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An Adaptive Thermal Comfort Policy for a Geographically Dispersed Property Portfolio; Deciding When and Where to Air-Condition in a Warm Climate Zone

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Abstract

This paper describes a *Thermal Comfort Policy* recently developed for a client who owns a large portfolio of buildings in Australia. To date the client's decisions about where and when to install HVAC have been based on a static isotherm on the climate map of the region in which they operate, regardless of how well the building performs. The client's brief aims to shift air conditioning decisions onto a more rational footing, based on the climatic context, the building's thermal performance and occupants' thermal comfort. The solution we proposed was based on ASHRAE's 55-2010R adaptive model, with an exponentially-weighted running mean outdoor temperature for input. Of the three different metrics proposed for the diagnosis of systematic overheating, the simplest was finally selected by the client (>1 % of occupied hours annually during which indoor temperature exceeds the ASHRAE 55 upper limit (80% acceptability).

Keywords: Adaptive comfort standards, compliance, exceedance, heat-wave

Introduction

Adaptive comfort standards have two broad types of application; design and compliance. In the former application the standards are used to assess feasibility of natural ventilation or at least minimising reliance on air conditioning. This can be done with simplified assessment tools, including software, at the very earliest design phase, or later in the design process with the aid of dynamic thermal simulation software and TMY weather data.

Comfort compliance checking of extant buildings, is less well documented in the research literature. A common problem affecting many of Australia's older property portfolios is that the comfort expectations of the occupants have increased significantly since the buildings were constructed. Indoor temperatures that were considered perfectly normal and acceptable to one generation of occupants are dismissed as unacceptable by the next generation. This inexorable rise in expectations is perhaps best illustrated with the rapid penetration of air conditioning across the residential sector. According to data from the Australian Bureau of Statistics (2010), the proportion of households with a cooler in use (either a refrigerated air conditioner or an evaporative cooler) increased from 59% in 2005 to 73% in 2010. The same phenomenon can be discerned in the commercial sector. In the Australian context, private sector commercial buildings nowadays, with very few exceptions, always air-conditioned. But much of the public sector's floor-space still remains naturally ventilated. For example, much of the education sector's building stock for pre-school, primary, secondary and tertiary levels, remains naturally ventilated, despite considerable pressure from occupants, including employees (teachers, administrators and the unions representing their interests), students and their parents (represented by parents-and-teachers organizations) to retrofit air conditioning to the entire building stock. In some cases the pressure has seen one or other of the occupants' groups purchasing and installing the hardware with funds outside the property owners' budget in recent years, due to the availability of very cheap equipment imported from China.

But many properties owning public sector organizations remain committed to minimizing their energy consumption for indoor comfort purposes. They are also often keen to reduce the operational costs of HVAC operation impacting their annual budgets, so there is an ongoing tension in these naturally ventilated property portfolios between the owners and the occupants (or their representatives). Another dimension of the problem is the very heavy loads resulting from air conditioning, often straining the electrical infrastructure such as sub-stations. These HVAC-related electricity loads often bring heavy financial penalties to their utility bills during peak-demand events such as heat-waves.

Policies aimed at managing thermal comfort problems like this across large property portfolios have, to-date, usually been crude and almost always contentious. At one extreme some organizations have totally acquiesced and retrofitted air conditioning across their entire naturally ventilated property portfolio, regardless of discomfort levels or needs, simply to preserve peace on the industrial relations front. At the other extreme some organizations have placed a blanket-ban on all new air-conditioning installation across their building-stock, regardless of the building envelope's thermal performance or indoor climatic extremes and thermal discomfort experienced by occupants.

In the current study an owner of a large property portfolio that is the subject of this study has, to date, based decisions about where and when to install HVAC on a static isotherm on the long-term (30 year average) climate map of their region. Buildings located on the warm-side of the 33^{o}C mean daily maximum January (Austral summer) isotherm are air-conditioned by default, regardless of how well the building performs in that climate zone, and on the cooler side of that same 33^{o}C mean daily maximum January isotherm, buildings are denied air conditioning, regardless of how poorly the building's thermal performance rates, or how little adaptive opportunity the building presents to its occupants.

This paper outlines a more rational solution – *An Adaptive Thermal Comfort Policy* – for the owner of a large portfolio of buildings in Australia. The organisation's pro-environmental ethos was the starting point in the project briefing, but this needed to be balanced by consideration of thermal acceptability and productivity concerns in excessively hot conditions. The client's intuitive understanding of thermal comfort was readily translated into an adaptive framework in which there was a stated objective to exploit the *full* spectrum of warm-climate adaptive opportunities *before* considering air conditioning as the "comfort solution of last resort." This position statement reflect the client's experience with the air-conditioned buildings already in their portfolio; once HVAC is installed, their occupants tend to rely exclusively on it regardless of whether it's actually necessary, even during normal or moderate weather conditions. In short, when someone else is paying the utility bills, once HVAC is installed it quickly becomes the *default* mode of comfort operation, even when other adaptive opportunities such as operable windows may be capable of delivering thermally acceptable indoor conditions.

