ADAPTIVE COMFORT APPLICATIONS IN AUSTRALIA AND IMPACTS ON BUILDING ENERGY CONSUMPTION

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ABSTRACT
The buildings sector offers the greatest potential for cost-effective reductions in greenhouse gas emissions out of all the sectors examined by the Intergovernmental Panel on Climate Change. However that potential was based purely on technical measures applied to existing buildings and new construction. It is becoming increasingly clear that non-technical options involving building occupant comfort, culture and behaviour will also need to be implemented in order to stabilise atmospheric concentrations of CO2 within a useful timeframe. The adaptive comfort model provides a theoretically coherent option that opens up many cost-effective, low energy design alternatives. Numerous example applications are appearing all over the world. This paper describes Australian applications in mixed-mode buildings. Estimates of building energy conservation are 40% and 45% for the Sydney and Melbourne case-studies respectively, compared to the Australian conventional HVAC benchmark. A pattern is emerging Post Occupancy Evaluations of Australia’s recent ‘green’ building stock; low-energy buildings designed around adaptive comfort principles are often evaluated as warmer in summer and cooler in winter, sometimes uncomfortably so. The POE literature indicates that, despite some minor discomforts, occupants are still favourably disposed towards Australia’s new green buildings, auguring well for mainstream acceptance of adaptive comfort strategies.

KEYWORDS
adaptive comfort, mixed-mode ventilation, energy conservation, greenhouse mitigation

INTRODUCTION
Latest estimates of emissions from the world’s buildings sector including through electricity use are about 8.6 Gt CO2 plus another 2.0 Gt CO2-eq from other greenhouse gases. This represents about a quarter of the global total carbon dioxide emissions. Global CO2 emissions resulting from energy use in buildings have been increasing at an average of about 2.7% per year between. Business-as-usual scenarios indicate about 11.1 Gt of emissions of CO2 in 2020, rising to 14.3 Gt CO2 in 2030.

Greenhouse gas (GHG) abatement measures for the building sector can be classified into three categories: reducing energy inputs to buildings (embodied and operating), switching to low carbon or renewable energy, or reducing emissions of non-CO2 GHG gases, but the first of these contains the largest and most cost-effective options for global GHG mitigation in buildings. The Intergovernmental Panel on Climate Change’s Fourth Assessment Report indicates that there is potential to reduce cost-effectively about 29% of the projected global baseline emissions from the residential and commercial building sectors by 2020. Most importantly, this estimate ranks the highest among all sectors studied by IPCC (IPCC 2007).

It should be noted that these estimated potential reductions at a global scale were based on technological solutions designed into new buildings and retrofitted to existing building stock. Non-technical options for greenhouse mitigation involving occupant behaviour, comfort, culture and consumer choice, while acknowledged as being major determinants of GHG emissions, have not yet been factored into the IPCC’s potential mitigation estimates. To date non-technical abatement has received scant quantitative research attention, either at national or global scales, probably because the policy options relating to comfort, consumer choice and behaviour are not as well understood as are regulations focused on specific engineering solutions or strategies.

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Nevertheless, “soft” issues like thermal comfort inside built environments need to be factored into the global equation. Shifting comfort limits (adaptive comfort) have obvious potential for energy savings, with rule-of-thumb estimates at the scale of individual buildings ranging up to 10% saved for every degree of comfort-zone widening. And unlike most of the technical fixes considered in the IPCC’s Fourth Assessment Report, shifting comfort boundaries are better than cost-effective due to savings on energy bills, along with other non-monetary co-benefits. The Japanese Ministry of Environment’s “Cool Biz” and “Warm Biz” campaigns over recent years probably represent the most ambitious applications of the adaptive comfort concept to date because they extended setpoints all the way to 28°C in sealed envelope buildings with central air-conditioning. A web-based questionnaire survey was conducted after the 2005 “Cool Biz” campaign covering approximately 1,200 men and women randomly extracted from an “internet panel” owned by a research company. The results indicated that a third of building occupant respondents answered that their offices set air conditioning set-points higher than in previous years. Extrapolating that finding across the Japanese commercial building sector, the CO2 reduction in summer of 2005 was estimated to be equivalent to the amount emitted from approximately one million Japanese households for one month (Ministry of Environment Japan 2005).

