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## Improving thermal comfort in naturally ventilated university buildings

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# Improving Thermal Comfort in Naturally Ventilated University Buildings

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## Abstract

A substantial fraction of Australian university buildings are naturally ventilated. These buildings consume a significant amount of energy and frequently suffer from overheating problems, resulting in poor indoor thermal comfort. This paper presents an investigation on the effectiveness of a range of energy conservation measures (ECMs) that can potentially be used to enhance energy performance and thermal comfort of these buildings. The ECMs considered in this study include information technology (IT) equipment and lighting upgrades, and measures focussed on occupant behaviour change. The effectiveness of each ECM was evaluated through modelling of a case study building at the University of Wollongong using the building energy simulation software DesignBuilder™. The thermal comfort of occupants was evaluated using the adaptive thermal comfort standards ASHRAE Standard 55 and EN15251. Results indicated that both adaptive thermal comfort standards can be useful in providing a clear picture of occupant comfort conditions. It was found that office IT equipment and lighting upgrades can potentially result in 50% savings in total office energy consumption, which in turn led to a reduction of up to 50% in overheating hours, compared to the base case condition. It was also found that 40% energy savings and a 50% reduction in overheating hours could be achieved through modelled occupant behaviour changes (i.e. turning off IT equipment and lighting as far as possible and night-purging in summer).

**Keywords:** energy conservation, natural ventilation, adaptive thermal comfort, occupant behaviour change.

## Introduction

Satisfactory and comfortable indoor conditions in educational buildings are essential if significant health, performance and learning improvements for students and staff are to be achieved (Kats, 2006; Corgnati, Filippi & Viazzo, 2007). However, the majority of existing Australian educational buildings are naturally ventilated, designed without taking sustainability and occupant's comfort into consideration (Green Building Council of Australia, 2009). This in turn frequently results in inefficient building operation and unacceptable thermal comfort for building occupants throughout much of the year.

A good opportunity for enhancing the performance of such buildings would be the implementation of energy conservation measures (ECMs) (Asadi, da Silva, Atunes & Dias, 2011). Based on the assessment of energy performance of a set of ECMs, Yalcintas (2008) stated that reliable predictions of energy savings from the implementation of ECMs are essential to successful completion of any upgrade projects. However, this is a challenge since the energy performance of buildings is highly dependent on the behaviour of the occupants. Lenoir, Cory, Donn & Garde (2011) concluded that the occupants' behaviour is the most significant input parameter affecting building performance. An assessment conducted to compare the building performance in the design stage without occupants, and during the actual operation phase with occupants, showed that discrepancies of up to 50% existed between both phases. Therefore, building user behaviour change could potentially result in significant energy savings. Nonetheless, changing occupants' behaviour is an arduous task hindered by significant barriers, such as the tendency of the occupants to ignore small energy savings opportunities, their habits, social norms and the lifestyle patterns (United Nations Environment Program, 2009). Moreover, some hold that occupants have taken energy consumption for granted, and thus energy is seen as a commodity that can be consumed without any consideration for cost or environmental effects (Energy Efficiency in Buildings, 2007). Although the human behaviour is hard to

change, some of the proposed remedies to transform occupants' behaviour include support, information, training, motivation and education (Energy Efficiency in Buildings, 2007).

In addition, if building users are provided with an elevated level of flexibility in the control and use of the building and their own circumstances (e.g. through measures such as operable windows, modifying clothing, access to hot and cold beverages, to manage and control indoor thermal comfort by themselves) they can then accept a wider range of temperature and humidity than the conventional thermal comfort theory predicts (de Dear & Brager, 1998; Barlow & Fiala, 2007). This phenomenon is ascribed to the adaptive thermal comfort approach, which states that if occupants undergo to a change leading to an uncomfortable environment, they will react accordingly to ensure that their comfort will be restored (Auliciems, 1983). Conversely, the conventional thermal comfort model was derived from experiments that did not enable individuals to interact with the environment, and building occupants are considered as passive receivers of the thermal environment controlled by the building services systems (de Dear, 2004). Several field studies (de Dear & Brager, 1998; Nicol & Humphreys, 2002; Moujalled Cantin & Guarracino, 2008) have corroborated the unreliability of the conventional thermal comfort model for naturally ventilated buildings as compared to the adaptive model. It was found that the results from the adaptive approach can closely match those from experimental tests. Therefore, the adaptive thermal model could be more useful than the conventional thermal comfort model in properly assessing the thermal comfort in naturally ventilated buildings (Buratti & Ricciardi, 2009).

This paper presents an investigation of the effectiveness of a range of ECMs that can be potentially used to improve energy performance and thermal comfort of existing naturally ventilated university buildings. The ECMs considered include information technology (IT) equipment and lighting upgrades, and occupant behaviour change (i.e. turning off the IT equipment overnight, using day-lighting as far as possible and leaving the windows open overnight during the summer period). The performance of the ECMs was tested against a full-scale virtual building representing a real building at the University of Wollongong.

## Methodology

### Overall modelling structure and process

Figure 1 is a schematic of the modelling method employed in this study. Firstly, a range of ECMs, as summarised in Table 1, were identified based on the characteristics of university buildings. Secondly, a full scale building simulation model which represents a real building in University of Wollongong was developed using the building energy simulation software DesignBuilder™. Thirdly, the performance of the building without implementation of any ECMs was evaluated and its performance was used as the benchmark. Lastly, different energy conservation scenarios were incorporated into the simulation model and the building energy performance and thermal comfort were then evaluated by comparing with that of the benchmark to provide a qualitative level of validation.

