitness level (Schofield 1985; Gillooly et al. 2001).

Table 6: Metabolic Rates

Metabolic Rate	% Total	Met	Std. Dev.
Female	16.79%	1.095	0.100
Male	83.21%	1.103	0.165
Total	100.00%	1.101	0.156

Metabolic rate was surveyed by asking participants to find the corresponding value for their particular activity by using standardised tables provided (ASHRAE 2004). Average recorded metabolic rate was 1.1 ±0.156, corresponding generally to sedentary, seated office activity. However, this may be an underestimation when considering a laboratory environment where students are returning from other lectures and other areas of the campus. In addition, food intake is not accounted for in these figures. As discussed in the previous section, food intake can increase metabolic rate by up to 15% immediately after consumption.

Adaptations

Humans cannot be assumed to be passive observers when considering thermal comfort. Each individual has the freedom to make adaptations to their personal attire and local environment to increase thermal comfort (Baker and Standeven 1996). However, with the increasing shift towards further automation in buildings, humans are given less control over their environment. A sense of control and ability to interact with one's environment is generally assumed to have a positive influence on user satisfaction (Kuchen and Fisch 2008). In this study, users had little opportunity to interact with their overall environment. Instead, in order to have any impact on their personal sense of thermal comfort, personal adaptations were required. This was demonstrated in the significant number of participants (~39%) who removed one or more items of clothing (Refer Table 7):

Table 7: Clothing Adaptations

Clothing	No.	Percent	'clo'	CV	Std. Dev.
Added	1	0.5%	2.00	-1.00	
No change	132	60.3%	0.88	0.72	0.86
Removed	86	39.3%	0.80	1.00	0.89
Total	219	100.0%	0.86	0.82	0.89

3. Simulation-based PMV

Discussion of the model development process is outside of the scope of this paper. However, two previously published papers (Coakley, Raftery, and Molloy 2012; Coakley et al. 2011) describe the model development and calibration process in detail. To summarise, the overall process may be broken down into five main steps:

1. Data gathering / building audit.
2. Evidence-based BES model development.
3. Bounded grid search
4. Refined grid search (optional)
5. Uncertainty analysis

A single zone model for the computer lab, adapted from a whole-building BIM, is used for the purpose of this study.

Table 8: Summary of measured and surveyed values for New Engineering Building Computer lab

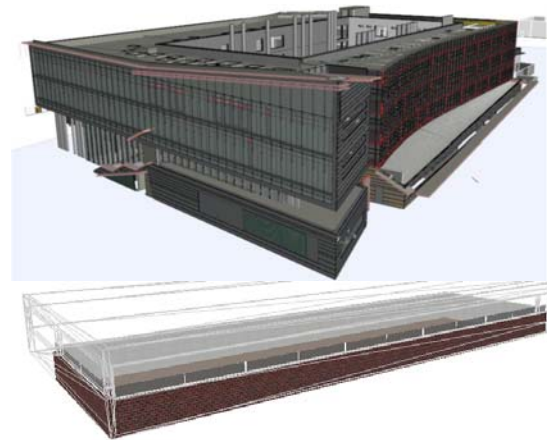| Parameter	Air temperature (t_{air})	Mean radiant temperature (t_{rad})	Operative Temperature (t_{op})	Relative Humidity (RH)	Air speed (v_a)	Activity Level	Clothing value	Clothing surface temperature (t_{clo})	TCL	Comfort Vote (CV)	Predicted Mean Vote (PMV)	Predicted Percentage Dissatisfied (PPD)
	°C	°C	°C	%	m/s	met	clo	°C	°C			%
Source	Measurement	Measurement	Measurement	Measurement	Measurement	Survey	Survey	Measurement	Calculation	Survey	Calculation	Calculation
Mean	24.18	24.14	24.16	31.76	0.229	1.101	0.86	29.06	28.20	0.82	-0.216	13.63
Min	18.00	22.40	21.00	21.90	0.000	0.800	0.31	23.40	24.73	-2.00	-2.824	5.00
Median	24.00	23.70	23.80	32.00	0.200	1.000	0.82	29.00	28.14	1.00	-0.183	8.55
Max	30.00	33.30	28.65	55.00	0.600	2.400	2.00	37.00	31.05	3.00	1.603	98.05
Std.Dev.	1.36	1.50	1.10	5.04	0.096	0.156	0.26	2.00	0.99	0.89	0.632	14.51

