Retrofitting Adaptive Comfort Strategies into Conventionally Air Conditioned Commercial Buildings

Hisham Allam

The University Of Sydney

SUMMARY
Reducing the temperature difference between indoor HVAC set-point and outdoor ambient temperatures represents a direct energy conservation measure that requires minimal capital investment in commercial buildings. This paper reports on an intervention study that shifted the HVAC set-points from their normal engineering practices in Australia in an office building located in Sydney. The study manually tuned the building's HVAC set point using the ASHRAE adaptive comfort standard 55-2010 based on a running seven-day mean of outdoor temperature, but capping the set-point band at 26°C and 18°C in summer and winter respectively. Thermal comfort questionnaires, interviews and observations were conducted during the intervention study using a daily sample of twenty office occupants. This longitudinal field study started mid winter and ran till late summer eight months later. Statistical analysis of results showed a linear relationship between indoor comfort temperatures and the running mean outdoor temperature similar to that observed for naturally ventilated buildings that formed the basis of ASHRAE’s adaptive thermal comfort model. The research confirmed that occupants of an air conditioned building are capable of adapting to variable indoor temperatures like the occupants in naturally ventilated buildings, and the notion of “adaptive comfort HVAC” is feasible.

KEYWORDS
HVAC energy conservation, sustainable offices, field study, indoor temperature, adaptive comfort.

1 INTRODUCTION

1.1 Adaptive Thermal Comfort
The major role of heating, air conditioning and ventilation system is to maintain acceptable temperature and humidity to the human body. Recent years have seen significant innovation in sustainable buildings in response to global climate change and carbon dioxide emissions. The case for fossil-fuel energy conservation has strengthened the case for adoption of the adaptive thermal comfort concept in naturally ventilated and hybrid air conditioned buildings. But to date there has been scant research on thermal comfort in “adaptive HVAC” situations – i.e. centrally air conditioned buildings in which occupants have limited adaptive opportunity and windows are inoperable.

In naturally ventilated situations it is now accepted that occupants are able to accept a wider range of temperature than simplistic heat-balance models of comfort like PMV suggest, not only because of their psychological habituation and expectation and physiological acclimation, but also their behavioural adjustments (de Dear and Brager, 1998). In 2004, ASHRAE adopted a standard (ASHRAE-55 Thermal Environmental Conditions for Human Occupancy) which featured an adaptive comfort zone for naturally ventilated spaces, then the European adaptive comfort standard known as EN15251 followed suit in 2007.
1.2 Main Problem
The building sector is responsible for almost 40% of the total energy consumption in a form of heat or electricity in many countries (Kordjamshidi and King, 2005). International concern about greenhouse mitigation through energy conservation in buildings has prompted many new research enquiries into thermal comfort. A rule-of-thumb in the Australian HVAC sector suggests that one degree Celsius difference of air conditioning set point temperature is roughly equivalent to 10% of HVAC energy. According to the ASHRAE 55 standard (2004, 2010), thermal comfort is managed in an air conditioned building by applying the PMV concept, and in naturally ventilated buildings in which windows represent the primary means of thermoregulation by applying the adaptive model. The adaptive model provides wider indoor temperature range of acceptability which narrows the difference between indoor and outdoor temperature. However, in the Australian commercial building sector both PMV/PPD and adaptive comfort guidelines are largely ignored, and buildings are generally regulated with HVAC at about 22°C, summer and winter. This information prompts two questions; why do Australian buildings disregarding the environmental and financial implications of adaptive thermal comfort standards? Can Australian office building occupants accept adaptive comfort conditions like their counterparts in other parts of the world such as Japan? (CoolBiz press release, 2005). The two main adaptive comfort standards (ASHRAE 55-2010 and EN15251) were developed from data within naturally ventilated buildings, so the scope of their application is limited to these types of buildings though human adaptation is also relevant to air conditioned buildings, so there is a need for research into the concept of “adaptive HVAC”.

1.3 Research Objectives and Significance
The main aim of this study was to apply the adaptive model in an air conditioned commercial building. The significance of this research in the long-term is the potential to reduce greenhouse gas emissions from the commercial building sector, not only for new-build but also existing building stock, as this concept can readily be retrofitted to any building with a programmable Building Management System (BMS). The occupants of office buildings are able to maintain thermal comfort and energy conservation when provided with the knowledge of making personal and environmental adjustments.

2 MATERIALS/METHODS
Longitudinal field study was selected as the most appropriate research methodology to examine human adaptive thermal comfort inside an air-conditioned office building because it relies on a relatively small number of cooperative subjects over a prolonged monitoring period. The adaptive approach to thermal comfort is based on the findings of surveys of thermal comfort conducted in the field (Nicol & Humphreys, 2007). The method used in this project involved collection of physical indoor and outdoor measurements along with simultaneous comfort questionnaires from occupants of the building offices Figure 1 and Figure 2. Outdoor environmental data was collected from Latest Weather Observations in Bankstown weather station (Commonwealth of Australia 2010, Bureau of Meteorology) which allowed calculation of a seven-day running mean outdoor temperature with the following equation:

\[ Trm = 0.34 \cdot T_{-1} + 0.23 \cdot T_{-2} + 0.16 \cdot T_{-3} + 0.11 \cdot T_{-4} + 0.08 \cdot T_{-5} + 0.05 \cdot T_{-6} + 0.03 \cdot T_{-7} \]  

(1)

Where:

\( Trm \): The seven days running mean outdoor temperature measured in °C (de Dear, 2006).
The mean outdoor temperature in °C, \( T_{-1,-2,-3,-4,-5,-6,-7} \) refer to yesterday, the day before yesterday, the day before the day before yesterday etc.