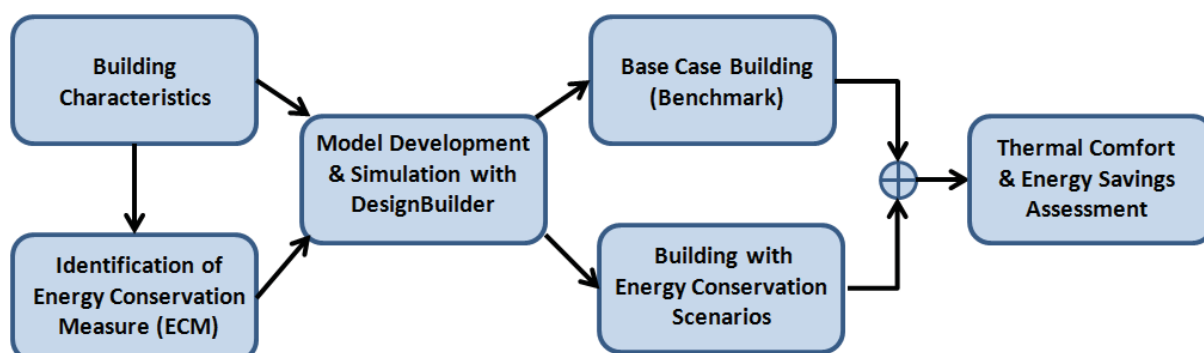


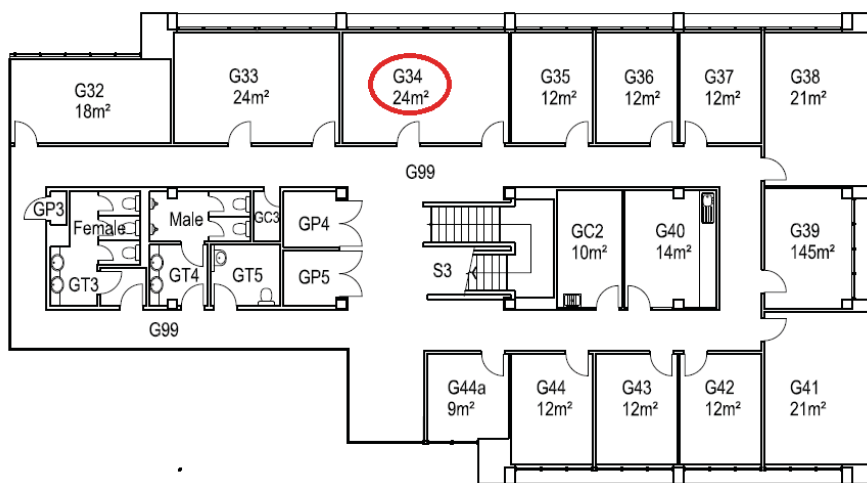
Figure 1: Schematic of the modelling method employed.

### Model Development

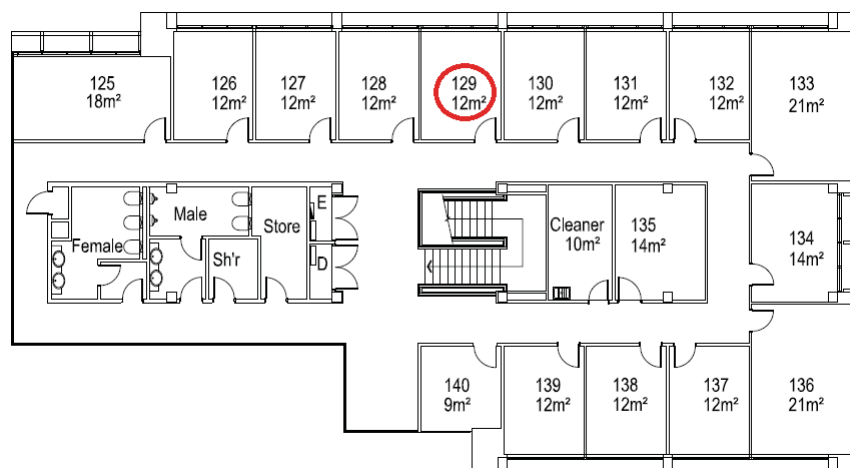
This study focused on a case building of the west wing of Building 4 at the main campus of University of Wollongong. Figure 2 shows the floor plan of the building. It was constructed in the 1960's and is a multi-purpose building, combining staff and research student offices as well as small classrooms.

**Table 1: Energy Conservation Measure (ECM) Scenarios considered**

Scenario	Energy Conservation Measures
I	Base case without implementation of any energy conservation measures
II	Occupant behaviour measures (i.e. Shut down IT equipment overnight, night purge and switch off the lighting when daylight is available)
III	IT equipment and lighting upgrades
IV	Combination of occupant behaviour measures with IT equipment and lighting upgrades