Figure 12: Whole Building BIM (top) and single-zone model of computer lab (DesignBuilder)

Conducting a comfort study requires minor adaptations to the 'people' object in EnergyPlus, to include the following key metrics:

- **Work Efficiency Schedule** – determines the efficiency of energy usage within the human body (0 to 1), where 0 corresponds to all energy produced being converted to heat and 1 corresponding to all energy produced being converted to mechanical energy. This has been set to 25%.

- **Clothing Insulation Schedule –** defines the amount of clothing worn by a typical zone occupant. Values of clo for individual garments can be found in ISO 7730:2205 (International Standards Organisation (ISO) 2005). For simplification purposes, we have used a constant 'clo' value of 0.85 for all simulations, corresponding to survey data. (Refer Table 4)

- **Air Velocity Schedule** - This field is the name of the schedule that approximates the amount of air movement in the space as a function of time throughout the simulation period. For simplification purposes, we have used a constant 'v_a' value of 0.1m/s for all simulations.

- **Thermal Comfort Model Type** - The final option triggers various thermal comfort models within EnergyPlus. Here, we have specified the Fanger model for PMV calculation.

In addition to the additional input variables, the following outputs were appended to the .idf model:

- Output:Variable,*,FangerPMV,hourly;

- Output:Variable,*,FangerPPD,hourly;

Finally, an hourly simulation is run, using local weather data for the period January-December 2012.

RESULTS

A yearly simulation of the computer lab, using the data gathered during the space audit and thermal comfort survey, yielded the following results (Table 9):

Predicted Mean Vote (PMV)

In respect of simulated predicted mean vote, we find that the simulation yields a relative consistent yearly PMV, with an average value of 1.043 ±0.08. This compares favourably with the thermal comfort survey conducted above which yielded an average PMV of 0.82 ±0.89. Of course, a smaller standard deviation is present as we are only simulating single average values for PMV as opposed to an actual random sample of comfort votes, as was the case in the field study.
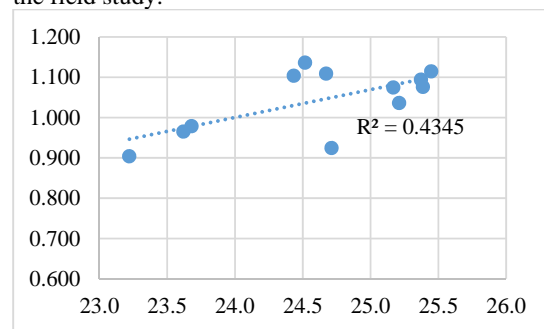

Figure 13: Regression analysis of simulated operative temperature versus predicted mean vote (PMV)

Again, we can see a reasonable direct correlation between operative temperature and predicted mean vote (PMV). Significantly, outside dry-bulb temperature has relatively little direct influence on PMV as the simulated environment is dominated by internal thermal gains, thus negating the effect of natural solar and ventilation gains and losses.

Internal Gains

It is interesting to examine the simulated internal heat gains for the computer lab (Refer to Figure 14). These can be broken down as follows.

- Computers & Equipment (70.4%)
- Occupancy (17.6%)
- Solar Gains (9.2%)
- Heating Gains (2.8%)

The gains resulting from computers and equipment dominantly effect how the space operates. In contrast, the current cooling strategy struggles to maintain satisfactory conditions, particularly during summer periods.

Operative temperature

Annual simulated air temperature (t_a) is 23.53 ±0.51 °C, radiant temperature (t_r) is 25.71 ±1.02 °C while mean operative temperature is 24.62 ±0.76 °C. Again, these values compare favourably to those measured during the field study. Of course we are looking at annualised simulated averages compared against a single measured instance. However, in the case of thermal comfort, it will never be possible to practically evaluate perceived occupant satisfaction over extended periods, so we must rely on one-off audits and surveys. In this case, the simulation appears to provide sufficiently accurate information when compare against our field study.