Since air-conditioning is regarded by the client as appropriate, only in *exceptional* rather than typical circumstances across their portfolio of buildings, we had to identify the meteorological criteria that could potentially inflate the frequency of overheating incidents, and in so doing, lead to excessive triggering of the air-conditioning requirement criteria. Popular Australian usage of the term heat wave suggests that they are *rare* and *extreme* meteorological events, occurring maybe once a year, if at all. To be consistent with this popular interpretation the client requested heat waves be explicitly excluded from the overheating metric we were developing for their air conditioning policy. It is unrealistic to expect a passive, naturally ventilated building to be able to temper the extremes of a heat wave, no matter how ingeniously the bioclimatic design strategies have been implemented. If the overheating metric included heat wave conditions as exceedances, it is highly likely that air conditioning would have to be installed in *every* building in the portfolio after the next heat wave was experienced (with a probability of one a year. And once installed, air conditioning would quickly become the default mode of building operation, even during non-extreme weather conditions.

Method

The broad conceptual approach behind this thermal comfort policy is to develop an objective overheating metric based on the ASHRAE 55-2010 adaptive comfort standard.

The Climatic Context

The client's portfolio of buildings was scattered across a very large and environmentally diverse part of Australia. The property portfolio was scattered across eight distinct Koppen climate zones, including 1) hot arid desert, 2) hot-arid grassland, 3) hot and semi-arid grassland, 4) humid subtropical without dry season, 5) temperate with hot summer and no dry season, 6) temperate with mild summer and no dry season, 7) temperature and dry-warm summer, 8) grassland with summer drought. Most of the buildings were located in metropolitan areas near the boundary between humid subtropical and temperate with hot summer and no dry season.

Despite the climatic diversity virtually every building in the client's portfolio is exposed to a heat wave in a typical summer. The client's intuitive understanding of heat waves in the Australian context is that they represent climatic extremes – exceptional events – and as such, indoor temperatures occurring within the building portfolio during these exceptional events shouldn't be included within the tally of comfort threshold exceedances. According to the client it was unreasonable to expect bioclimatic design strategies to maintain comfort under the assault of a climatological extreme in the form of a heat wave, and the fact that overheating occurred during such extreme events did not constitute sufficient grounds to require installation of air conditioning.

Given the exemption of official heat waves from the overheating metric being used in this comfort policy, it is important that they are precisely defined. While there is no universally accepted, quantitative definition of what constitutes a heat wave in Australia, the Bureau of Meteorology's website (www.bom.gov.au) refers to "*… more than three consecutive days in which the daily temperature maxima all exceeded 30°C and the overnight temperature minima also exceeded 20°C for at least two nights.*" However, according to the World Meteorological Organization, this definition is fundamentally flawed because it ignores human thermal adaptation. For example, when it is applied to the warmer climates of northern Australia, the BoM's heat wave criteria are met for more than half of the typical meteorological year, which is clearly nonsensical. As noted by Robison (2001) "heat wave" is fundamentally *relative* to the usual weather of a particular area. Temperatures that people from a hotter climate consider normal can be termed a heat wave in a cooler area.

Robinson took the US National Weather Service approach of declaring a heat wave whenever probabilistically defined thresholds of daytime maximum and night time minimum temperatures are exceeded for two or more consecutive days. In an analysis of the climatic database for the US, Robinson noted the average number of heat waves per decade for each weather station in the US database was 21.8 when the threshold temperature percentile was set to 5%; 14.1 heat wave events when the threshold percentile was set at 4%; 13.2 heat waves per decade for 3%; 8.5 events per for a 2% threshold, and 3.6 heat waves per decade when the threshold percentile is set at 1%. On the basis of these probabilities, in this project we adopted a threshold temperature percentile of 3% for two consecutive days' maxima and minima temperatures as our operational definition of heat-wave. In this way they are relative to local climatic norms and expectations, and as such, more compatible with an adaptive concept of thermal comfort than a static temperature threshold definition such as the Australian BoM's heat wave criterion (see above). An interesting consequence of adopting this probabilistic definition of heat wave is that it will "adapt" in a globally warming climate. Many heat episodes that fall above the 3rd percentile today in a given location will probably fall below that threshold when the climatology of the location in question has systematically shifted into warmer temperatures, as is expected to happen in the current century.

The Occupancy Type and the Building Stock

The buildings are in the education sector. Details of the building portfolio cannot be divulged without disclosing the identity of the organisation owning it. However, the buildings range in age from about the late 19th century through to the early 21st century.