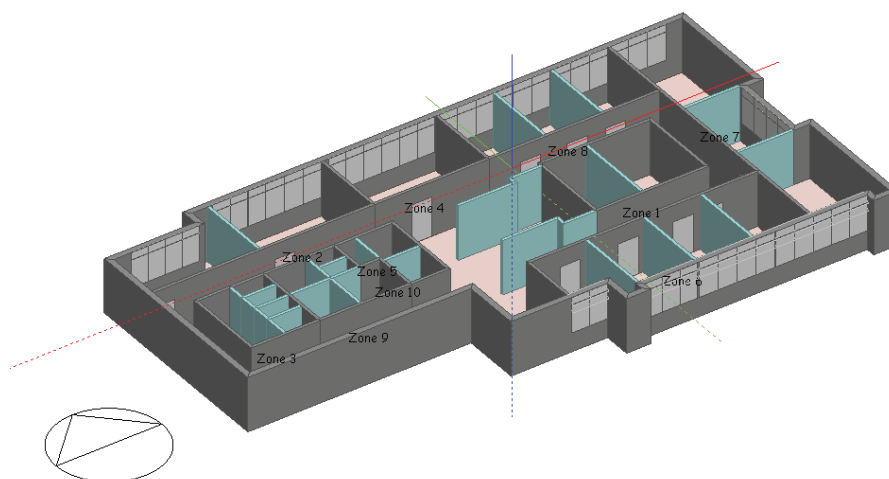


(a) Ground floor



(b) First floor

**Figure 2: Floor plan of Case Study Building.**



**Figure 3: Sketch of the ground floor geometry of the case study building.**

The building thermal performance was tested and compared to actual measurements in several rooms and the energy performance was estimated for the building as a whole. Room 4.G34 in the ground floor and room 4.129 in the first floor were selected as representative rooms to demonstrate the occupants' thermal comfort by using different energy conservation scenarios. The building internal loads before and after the implementation of ECMs are summarized in Table 2.

**Table 2: Summary of Internal loads before and after the application of the ECMs.**

Internal load	Number		Base Case		Upgrades	
	4.G34	4.129	Item description	Average power consumption (W)	Item description	Average power consumption (W)
Office IT equipment	6	-	DELL – Optiplex 755 MT	50	DELL – Optiplex FX 170	10
	6	-	Monitor-Display	40	Monitor - Display IN1930F	13.5
	-	2	Monitor-U2410	64		
	-	1	DELL-Precision	128	DELL Precision	98
	-	1	Laptop Dell Precision	17	Laptop Dell	17
Lighting	10	9	T8 1200 mm	36	T5 1200mm	28
	corridor: 75 x two floors		T8 600mm	24	T5 600mm	18

### Comparison of experimental and predicted room temperatures

Before the implementation of ECMs, the performance of the simulation model was compared with experimental data (i.e. indoor temperature) collected with a data logger via a thermocouple located in room 4.G34. Figure 4 shows the model results for ten days in February (i.e. 15-02-2011 to 25-02-2011). It was found that the model gave results that matched reasonably well with the experimental data for most data points (as illustrated in Figure 4a). However, in this first phase of the present study only limited data was available on weather and behaviour of occupants (e.g. experimental hourly solar radiation and wind data was not available and the actual internal heat gains due to occupant activities could not be accurately assessed). Nevertheless the results from the building simulation model gave a reasonably close agreement on the basis of cumulative frequency of hours in the year that the representative rooms were above a given temperature.

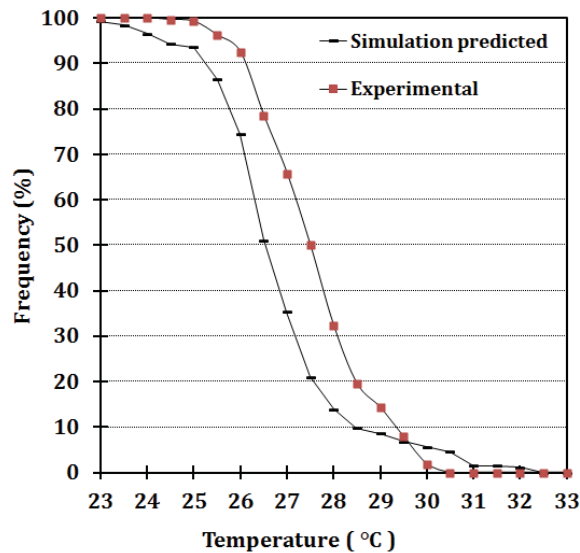


Figure 4: Comparison of predicted and experimental cumulative frequency of experimental and predicted temperature in ground floor room 4.G34.

## Results and Discussion

The results and analysis of the aforementioned energy conservation scenarios tested in the case study building are presented in this section. The predicted building energy consumption is given for each scenario and together with the potential estimated energy savings. The thermal comfort was assessed by calculating the overheating risk, i.e. operative temperature above 28°C during occupied hours (Race, 2006), and subsequently by the adaptive based comfort zones defined in ASHRAE Standard 55 and EN15251 European Standard.

### Energy Performance Analysis

The potential energy savings from the computers and lighting by using different energy conservation scenarios are shown in Figure 5.

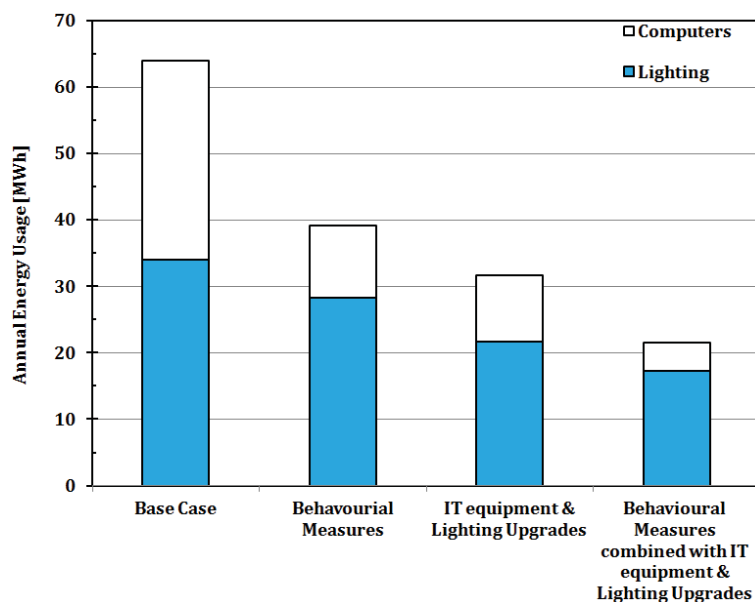


Figure 5: Annual energy consumption by using different energy conservation scenarios.