Table 9: Summary of Simulated Data (Monthly Averages)

| Month	Outside Dry-Bulb Temperature	Air Temperature	Mean Radiant Temperature (t_r)	Operative Temperature (t_{op})	Relative Humidity (h)	Predicted Mean Vote (PMV)
	°C	°C	°C	°C	%	
January	7.84	22.884	24.357	23.620	37.845	0.965
February	7.98	22.927	24.432	23.680	38.760	0.979
March	9.53	23.502	25.842	24.672	36.779	1.109
April	7.86	23.409	26.015	24.712	32.447	0.925
May	11.42	23.875	26.547	25.211	38.961	1.036
June	12.40	23.993	26.780	25.386	41.074	1.076
July	14.52	24.130	26.766	25.448	46.165	1.115
August	14.08	24.052	26.691	25.372	44.782	1.094
September	13.91	23.953	26.384	25.168	47.393	1.075
October	12.06	23.588	25.447	24.518	45.958	1.136
November	10.63	23.470	25.398	24.434	42.051	1.104
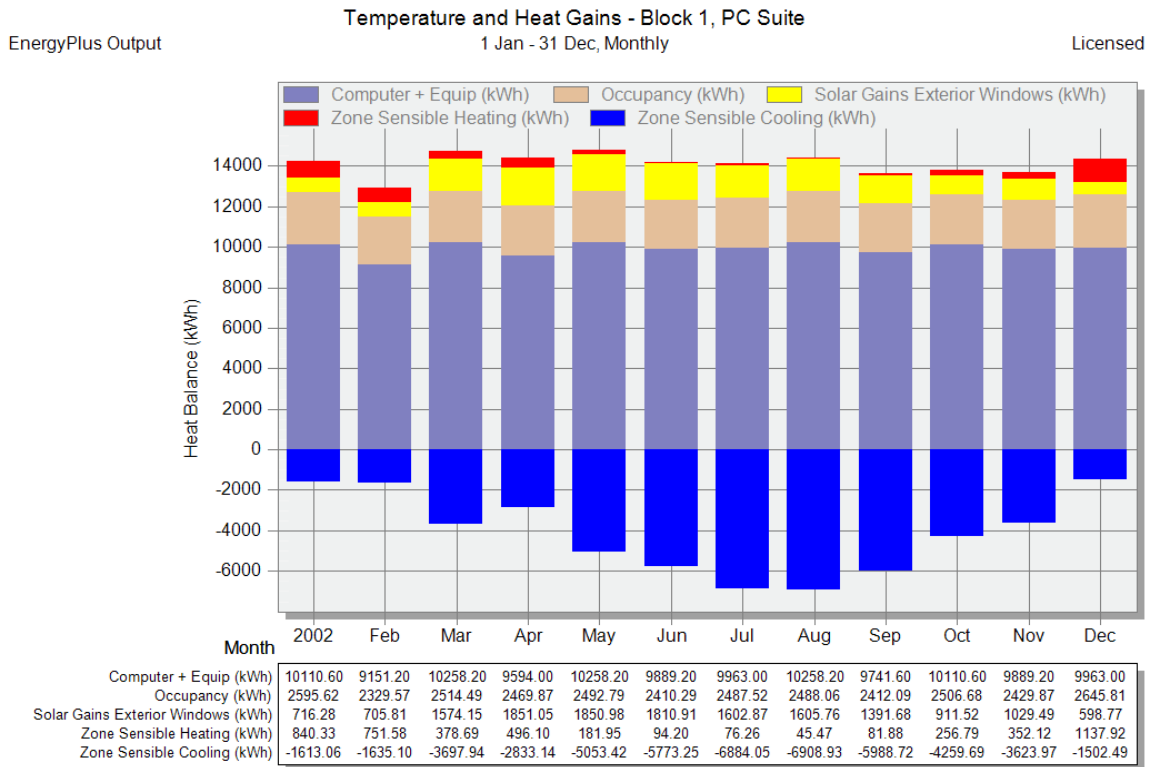
Figure 14: Summary of simulated internal gains