Defining Thermally Acceptable Indoor Temperatures

There has been a significant shift in recent years of international standards towards the concept of adaptive thermal comfort (de Dear and Brager 1998; Nicol and Humphreys, 2010). The basic concept of adaptive comfort is that the comfort zone, or range of acceptable indoor temperatures, drifts upwards in warm weather and downwards in cool weather, particularly in environments where occupants have a variety of adaptive opportunities at their disposal. Adaptive comfort is not applicable to environments where occupants are detached from the thermoregulation of their built environment, such as in centrally air-conditioned, sealed façade, or open-plan offices. But for naturally ventilated buildings, where occupants have access to operable windows, the adaptive comfort concept is particularly relevant. The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) was the first standards organization to formally incorporate this adaptive comfort concept into a regulatory document (Brager and de Dear 2000; ASHRAE 2010), with the comfort chart shown in Figure 1. A similar

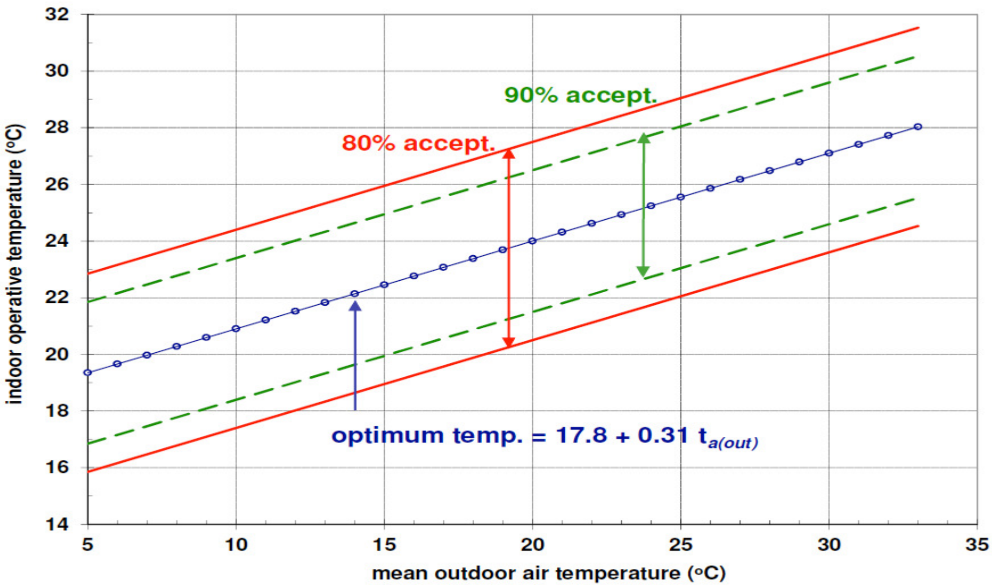

Figure 1 - The ASHRAE 2004 (2010) adaptive comfort standard in naturally ventilated spaces as a function of prevailing outdoor temperature. $t_{a(out)}$ is mean of daily dry bulb temperatures for the period in question.

The Upper Acceptable Adaptive Temperature Threshold:

Figure 1 indicates the optimum indoor temperature as a linear function of mean monthly outdoor temperature, with two acceptable comfort zones straddling the optimum – 80% and 90% acceptability. The meaning of these percentages is as follows: an indoor operative temperature falling within the 80% range should be regarded as acceptable or satisfactory to at least 80% of building occupants who are exposed to it, and the tighter 90% acceptable temperature range is likely to satisfy 90% of occupants. For the purposes of the current application the client selected the 80% acceptable temperature range, the upper limit of which can be written as:

Upper 80% Acceptable Temperature Threshold = $0.31\ t_{a(out)} + 21.3$ (°C) (eq1)

ASHRAE's adaptive model originally used monthly mean outdoor air temperature as its expression for prevailing outdoor temperature (as either a climatological calendar month or 30-day running mean). This choice of input parameter was largely based on pragmatic considerations at the time – climatic data are readily available as mean monthly temperatures for most locations around the world. But there was also an analytic constraint on the choice of outdoor temperature in the ASHRAE adaptive model. To understand this one needs to remember how the ASHRAE adaptive model was derived, namely by regressing building neutralities (the dependent variable) on prevailing outdoor temperature (the independent variable). But each building's neutrality going into the adaptive meta-analysis was derived by regressing the comfort votes registered by hundreds (or even thousands) of occupants over several days to weeks, on the operative temperatures recorded at the same time and place as each questionnaire response was made. Therefore *neutrality* of a building in the RP-884 database does not correspond to an instant in time, and so the correct expression for prevailing outdoor temperature in the adaptive model (like Figure 1) cannot be temperature of any particular day, but rather something spanning a comparable time-period as the questionnaire survey used to generate the neutrality. The strong correlation coefficient it achieved with building neutrality justified that approach in ASHRAE's adaptive comfort analysis (de Dear and Brager 2001).