The energy consumption of the base case is illustrated for comparison with the different scenarios. Compared to the base case condition, up to 65% of total energy can be saved by combining the IT equipment & lighting upgrades with behavioural measures. Implementing behavioural measures is

predicted to achieve 40% energy savings, while the upgrading of IT equipment & lighting can potentially reduce energy consumption by 50%.

### Overheating Hours and Adaptive Thermal Comfort

#### Overheating hours

The cumulative hours exceeding a given operative temperature for rooms 4.G34 and 4.129 are presented in Figure 6. The indoor operative temperatures for the base case demonstrated that the building has significant overheating problems since around 5% and 9% of the occupied time the operative room temperatures for the rooms 4.G34 and 4.129 was predicted to be above 28°C, respectively.

Compared to the base case, the overheating hours decreased significantly when the ECMs were applied. For instance, the maximum reduction in the temperature above 28°C was obtained with the incorporation of the behavioural measures together with the IT and lighting upgrades. The model predicted a decrease in the number of hours the temperature exceeded 28°C of approximately 60% and 75% for the rooms 4.G34 and 4.129, respectively. Therefore, when behavioural measures combines with the IT and lighting upgrades are implemented, the building would not suffer a significant overheating risk.

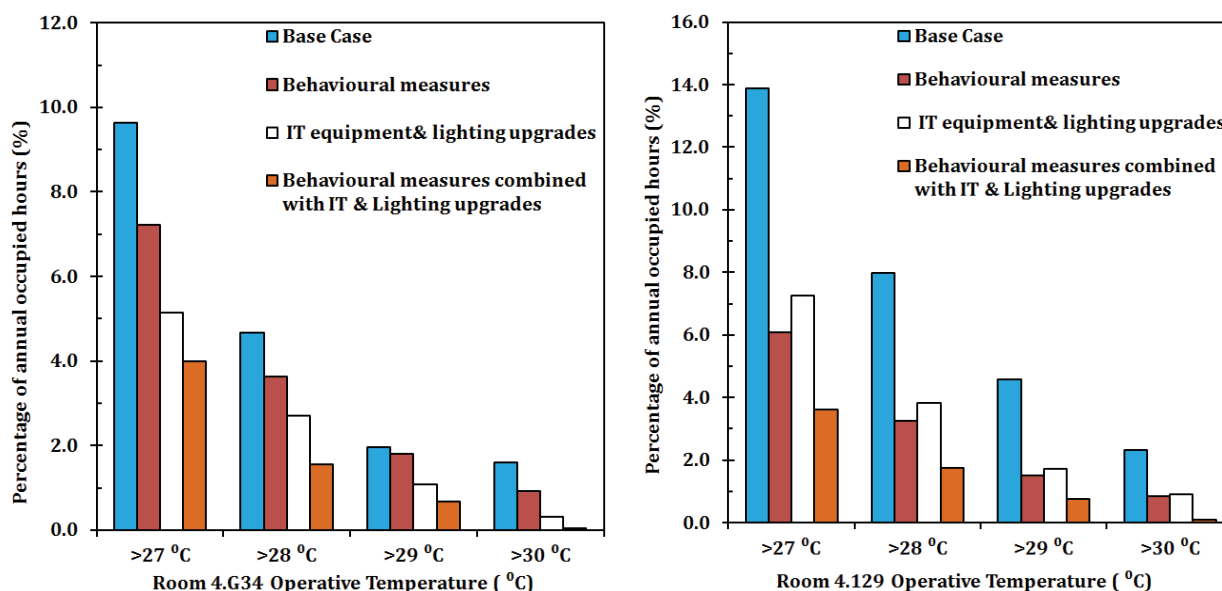


Figure 6: Percentage of occupied hours (i.e. from 8am to 6pm weekdays) that internal temperatures are exceeded for different ECM scenarios.

Table 3: Description of the comfort bands for EN15251

Category	Description
I	High level of expectation and is recommended for spaces occupied by very sensitive and fragile persons
II	Normal level of expectation and can be used for new buildings and existing building renovations
III	An acceptable, moderate level of expectation and may be used for existing buildings