Widening the permissible indoor temperature range renders some low-energy design solutions feasible where they were previously dismissed as unacceptable. Natural ventilation is now a design option that is being increasingly employed in commercial buildings in Europe, and is starting to be used in North America (McConahey et al. 2002) and Australia. Apart from the direct physiological impacts of natural ventilation on the occupant, it is being used increasingly for nocturnal cooling of exposed thermal mass which can store the coolth for subsequent release during the building’s occupied hours.

Natural ventilation also has the important effect of increasing the acceptable temperature range through psychological adaptation, particularly when occupants have control of operable windows (Brager et al. 2004). Conventional buildings with central HVAC systems that were typical of the late 20th century shifted the locus of indoor environmental control towards a facilities manager. If the occupants of such buildings were prepared to wear a standard level of clothing insulation (typically 0.5 clo), generate a standard amount of metabolic heat (typically 1.2 met units), then their thermal comfort requirements could be met by a centrally managed, spatially homogeneous and static indoor climatic regime (in Australia, typically 22~23°C operative temperature, 50%rh and air velocity <0.20 m/s). Indeed, the commercial value of such office environments is usually rated on the basis of how tightly their indoor climates can be controlled. Theoretically the occupants of such buildings do not have to do a thing to achieve thermal comfort because all of their requirements are taken care of by the centralised HVAC services. In contrast, the emergent ‘green’ buildings with increasing provision of natural ventilation present more loosely controlled, interactive environments to their occupants, leading to the adage – active buildings for passive occupants and passive buildings for active occupants.

The adaptive comfort concept

This discussion of interactive buildings logically introduces adaptive comfort theory which is premised upon the building occupant being responsible for achieving their own desired comfort conditions through a variety of adaptive opportunities (Baker and Steemers 2000). These include clothing adjustments, adjustments to window awnings, fans, and most importantly, operable windows through which natural ventilation is delivered. As noted above, occupants who are more directly engaged in managing their personal indoor environment, ipso facto, tend to be comfortable across a wider range of indoor temperatures than is the case in conventional centrally air-conditioned premises.

In addition to behavioural interaction with indoor climates, adaptive comfort theory is also premised on a psychological adaptation referred to as “occupant expectation” (Fountain et al 1996). Facilities managers in charge of conventional HVAC buildings are often perplexed by the frequency of occupant complaints whenever temperature strays as little as a single degree from the usual set-point. Why have occupants of such buildings become so sensitive, or even hypersensitive, to such subtle fluctuations in workplace temperature? The adaptive hypothesis is that they have come to expect thermal constancy and even the slightest departure away from that expectation is sufficient to prompt complaint. Failures to meet thermal expectations rather than physiologically driven discomfort per se probably explains why so many so-called “A-grade” office buildings around the world have been unable to meet design specifications of 90% or even 80% occupant satisfaction. By contrast, long-
term occupants of naturally ventilated buildings come to expect thermal variability, both spatially and temporally, and according to adaptive comfort theory, this leads to a broadening of the range of indoor temperatures deemed acceptable.

Apart from the interactive nature of adaptive comfort and a wider range of thermal acceptability, the other defining feature of the theory is the relationship between outdoor temperature and indoor comfort. The optimal comfort temperature for a building occupant seems drifts in the direction of the weather to which they have recently been exposed; as winter turns to summer, so does the comfort optimum drift from cool to warm. Different statistical relationships have been fitted to this indoor-outdoor relationship over the years, dating back to the 1970s (Humphreys 1979) and 80s (Auliciems 1981), but the most recent models show remarkable agreement despite having come from fundamentally different databases and assumptions (de Dear and Brager 1998; Nicol and Humphreys 2002). Figure 1 shows the de Dear and Brager adaptive comfort model, as it appears in ASHRAE Standard 55 (ASHRAE 2004). The standard clearly states that this model is exclusively for use in naturally ventilated buildings, and there is no reference to the naturally-ventilated mode of mixed-mode buildings because the database underlying ASHRAE’s adaptive model contained insufficient mixed-mode cases on which the model could be tested. Nevertheless, experience since Standard 55’s publication in 2004 indicates practitioners making that logical extension to mixed-mode contexts anyway. Mixed-mode buildings in most of Australia’s populated climate zones are regarded as predominantly naturally ventilated designs with supplemental cooling for a minority of months when external ambient conditions fall beyond adaptive comfort ranges.