It would be useful at this point to remember that the x-variable in the adaptive comfort charts (see Fig. 1) represents the broad climatic milieu to which people have become adapted. Adaptive comfort theory emphasises the temporal variability of building occupants' "comfort setpoint," particularly as it responds to changes in the atmospheric environment outside the building. Our thermal comfort optimum drifts in the direction of the climate to which we have been exposed; as winter turns to summer, so does our comfort optimum move from cool to warm. The thermal adaptive processes are complex and operate on several levels, including physiological (also known as acclimatization), behavioral, and psychological (also known as expectation). Presumably each level of climatic adaptation has its own time-constant, and so the seemingly simple task of fixing the definitive adaptive "exposure time" turns out to be quite complex.

In contrast to ASHRAE 55 (2010) and EN15251 (2007) adopted an exponentially weighted, running mean, in reflection of the longitudinal research design underpinning its adaptive model. EN15251's approach captures and puts greater emphasis on the immediate, perceptual and behavioural layers of human thermal adaptation relative to the longer-term adaptive processes operating at the phsyiological level. EN15251's exponentially weighted, running mean temperature T_{rm} for any given day is expressed in the following equation by Nicol and Humphreys (2010):

$$T_{rm} = (1-\alpha)(T_{od-1} + \alpha T_{od-2} + \alpha^2 T_{od-3} + \alpha^3 T_{od-4} \ldots) \qquad \text{(eq2)}$$

where α is a constant (<1) and T_{od-1} is yesterday's daily mean temperature, the day before (T_{od-2}), the day before that (T_{od-3}), etc. Since α is less than unity, equation (1) emphasises recent days' temperature more heavily than days further in the past. As α approaches unity the rate of decay in daily temperature weighting coefficients approaches zero, and eq2 approaches a simple monthly mean temperature. Nicol and Humphreys (2010) suggested an α =0.8 because it maximized explained variance (R^2=0.358) within the free-running building neutralities contained in their SCATs database. But the increment in explained variance over that obtained when α =0.45 was negligible (R^2=0.354), therefore the "true" value of α in equation (1) remains moot, and represents a useful question for future research.

Figure 2 (below) illustrates a hypothetical sequence of mean daily temperatures (T_{od}) for a period of 40 days. The EN15251 weighted, running mean outdoor temperature has been calculated using three different weights for α. For comparative purposes Figure 2 also displays some observational data from a clothing study by Morgan and de Dear (2003). That study examined the strength of correlations between mean daily clo values in a Sydney shopping mall, and mean daily outdoor dry bulb temperature. The correlations were tried for seven different lags on the daily outdoor temperature (i.e. today's clo and today's temperature, yesterday's temperature, the day before yesterday's temperature … the daily temperature 7 days ago), and a very clear exponential decay was noted in explained variance r^2, with the strongest correlation being with today's temperature and the weakest being with temperature 7 days ago. Interpreting these correlation coefficients as a proxy for the strength of human behavioural adaptation, the exponential decay in r^2 was used to derive weighting coefficients on the last seven days' outdoor mean dry bulb temperature. Those weighting coefficients have been used to calculate a running mean outdoor temperature function, and plotted in Figure 2 (de Dear, 2006).