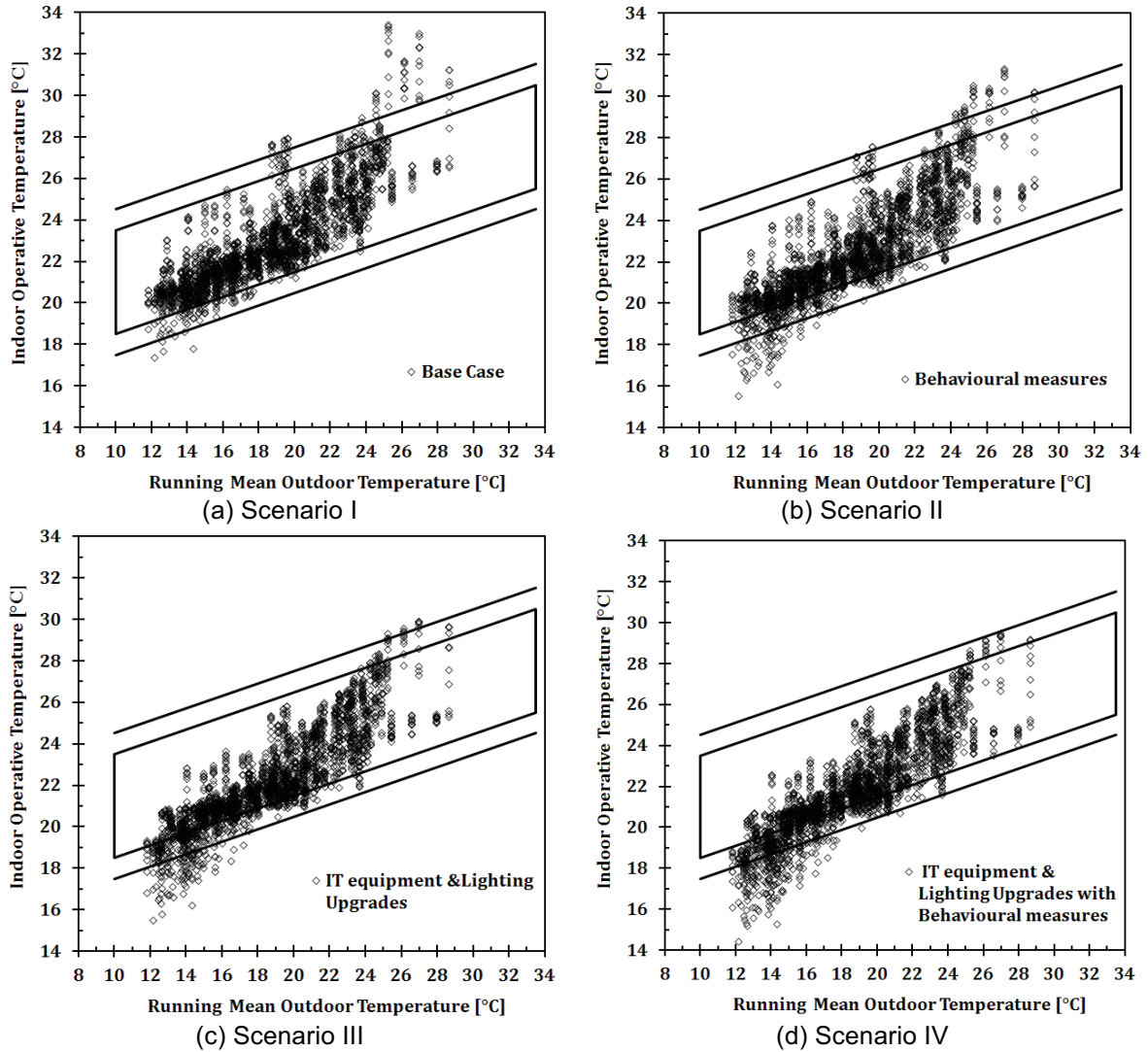
#### Adaptive thermal comfort

Adaptive thermal comfort may be determined from algorithms given in standards such as ASHRAE Standard 55 and EN15251. Both standards allow the determination of thermal comfort in naturally ventilated spaces accounting for the adaptive opportunity for the building users. The charts for both standards present a similar concept but with some differences underlined below (Nicol & Humphreys, 2010):

- Each standard has its own adaptive equation and the comfort limits are therefore different.



- The standard data used to develop ASHRAE 55 was worldwide whilst the EN15251 data is only from Europe.
- ASHRAE Standard is only applicable to naturally ventilated buildings whereas the EN15251 Standard can be applied to free running buildings where a mixed mode could be used in some seasons.



**Figure 7: Adaptive comfort zones for ASHRAE 55-2004 with the annual indoor operative temperature for ground floor room 4.G34 during occupied hours under the different scenarios.**

The simulation results for room 4.G34 and room 4.129 are shown against adaptive thermal comfort zones of ASHRAE Standard 55 are shown in Figures 7 and 8 and against the adaptive thermal comfort zones of EN15251 in Figures 9 and 10. It should be noted that the ASHRAE chart is slightly modified as it is expressed in terms of the running mean outdoor temperature instead of the monthly mean outdoor temperature. The running mean outdoor temperature, as expressed in Equation 1, is able to handle diurnally changing weather conditions as it is a weighted average of the previous days (Nicol & Humphreys, 2010) rather than a monthly average.