Figure 1. The adaptive comfort model used in ASHRAE Std.55:2004. Optimum indoor comfort in a naturally ventilated building equates to 0.31* T_{mot} + 17.8°C. The 80% thermal acceptability band is the optimum ± 3.5°C, while the 90% acceptability band is ± 2.5°C. (de Dear and Brager 2001)

**How is the adaptive model applied during the design stage?**

Perhaps the most famous application to date of ASHRAE’s adaptive comfort option in a naturally ventilated building is the new San Francisco Federal Building (McConahey et al. 2002) so it therefore represents an obvious exemplar of the adaptive comfort design process. Climatological data for the site were applied to the 80% thermal acceptability functions in the ASHRAE adaptive model (Figure 1) to derive the comfort zones depicted below in Figure 2. The resulting graph indicates that adaptive thermal comfort that would be deemed acceptable to 80% of occupants extends from a minimum of about 18.5°C in winter to a maximum of about 27°C in summer. The building energy simulation program EnergyPlus was then used to compare the performance of different ventilation strategies and the results indicated that wind-driven ventilation could deliver sufficient nocturnal cooling to maintain acceptable indoor conditions during occupied hours (McConahey et al. 2002).

High performance buildings designed around permanent natural ventilation have yet to make inroads into the Australian market. A policy vacuum in the green building arena combined with undervalued electricity (typical retail price is ~$12/kWh) conspire to render such options too adventurous for mainstream acceptance in Australia at this stage. Mixed-mode solutions are much more common and
therefore this paper will be confined to such buildings. A building will be deemed to be “adaptive” if
the designers have discarded static indoor design temperatures (typically 22-23°C year-round in
Australian grade-A office buildings) in favour of flexible comfort boundaries that correspond more
closely to outdoor weather and seasonal conditions.

APPLICATIONS OF ADAPTIVE COMFORT IN AUSTRALIA

Two office building case studies are presented here; a new building in the sub-tropical climate zone of
Sydney and the other being a refurbished 1980s building in temperate Melbourne. Both cases are
mixed-mode ventilation designs.

Case Study 1: Macquarie University Commerce Building, Sydney

The site falls within the Sydney metropolitan region, 18 km inland from the coast. Sydney’s climate is
described as humid sub-tropical, characterised by warm-to-hot summers combined with moderate-to-
high humidity. Winters are mild temperate, and the annual rainfall of 1200mm is evenly distributed all
year round. Table 1 presents 30yr climatic normals for the site along with the 90% acceptable indoor
operative temperature limits derived from the ASHRAE Std.55-2004 adaptive comfort model
(calculated using the equation in Figure 1, plus or minus 2.5°C).

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<th>Ave daily max outdoor temp</th>
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The client’s design brief specified a focus on reduced energy consumption and greenhouse gas
emissions within an environment that would be both thermally and visually comfortable. On the basis
of the preliminary assessment in Table 1 above, the months of December, January and February were deemed highly likely to present daily maxima falling outside the 90% thermal acceptability limits. The university is set in parkland in suburban Sydney where noise and urban air quality are less of an issue. These site characteristics along with a preliminary analysis of the type presented in Table 1 led the design team to propose a naturally ventilated building with a range of passive solar design features, plus supplemental air conditioning to keep within the adaptive comfort zone during the winter and summer seasons. Mixed-mode ventilation designs were assessed with a dynamic building energy simulation package and the relevant Typical Reference Year meteorological data file. These iterative simulations led to a design that was expected to be thermally acceptable for 70% of the typical meteorological year under the naturally ventilated mode. The design consists of a 9000 m² seven storey office block linked to a three-storey teaching and computer laboratory wing. The building has an east-west orientation, and six zones with three temperature sensors in each zone. Each wing consists of mixed-mode north and south perimeter zones comprising cellular offices separated by an air-conditioned central zone comprising of open-plan office space.