### Figure 1: Occupant questionnaire completion.

### Figure 2: Desk-top comfort instrument.

This expression for outdoor mean temperature was then input to the adaptive model in order to calculate each day’s target set-point temperature \( T_{c} \) for the air conditioning control system. The proposed adaptive model equation was that for naturally ventilated buildings in ASHRAE’s Standard 55 (ASHRAE, 2010).

\[
T_{c} = 0.31 \cdot T_{rm} + 17.8 
\]

\[
T_{c} = \left[ \frac{26^\circ}{18^\circ} \right] 
\]

#### 2.1- Office Building Description:

The selected building is located in Sydney, two kilometers away from Bankstown Airport where the weather station data was collected. The weather station belongs to climatic zone 5 which is a seasonal subtropical humid climate. The building recognized as a typical suburban office building and categorized under Class 5 building in the Building Code of Australia (BCA, 2009). The building comprises a warehouse and two levels of offices. The building envelop structure was made of pre-fabricated concrete walls and metal deck roofing. Single glazed façade, facing North West, made of tinted glass and shaded internally by vertical blinds. Office area was 440 square meters occupied by 26 employees. An air-cooled split ducted air conditioning unit of 40kW cooling capacity was used to cool and heat the offices in each level. The air-handling units were located in the ceiling space, supplying air-conditioned air to the rooms via insulated ducts connected to ceiling-mounted diffusers. The indoor set point temperature was controlled manually by a wall-mounted touch pad on each office level.

#### 2.2 Measurement equipment and Questionnaire

A customized “comfort package was used to measure the ambient comfort variables within the occupied zone. The package (Figure 2) very portable and provides 3-minute climatic readings at the desk-level of the respondent. The American Society of Heating, Refrigeration
and Air Conditioning Engineers designed a standard questionnaire for thermal environment survey (ASHRAE 2004) that we have used and modified to suit our research purpose. The questionnaire is intended to characterise whole-body thermal comfort and comprised eight major questions. The first corresponded to the demographic information such as age, height, weight and gender. Occupant’s Clothing questions followed and provided information needed for calculation of clo value. The third question dealt with occupants’ activity within half an hour in order to determine metabolic rate. The fourth section included questions relating to thermal comfort, (thermal sensation, thermal preference and thermal acceptability). Thermal sensation was measured on the ASHRAE seven-point scale ranging from cold (-3) to hot (+3). Thermal preference classified subjects into three groups; those preferring to be in a warmer place, those who preferred cooler, and the remainder who preferred temperature to remain as is. Thermal acceptability was captured with a binary “right-here right now” question (acceptable/unacceptable). The last two questions allowed the occupants to assess their own productivity and stress level on percentage and integer scale respectively.

Each office space was equipped with unobtrusive sensors to record temperature, humidity and air speed throughout the month. Every subject completed sets of comfort surveys, distributed every morning to all building occupants. The indoor environmental data checked against the proposed adaptive comfort temperature (Tc) which was derived from the outdoor weather observations. The one-page questionnaire was been designed to record the thermal comfort within the office and did not take longer than two minutes to complete.

3 RESULTS AND DISCUSSION

3.1 Occupants Thermal Sensation

Figure 3 displays a simple comparison between Actual Mean Vote (AMV) and Predicted Mean Vote averaged (PMVav). Predicted Mean Vote is an index calculated for each respondent on the basis of four environmental parameters \( (t_a, t_r, v, r_h) \) and two personal parameters (clo, met). It can be seen for all votes within the cooler operative temperature bins from 18°C to 21°C that the average PMVav registered lower thermal sensation than the actual votes from these occupants (AMV), meaning that these occupants felt more comfortable (neutral) in the cooler temperatures than the six thermal comfort parameters would suggest. However, for the operative temperature bins 22 through 26°C, there was generally close agreement between predicted and actual thermal sensations.
Figure 3: Comparison between average actual votes (AMV) and average Predicted Mean Vote (PMV) with respect to indoor operative temperature bins.

3.2- Indoor comfort temperature and seven days running mean outdoor temperature relationship.

Figure 4 plots the relationship between average indoor neutral operative temperature (To) and the corresponding running seven-day outdoor temperature mean. This graph represents the indoor operative temperatures recorded every time a subject expressed thermal neutrality (i.e. voted between -0.5 and +0.5). It indicates clearly that thermal neutrality inside an air conditioned building is related to the prevailing outdoor temperature. We found the linear equation link between acceptable indoor temperature To and seven-day running mean outdoor temperature (Trm) plateaued at about 25~26°C during the hottest weather conditions, but this is probably reflecting the way we implemented the adaptive comfort algorithm in this building’s BMS system (we capped the set-point algorithm at 26°C). While a simple linear regression model has been fitted in Figure 4, a parabolic equation explains more variance (73% versus 84%). Interestingly the gradient on the linear adaptive comfort model in Figure 6 is virtually identical to its counterpart in ASHRAE’s adaptive comfort standard (2010) for naturally ventilated buildings, but because the range of indoor temperatures in this air conditioned building was capped at 26, we can’t read too much into this coincidence.

4 CONCLUSIONS

The results found a relationship between neutral operative temperatures recorded inside an air conditioned office building, and the outdoor temperature prevailing over the last seven days (exponentially weighted). While this kind of adaptive comfort relationship is very familiar in a naturally ventilated (or free running) context, we think this study is one of the first to confirm the relevance of the adaptive comfort concept in air conditioned buildings where occupants have more constrained adaptive opportunity.
ACKNOWLEDGEMENT: This research was supported by Human Research Ethics Committee in The University of Sydney

5 REFERENCES
Kordjamshidi, M. King, S. st al. (2005). Towards the development of home Rating Scheme for free running buildings, Faculty of the Built and Environment, UNSW.Solar 2005 ANZSES