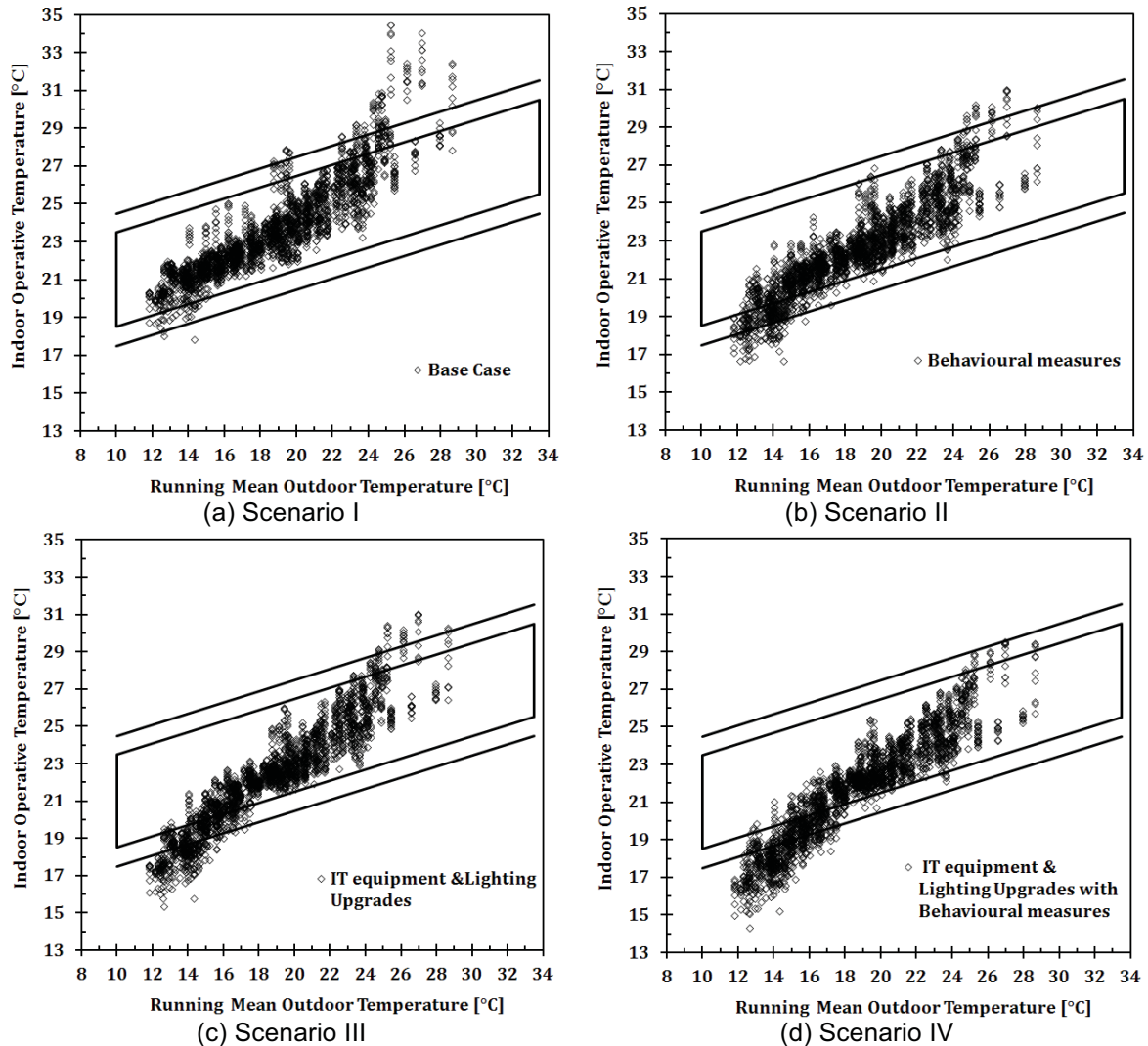
The running mean temperature is defined according to EN15251 (2007) as in Equation 1. Equation 2 can be used where records of daily mean external temperature are not available. In this study, this formula is applied for the first 7 days and then Equation 1 is used.

$$T_{rm} = (1 - \alpha)T_{rm} - \alpha T_{rm-1} \quad (1)$$

$$T_{rm} = (T_{ed-1} + 0.8T_{ed-2} + 0.6T_{ed-3} + 0.5T_{ed-4} + 0.4T_{ed-5} + 0.3T_{ed-6} + 0.2T_{ed-7})/3.8 \quad (2)$$

where  $T_{rm}$  is the running mean temperature for the  $i^{\text{th}}$  day;  $T_{rm-1}$  is the running mean temperature for the  $i^{\text{th}}-1$  day;  $T_{ed-1}$  is the daily mean external temperature for the  $i^{\text{th}}-1$  day;  $T_{ed-2}$  is the daily mean external temperature for the  $i^{\text{th}}-2$ ;  $\alpha$  is a constant less than 1 (recommended to use 0.8). The derivations of the acceptability limits for both standards can be found in CEN (2007) and ASHRAE (2004).

The simulations reveal that each of the implemented energy efficiency measures decreases the overall indoor operative temperatures in the ground floor and first floor rooms throughout the year compared to the base case. This was especially significant during the summer season, in agreement with the reduction in the overheating hours shown in Figure 5.