Figure 3. The new Macquarie University Commerce Buildings, Sydney Australia

The passive system maintains thermal acceptability within adaptive comfort limits most of the year by lowering radiant temperatures by solar shading, and cooled building mass, plus elevated natural ventilation through automated air vents and user-operable windows within perimeter staff offices. Exposed mass in the building, including un-panelled concrete ceilings over the perimeter offices, is exploited in a night-purge routine whenever external weather conditions are amenable (the average diurnal outdoor temperature range in Table 1 exceeds 10°C in all 12 months of the year). The entire façade is built on a louvre system featuring external shading over the windows on the northern façade. Automated high and low level external louvres provide the natural ventilation on each floor, with adjustable internal grilles to control airflow, supplemented by manually operable windows. Window state is transmitted to the Building Management System (BMS) to optimise air conditioning efficiency during active-mode operation. The automated louvres close during air-conditioned mode. Independent automatic weather stations installed on the rooves of both the teaching and staff office wings relay continuous air temperature, humidity, wind-speed and direction, and rainfall data to the BMS. A separate algorithm for each of the six zones per floor runs within the BMS. An average sensed temperature greater than 25°C in any zone (meaning some workstations could be as high as 27°C) prompts the BMS to switch over to air-conditioned mode which is currently operating to the Australian standard air conditioning set-point of 22°C. BMS switch-over to natural ventilation is conditional upon external meteorological conditions meeting a matrix of linked criteria, including appropriate indoor-outdoor thermal gradients, roof-top wind-speeds less than 10 m/s, and the absence of driving rainfall.

Figure 4. Principles of operation. Section through the new Macquarie University mixed-mode building (image from Chris Arkins, Steensen Varming, Sydney).
The building has not yet completed its first full year of operation, but dynamic building energy simulations benchmarked against the standard Grade-A office building with centralised air-conditioning running to an indoor setpoint of 22°C indicate energy savings in excess of 40%.

**Case Study 2: 40 Albert Rd, Melbourne**

The site is near urban parkland just south of Melbourne’s central business district and approximately two kilometres from Melbourne’s Port Philip Bay. Melbourne’s climate is described as warm temperate, and is characterised by mild to cool winters with low humidity and warm to hot summers with moderate humidity. While the mean maximum temperature in summer is 25.5°C, the city experiences temperatures up to 32°C on at least 10% of summer days (December through February) and a diurnal temperature range of 10-11°C. Table 2 presents 30yrr climatic normals for Melbourne along with the 90% acceptable indoor operative temperature limits according to the ASHRAE Std.55-2004 adaptive comfort model (calculated using the equation in Figure 1 plus or minus 2.5°C).

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Unlike the preceding example from Sydney, this Melbourne case-study is a refurbishment (Thomas and Vandenberg 2007). The original nondescript 1980s building was redeveloped with an explicit goal “to be Australia’s greenest building within a conventional office concept”. The client’s own business interest in ecologically sustainable development (ESD) meant that the building was intended to showcase various ESD design technologies. The design team set out to create Australia’s first 6-star Green Star Office Design Rating. Green Star, as implemented by the Green Building Council of Australia, uses information from design to rate potential (design intent) environmental impact. Credits are awarded for management, indoor environmental quality, energy, transport, water, materials, land use and ecology, pollution, and Innovation. Performance at 6 Star (75+ pts) earns “World Leader” status, while 5 Star (60–74 pts) and 4 Star (45–59 pts) denote “Australian Excellence” and “Best Practice” respectively. The design brief also included a “commitment agreement” for a 5 star Australian Building Greenhouse Rating (by simulation at design stage). Such a rating corresponds to <170 kg CO2/m2/yr in Melbourne’s climate zone, and represents the current top building energy rating for greenhouse gas emissions in Australia.