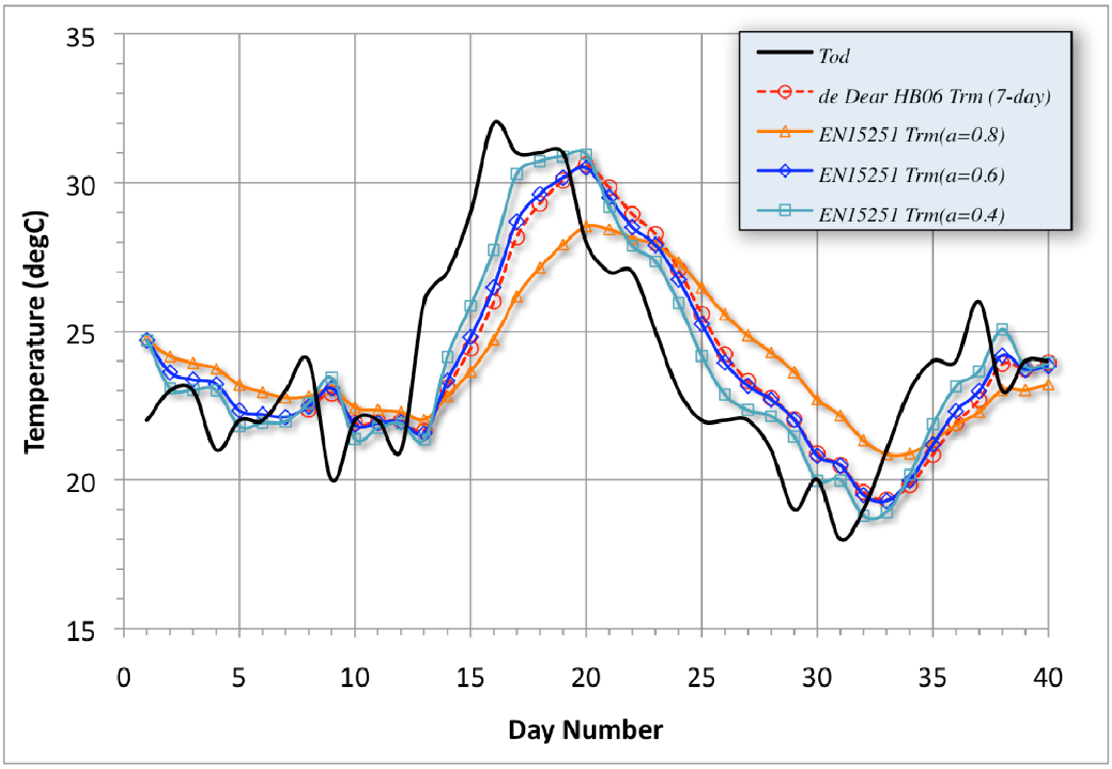

Figure 2. A hypothetical sequence of outdoor daily dry bulb temperature (T_{od}) and the EN15251 running mean outdoor temperature (T_{rm}) with three different values for α. The running mean of outdoor temperature calculated using daily weighting coefficients from Morgan and de Dear's Sydney clothing study is also plotted (note the almost perfect match with the EN15251 curve for α = 0.6)

Three of the running mean outdoor temperature functions plotted in Figure 2 have been applied to the ASHRAE 55-2010 adaptive comfort temperature limit (upper 80% acceptability limit) in Figure 1 using equation 1, and the results are displayed in Figure 3. Since the '*de Dear HB06* $T_{rm\ 7\text{-}day}$' and '*EN15251* $T_{rm\ (\alpha=0.6)}$' running mean outdoor temperature functions were virtually indistinguishable in Figure 2, only the former has been used in Figure 3. The main point to note is the impact different decay coefficients (α) have on the amplitude of acceptable indoor temperature responses to outdoor weather transients. After the cool spell that began on day17 the α =0.4 curve in Figure 3 indicates a cooling response in the adaptive temperature limit a few days later (day 21), continuing to cool by nearly 4K by day 32. In contrast the drop in acceptable temperature threshold was dampened to just over 2 K when α is set to 0.8 in the outdoor running mean temperature function (eq.2).