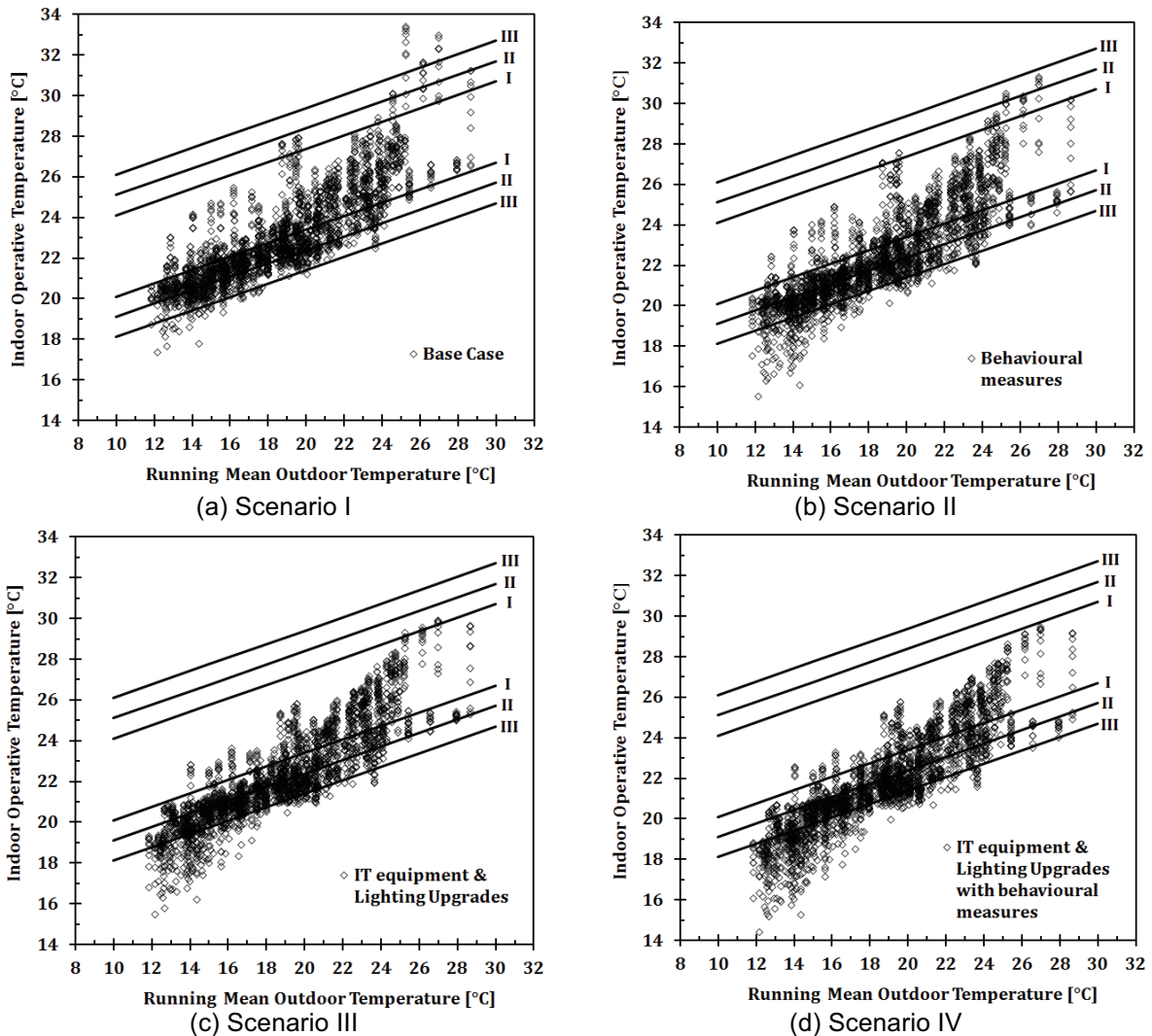
**Figure 8: Adaptive comfort zones for ASHRAE 55-2004 with the annual indoor operative temperature for first floor room 4.129 during occupied hours under the different scenarios.**

One interesting outcome of the implemented ECMs is the decrease in the indoor temperatures throughout the year including winter and the lower adequacy limits of the adaptive thermal comfort during winter are not fully met. This issue will be addressed in future work by modelling improvements to the building envelop or incorporating heating in the model during the cold period.

Figure 7 for the building's ground floor shows that the incorporation of behavioural measures (Figure 7b) resulted in a significant decrease of overheating hours outside the comfort zone in comparison with the base case. Two of the scenarios permitted maintenance of thermal comfort during summer

within the 80% acceptability requirement, i.e. through upgrades in IT equipment & lighting (Figure 7c), combination of IT equipment & lighting upgrades with behavioural measures (Figure 7d).