The building is a five-storey office block accommodating ca 50 staff, 1215 m² floor area in total and a narrow floor plate 10m wide with windowless walls on both the north and south façades. Key design initiatives included creation of a light well within an existing stairwell by installation of a skylight in combination with an open-riser stair-case. High performance glazing (1.9 W/m².K) was also installed on the east and west façades, and suspended ceilings were removed to expose thermal mass of concrete slabs. Perhaps most importantly, the refurbishment installed a mixed-mode ventilation system. Natural ventilation is provided through operable windows on the east and west façades using the stack effect through the open-riser staircase/light well. Natural ventilation is also used during summer, spring and autumn for nocturnal purging of heat stored in exposed thermal mass. The air conditioning system is a variable refrigerant volume heat pump consisting of two compressors. Twenty one fan coil units throughout the building are linked to the BMS with zone occupancy sensors. The outdoor compressors are powered by natural gas instead of electricity to reduce the greenhouse gas emissions.
emissions. Mechanical ventilation is delivered through a dehumidifier and filtration unit. The BMS has been initially programmed to maintain average occupied zone temperatures between 19 and 25°C but individual workstations may drift outside these limits. The BMS draws external weather data from an automated weather station located on the roof.

Fifteen months after occupation the building has achieved normalised carbon dioxide emissions of 170 kg CO₂/m² per annum for the period April 2006 to April 2007, suggesting that its 5 Star ABGR Commitment Agreement targets will be met. The energy and greenhouse impact of this building is 45% lower than the Australian benchmark (ABGR 2.5-Star), and 72% less than the building on this site before the refurbishment (Thomas and Vandenberg 2007).

DISCUSSION AND CONCLUSIONS
The buildings sector offers the most potential for cost-effective GHG reductions of all sectors examined by the IPCC in its Fourth Assessment Report (IPCC 2007). An estimated 29% reduction below projected 2020 baseline levels is thought to be possible through a variety of technical GHG mitigation options in buildings and equipment. However, it seems increasingly likely that engineering GHG abatement measures on their own will not be enough, and that our conventional definition of thermal comfort as a narrow, static band of temperatures will need to be revised. The adaptive comfort model provides the obvious theoretical platform upon which this redefinition can occur, and instances of its deliberate implementation are starting to emerge in several parts of the world. Perhaps the most radical example to date is the Japanese Ministry of Environment’s “Cool Biz” campaign (MOE 2005) which lifts temperatures inside sealed air-conditioned buildings to 28°C in summer. Strategies that are less ambitious but perhaps more broadly viable due to relatively high levels of occupant acceptance can be found in high performance green buildings with mixed-mode ventilation systems. To date this appears to be the most popular green approach in the Australian buildings sector. Its potential to effect GHG reductions must be regarded as very significant due to its suitability for new construction and refurbishments, short pay-back periods, along with a variety of non-monetary co-benefits such as increased levels of perceived productivity and reduced absenteeism compared to conventional HVAC installations with sealed building envelopes.

While the Macquarie University mixed-mode case study has not undergone a formal Post Occupancy Evaluation (POE) yet, some occupants have complained about indoor temperatures in summer months on the north façade. This anecdotal feedback is consistent with a more systematic pattern emerging in Australian green buildings that have undergone the Building Use Studies Post Occupancy Evaluation questionnaire (Leaman et al. 2007). In a comparison of some 22 green-intent buildings (most of which would have some adaptive comfort assumptions built into them) against 23 conventional HVAC office buildings, Leaman et al. reported that occupants perceived temperatures in the green buildings during summer to be higher than in conventional buildings. There was also a tendency for green buildings to be perceived as much colder in winter (Leaman et al. 2007). Although the standard BUS POE questionnaire was not accompanied by objective measurements of
temperatures, it is not surprising that the green buildings were perceived as being hotter in summer and cooler in winter, because they were in fact designed to perform that way. However, despite the greater perceived thermal variance in green buildings, their occupants were more tolerant or "forgiving" (Leaman et al. 2007) than in the conventional HVAC sample. There are several plausible hypotheses to account for these observations, but it seems likely that occupant expectations brought to green, adaptive buildings are more relaxed than those applied in conventional HVAC settings. It also seems plausible that occupants' environmental attitudes and beliefs may boost the "forgiveness factor" in buildings that have green adaptive comfort principles designed into them. If that is indeed the case, then prospects for future acceptance of such buildings must be good in Australia where the shift in public awareness of, and attitude towards greenhouse climate change since 2006 has taken most observers and commentators by surprise.

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