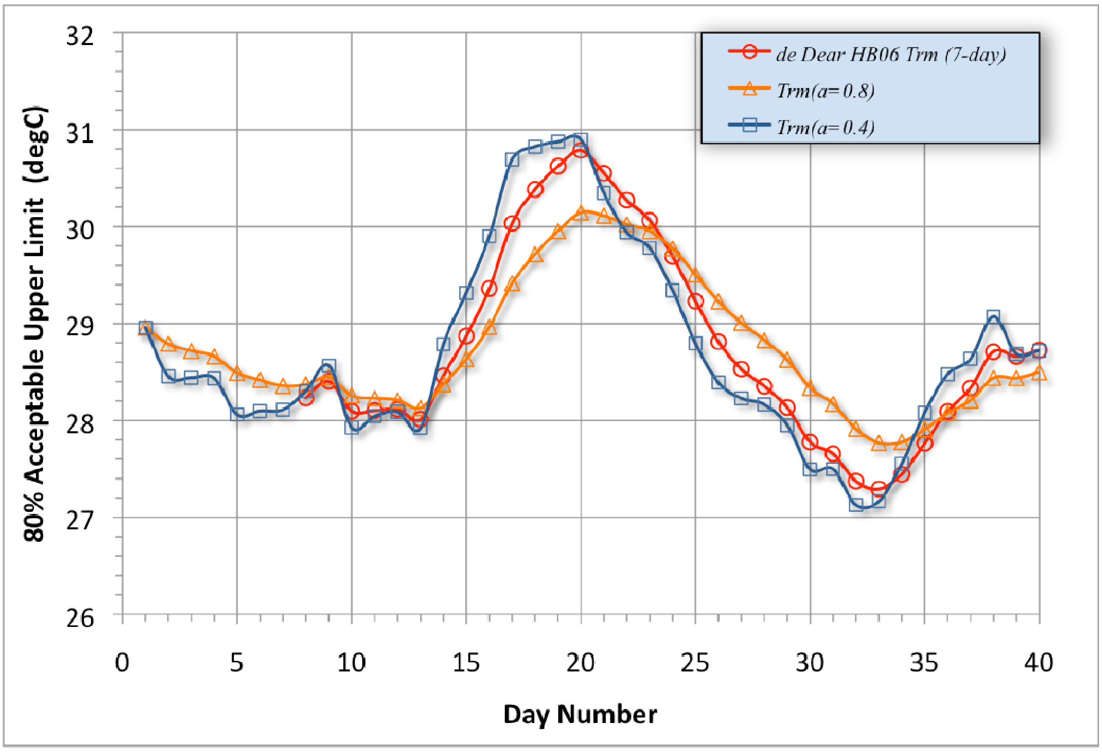

Figure 3 Effect of different running mean outdoor temperature functions on the upper 80% acceptable temperature limit in ASHRAE 55-2010's adaptive comfort standard. The same 40 days of hypothetical meteorological data used in Figure 2 have been used to calculate the running mean outdoor temperatures used in calculation of the adaptive temperature thresholds of acceptability plotted in this graph.

While the meteorological data used in these illustrations were hypothetical, and the dynamics probably unrealistic, they serve to emphasise how significant the α coefficient in (eq.2) is to the adaptive comfort temperature standard. It therefore seems deserving of more research attention than it has received to date. But ASHRAE's Standard 55 can't wait for this research question to be definitively resolved, and so a recent Addendum to ASHRAE 55-2010 offers a range of decay settings from α =0.6 up to α = 0.9 (at which point the mean outdoor temperature function resembles an unweighted 30-day running mean).

Defining the Overheating Index

At this point in the procedure we have established the adaptive comfort concept, and also defined the outdoor meteorological driver of indoor adaptive comfort as a running mean of the last seven days outdoor air temperature. If indoor temperatures happen to fall above the acceptable upper temperature threshold, then they are, *ipso facto*, unacceptably warm. The next step of logic in this definition of indoor overheating is to decide how many unacceptably warm hours per year are required to trigger an engineering intervention (i.e. installation of air conditioning)? Three possibilities have been found in the literature on overheating indices.

1. *The Duration of Unacceptable Overheating Index:*
   This same question was addressed in the Netherlands' revised indoor comfort guidelines (Van der Linden *et al.* 2006). Their approach tallied the number of hours exceeding the limit, and then express those exceedance hours as a percentage of the total number of occupied hours per year. If the tally of exceedance hours was less than *x%* of occupied hours per year, the building is rated Class A. If the exceedance hours tally >*x* but < than *y*, then the building is rated Class B, while an exceedance hour tally > *y%* of occupied hours earns a Class C rating.

2. *The Unweighted Overheating Degree-Hour Index:*
   Simply tallying the number of exceedance hours, as in the Dutch case study, can be criticised for ignoring the intensity of temperature exceedance. A room that is just one degree warmer than the acceptable limit is regarded the same as a room that is three degrees warmer than acceptable. One reasonable solution that gives equal weight to *intensity* of temperature excursions outside the comfort zone and their *duration,* is to invoke the degree-hour concept. For example, an internal temperature one degree warmer than the acceptable limit lasting for three hours carries the same weight in the degree-hour index as a three degree exceedance lasting just one hour. One simply calculates the degree-hour value for each hour of indoor temperature data recorded during occupied hours, and then compares the resultant index value (tally) against established criteria in order to make a decision. The logical weakness of this approach is the assumption that the subjective intensity of the temperature exceedance is linearly proportional to the difference between room temperature and the upper acceptable temperature threshold.

3. *The Weighted Overheating Degree-Hour Index:*
   This second degree-hour approach overcomes the conceptual weakness of the preceding approach by applying a non-linear weighting function to the magnitude of the temperature exceedance, in recognition of the nonlinearity of the subjective intensity psychophysical function. British Standard EN15251:2007 suggests Fanger's PPD function as the basis for the weighting of temperature exceedances. In a variation on the theme, Nicol and Humphreys (2007) developed an alternative to Fanger's PPD weighting function in the form of a logistic regression of comfort votes in some European office surveys.

Presented with three options for their overheating metric, the client in the current project selected the simplest – the duration of unacceptable overheating - because it was likely to present least difficulty in communication with the building occupants. The duration is expressed as a percentage of occupied hours per annum. At what % this index of overheating should remediation by AC installation be triggered? The 7th edition of CIBSE Guide A, (CIBSE 2006) specified a duration of exceedance for one or more percent (1%) of occupied hours per annum as their criterion for declaring overheating, and this has been adopted for the current project.