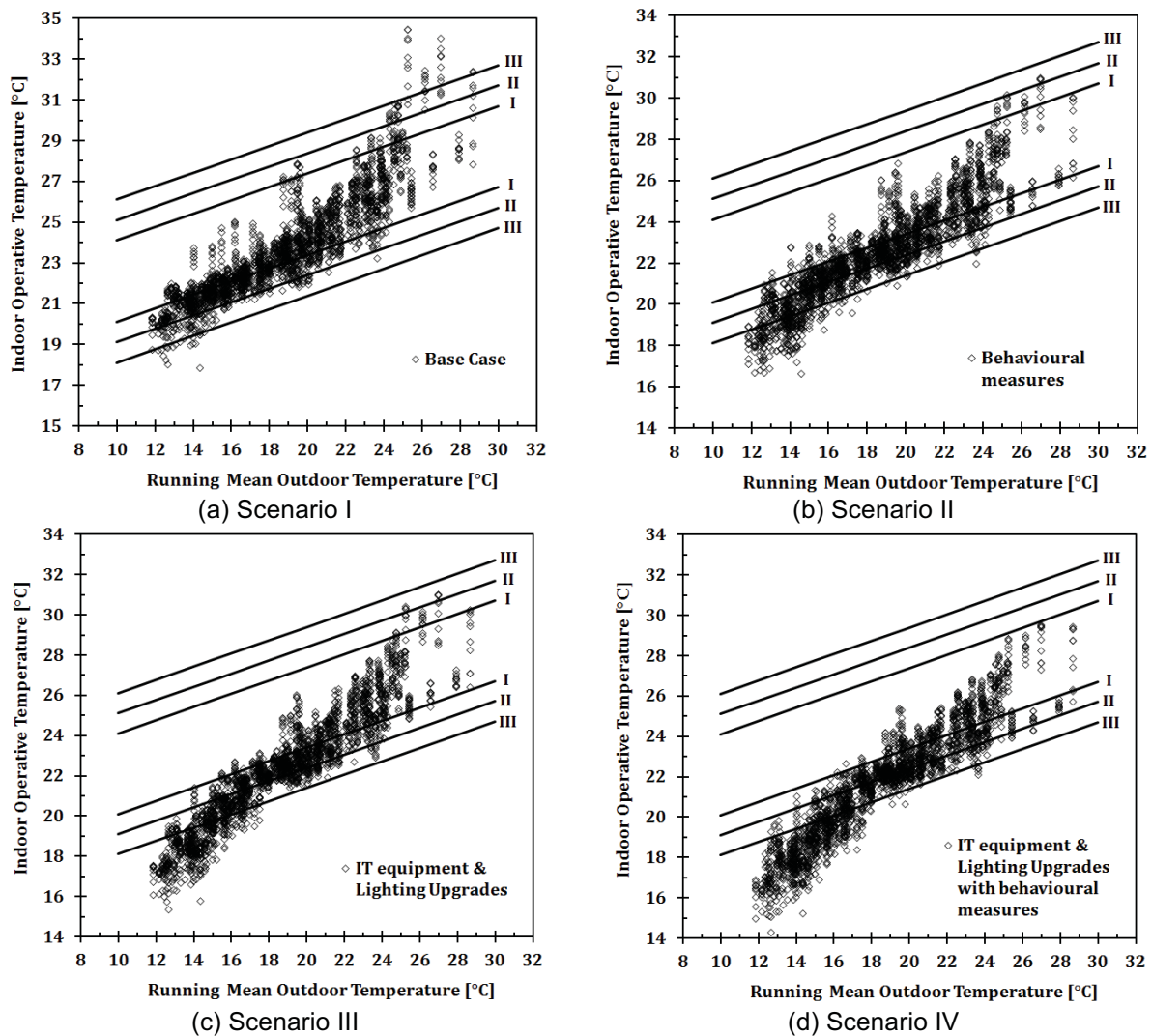
Simulations of the first floor room indicated warmer temperatures than the ground floor (see Figure 8). However, the predicted temperatures for the proposed ECMs showed very similar trends as for the ground floor. The first floor achieved a significant reduction of the summer days outside of the comfort bands with the behavioural measures and IT & lighting upgrades (Figures 8b and 8c, respectively). Completely satisfactory thermal comfort for summer was reached by implementing the behavioural measures together with IT equipment and lighting upgrades (Figure 8d).



**Figure 9: Adaptive comfort zones for EN 15251b with the annual indoor operative temperature for the ground floor room 4.G34 during occupied hours under the different scenarios.**

When the European Standard was used to correlate the simulated temperature data, the hours within the comfort zone for the summer period increased as compared to case of using the ASHRAE Standard. It is observed that, all the warm seasons are within the comfort zone for both rooms (Figures 9 and 10), when the proposed ECMs are simulated.

The implementation of the IT equipment & lighting upgrades would require a capital investment. A detailed cost-benefit analysis is therefore needed to help the energy management team to determine the best retrofit options. This has yet to be completed. Nevertheless, the implementation of the proposed ECMs could potentially save significant capital expenditure by removing the need to install air conditioning systems to avoid occupant complaints from overheating during summer. However, the reduction of internal loads does lead to a predicted increase in winter heating requirements, which in turn could be reduced by improving the thermal performance of the building envelope.



**Figure 10: Adaptive comfort zones for EN 15251 with the annual indoor operative temperature for the first floor room 4.129 during occupied hours under the different scenarios.**

## Conclusions

This paper reports on simulations of the effectiveness of a range of Energy Conservation Measures (ECMs) implemented in a naturally ventilated university building at University of Wollongong through computer simulations. The following conclusions can be drawn:

- Significant energy savings could potentially be achieved by implementing occupant behavioural measures or the IT equipment & lighting upgrades. The combination of both ECMs simultaneously can provide up to 65% energy savings compared to the base case. The equipment upgrades offer a higher energy saving potential (i.e. 10% more savings) than the behaviour change measures, however the investments required to ensure the success of each measure are significantly different.
- Two adaptive thermal comfort standards, ASHRAE Standard 55 and EN15251, were used to correlate the thermal results from the simulations. These standards were found to be extremely useful in providing a clear picture of occupant comfort conditions as a function of monthly/seasonal outdoor temperature variations.
- Summer overheating hours were predicted to be reduced significantly with the implementation of the behavioural measures and/or the IT equipment & lighting upgrades that have been proposed and modelled above. The simulations indicated that acceptable

comfort conditions, within the bands defined by the ASHRAE and European Standards, can be achieved over the summer months through these ECMs. Therefore, the incorporation of relatively simple interventions and behavioural modifications in the management of the building could avoid the need for retro-fitting of air-conditioning systems with a significant reduction in capital and operating costs into the future.

- The changes to occupants' behaviours regarding energy consumption could result in significant energy savings without requiring any additional costs. However, there are many barriers hindering occupant behaviour modification. The UOW Environmental Sustainability Initiatives (ESI) unit is in the process of establishing a range of strategies to inform, educate and motivate the building occupants to drive behavioural transformation.

It is clear from our initial simulations that the ECMs proposed could have very positive effects on both energy consumption and thermal comfort in naturally ventilated university buildings in regions with climates similar to the Sydney/Wollongong region.

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