December	7.08	22.567	23.875	23.221	36.977	0.904

CONCLUSIONS

In this paper we have described the measurement of thermal satisfaction from three differing points of view (1) measurement-based PMV, (2) survey-based PMV and finally (3) simulation-based PMV. We have shown, by means of an un-biased field study, how occupant's sense of thermal satisfaction is highly distributed in practice. Even in identical conditions, the spread of responses is quite large. As we have discussed, this can be due to a variety of factors: food intake, metabolic rate, clothing insulation and personal preference. It is important to remain conscious of this fact when simulating and designing built environments. Simulation programs provide a single PMV index, which should be considered in conjunction with the conclusions drawn from this, and previous field studies. Nevertheless, it appears that simulation packages can provide a useful predictor of the normal operating conditions for environments with relatively constant conditions, as per the above case study. Since the PMV index is highly correlated with activity levels (met) and operative temperature, it is important that these variables are well defined when compiling the simulation model.

FUTURE WORK

Future work will focus on the completion of a full-scale model of the engineering building presented above, to incorporate additional zones and operating environments (e.g. offices, lecture theatres, laboratories). Further field studies will be carried out to validate simulation results in these environments, particularly in more problematic areas.

ACKNOWLEDGEMENTS

REFERENCES

ASHRAE. 2003. ASHRAE Standard 55-2003: Thermal Environmental Conditions for Human Occupancy.

———. 2004. "ASHRAE Standard 55-2004: Thermal Environmental Conditions for Human Occupancy". Vol. 2004. ASHRAE.

Auliciems, A. 1969. "Effects of Weather on Indoor Thermal Comfort." International Journal of Biometeorology.

Baker, N., and M. Standeven. 1996. "Thermal Comfort for Free-running Buildings." Energy & Buildings 23 (3): 175–182.

Bedford, T. 1936. "The Warmth Factor in Comfort at Work."

CIBSE. 2006a. KS6:2006 Comfort. Edited by The Chartered Institution of Building Services Engineers (CIBSE). London, United Kingdom.

———. 2006b. CIBSE Guide A: Environmental Design. Edited by The Chartered Institution of Building Services Engineers (CIBSE). 7th Ed. London, United Kingdom.

Coakley, Daniel, Paul Raftery, and Padraig Molloy. 2012. "Calibration of Whole Building Energy Simulation Models: Detailed Case Study of a Naturally Ventilated Building Using Hourly Measured Data." In Building Simulation and Optimization, 57–64. Loughborough, UK: ISBN: 978-1-897911-42-6.

Coakley, Daniel, Paul Raftery, Padraig Molloy, and Gearoid White. 2011. "Calibration of a Detailed BES Model to Measured Data Using an Evidence-Based Analytical Optimisation Approach." In Proceedings of the 12th International IBPSA Conference. Sydney, Australia.

Fanger, P. O. 1970. Thermal Comfort. Danish Press.

Gillooly, J F, J H Brown, G B West, V M Savage, and E L Charnov. 2001. "Effects of Size and Temperature on Metabolic Rate." Science (New York, N.Y.) 293 (5538) (September 21): 2248–51.

International Standards Organisation (ISO). 2005. "ISO 7730:2005 Ergonomics of the Thermal Environment — Analytical Determination and Interpretation of Thermal Comfort Using Calculation of the PMV and PPD Indices and Local Thermal Comfort Criteria."

Kuchen, E., and M.N. Fisch. 2008. "Spot Monitoring: Thermal Comfort Evaluation in 25 Office Buildings in Winter." Building and Environment In Press,.

McCartney, Kathryn J, and J Fergus Nicol. 2002. "Developing an Adaptive Control Algorithm for Europe." Energy and Buildings 34 (6) (July): 623–635.

McIntyre, DA. 1978. "Three Approaches to Thermal Comfort." ASHRAE Transactions.

Schofield, WN. 1985. "Predicting Basal Metabolic Rate, New Standards and Review of Previous Work." Human Nutrition. Clinical Nutrition.