Indoor Climate Monitoring Campaign

Because the number of individual buildings in the client's portfolio is very large, a monitoring campaign that was fully compliant with the instrumentation criteria articulated in ASHRAE 55 (2010) was out of the question due to the equipment costs. The only way those criteria could be afforded was if the instrumentation were rolled out across the portfolio in batches, but this would take up to a decade of summers to complete. So a more affordable monitoring campaign had to be devised. The *iButton* is a temperature logging device with 12-bit A-to-D resolution and precision of +/- 0.15°C costing approximately US$30 in bulk orders. Being the size of a thumbnail this device can be installed discretely within the occupied zone, about 1m above floor-level in each room across the entire portfolio. A simple tamper-proof mounting was designed to ensure occupants could not deliberately bias the instrument's recordings and thereby force an overheating verdict for their room. The device was programmed to record every 30 minutes, enabling a total of about five months unattended data acquisition to occur, at the end of which a simple USB memory reader extracted the observations into a spreadsheet format. Since five months of data could be stored, the monitoring campaign was initiated in the month prior summer officially starting and continued till the end of the first month of Autumn, giving a total of five months of 30 minute occupied zone temperature readings, date- and time-stamped. While the denominator of the overheating index is total annual occupied hours, complaints of overheating are exclusively confined to the late-spring through summer and into early autumn, so confining the observations to the five warmest months is very likely to capture all of the overheating episodes for that year.

Results

An Adaptive Comfort Overheating Policy - Operational Protocol

Step 0: *Identification of local threshold temperatures for heat-wave criteria*
The first task was to identify the nearest official Australian Bureau of Meteorology weather station for each building in the portfolio. At least 10, but ideally 20 years of continuous records of daily maximum and minimum temperatures needed to be available before the station could be selected. For stations where less than 10 years of record were available, the next nearest station with at least 10 years record was substituted, unless that put the readings in a completely different climate zone to the building in question. Once the station was selected, its daily maximum temperature records were ranked, and the 3rd percentile maximum temperature was identified. This process was repeated for the 3rd percentile daily minimum temperatures.

Step 1: *Monitoring indoor thermal conditions across the property portfolio*
Initialise and install a temperature logger within each occupied, naturally ventilated room across the portfolio in November 2010 (the month before the official start of the Austral summer) and leave it *in situ* until late March 2011.

Step 2: *Monitoring outdoor weather conditions across the property portfolio*
For each day of indoor temperature monitoring, the daily maximum, minimum, and daily mean (arithmetic average of the first two) were obtained from the Bureau of Meteorology's "*Current Observations*" website, for each building in the portfolio. Each day's maximum and minimum temperatures were compared against that met station's 3rd percentile values for max and min, and when two successive days on which both criteria were exceeded, an official heat wave was declared. It remained in place until either a daily max or min in the time series fell below the local 3rd percentile heat-wave criterion.

***Step 3:** Tallying the number of occupied hours in an operation year*

All weekends, public holidays and any other days declared as official organisation-wide holidays were removed from the calculations. In view of the sensitivity of this overheating metric to bias by increasing or decreasing the number of annual occupied hours, agreement was sought (and received) from employees to declare 8am as the official start of the occupied period and 6pm as the official end of occupancy each working day.

***Step 4:** Calculating the running, exponentially weighted mean outdoor temperature*

We used the daily mean outdoor dry bulb temperature calculated in *Step 2* above to calculate a value of $T_{rm\ (\square=0.6).}$ In the interest of simplicity we adopted the following 7-day running mean function proposed by de Dear (2006) as a very close approximation to the EN15251 $T_{rm\ (\square=0.6)}$ function listed in eq.2 above:

$$T_{rm}=0.34T_{od-1}+0.23T_{od-2}+0.16T_{od-3}+0.11T_{od-4}+0.08T_{od-5}+0.05T_{od-6}+0.03T_{od-7} \qquad \text{(eq3)}$$

where T_{od-1} refers to the day before, T_{od-2} refers to the day before that, and so on.

***Step 5:** Calculate daily adaptive acceptable temperature threshold*

For each day of the monitoring period we calculated the ASHRAE 55-2010 Standard's adaptive upper 80% acceptable temperature threshold by applying each day's T_{rm} calculated in the preceding step to eq.1.

***Step 6:** Tally all temperature exceedance hours in the monitoring period*

After removing all official heat-wave days, official holidays and weekends from the half-hourly indoor temperature time series recorded by the *iButton (Step 1),* we compared each 30-minute indoor temperature record with the corresponding daily ASHRAE 55-2010 Standard's adaptive upper 80% acceptable temperature threshold (*Step 5*). Each *iButton* temperature exceedance counted as half-an-hour in the tally of exceedance hours for that particular room. Any room scoring more that 1% of occupied hours with an indoor temperature in excess of the ASHRAE 55-2010 Standard's adaptive upper 80% acceptable temperature threshold was declared to be systematically overheating.

***Step 7:** Decision regarding remediation of comfort conditions*

After repeating this process across each monitored room in each building across the entire portfolio, the client was able to rank the portfolio in terms of the duration of overheating throughout the monitoring period. This ranking was then used as a basis of prioritising the capital works across the portfolio.

Discussion

The first question asked by the client in response to the protocol proposed above was; "*What if the summer of 2010-11 was unusually hot? Wouldn't that force us to air-condition much larger percentage of the building stock than would've been the case in a more typical summer?"* That is, an abnormally hot sample period could potentially inflate the number of "false positive" decisions. However, we believe this risk is minimal because if the summer in question was an outlier from the climatological distribution, that would probably be reflected in a higher-than-usual frequency (and duration) of heat waves. But since heat waves are explicitly excluded from the tally of exceedance hours, the potential risk of false positive bias is reduced.

A possible alternative to the direct temperature monitoring approach would have been to use the nearest available TMY file for a simulated summer indoor temperature profile. The list of objections to this alternative was very long, but the most important one was the difficulty in *explaining* simulated temperatures to all the stakeholders and occupants in this organisation, and convincing them that simulation was as *valid* as instrumental observation. The Australian public are very sceptical about numerical simulations because of the large number of input parameters that need to be "guesstimated" – opening up the possibility for biasing outcomes in a predetermined direction. Instrumental temperature observations from factory-calibrated sensors were deemed by the client to be much more defensible. The second major difficulty with a TMY approach was the prohibitive costs associated with setting up software models for each and every room in each building across very large and architecturally diverse portfolio of buildings.

The introductory section of this paper described the overheating index as a decision support tool for when-and-where to install air conditioning. That is in fact an oversimplification of the client's use of this protocol. For each room exceeding the overheating criterion (i.e. >1% occupied hours), a more detailed investigation into the duration and intensity of exceedances was initiated. A frequency distribution of exceedances was prepared. If the modal exceedance (*DT*) fell within a few degrees of the ASHRAE 80% acceptability limit, the new air-speed provisions of the adaptive comfort method in ASHRAE 55-2010R were explored. If it could be demonstrated that heating up the 80% temperature threshold by 1.2 K would be enough to eliminate the modal exceedances (corresponding to a lifting of mean air speed within the occupied zone to 0.6 m/s), then installation of ceiling fans represented a preferable alternative to air conditioning, assuming of course the fans hadn't already been installed. Fans were not deemed appropriate in cases where the modal indoor temperature exceedances were 1.8 K or higher, despite the new air-speed provisions of the adaptive comfort method in ASHRAE 55-2010R indicating they could be dealt with by increasing occupied zone mean air speed to 0.9 m/s (or higher). This was because these speeds were impracticable in the most of the buildings under analysis.

Conclusions

This paper presented a Thermal Comfort Policy for a large property portfolio in Australia. The conceptual departure was to apply the ASHRAE's *adaptive* comfort model with a weighted running mean outdoor temperature as its input, when deciding whether or not a naturally ventilated building required remediation with air conditioning.

ASHRAE's Standard 55-2010 upper temperature threshold for 80% acceptability has been selected for the definition of indoor temperature exceedance. The standard was applied to local meteorological observations via the new exponentially weighted running mean function approved by ASHRAE's SSPC-55 in 2011. One percent of annual occupied hours with indoor occupied zone temperatures exceeding the ASHRAE 55-2010 upper temperature threshold flagged the room/building as systematically overheating and requiring some form of engineering remediation (typically air conditioning).

Another important feature of the procedure described here is the exclusion of indoor temperature recordings during extreme meteorological events (heat waves) from the tally of indoor temperature exceedances. This decision was accepted because it is unreasonable to expect bioclimatic design maintain indoor comfort during rare weather extremes. A rigorous statistical definition of what constitutes a heat wave was implemented for each location across the portfolio, to reflect the reality that a heat wave in cooler climates would represent normal weather conditions in a hotter climate zone. Two consecutive days with a) daily maxima exceeding the 3rd percentile of daily maxima on record, b) daily minima exceeding the 3rd percentile of daily minima on record for the site in question, was deemed to be a heat wave. In this the notion of human thermal adaptive comfort is embedded in the definition of heat wave.

This paper has also identified several research questions deserving future attention, particularly relating to the dynamics within the adaptive comfort model. How quickly does the acceptable band of indoor temperatures respond (adapt) to an external meteorological perturbation like a cold snap or a heat wave? What are the time-constants for the behavioural, perceptual and physiological layers of human thermal adaptation? And what is the optimum weighting of these different layers of adaptation within an adaptive comfort standard?

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