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RESEARCH PAPER

Comfort standards and variations in exceedance for mixed-mode buildings

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Mixed-mode buildings operate along a spectrum from sealed heating, ventilation and air-conditioning to 100% naturally ventilated, but little is known about their occupants' comfort expectations and experiences. Exceedance metrics, which quantify the percentage of time that a building's environment falls outside an expected thermal comfort zone, can help address the comfort trade-offs in building design and operation. Practitioners were polled on exceedance use in practice and comfort models and exceedance metrics were analysed: several comfort standards using EnergyPlus simulations of a mixed-mode building with radiant cooling in California's 16 climate zones. Results indicate that comfort model choice significantly influences predicted exceedance. Exceedance using PMV-PPD and the adaptive comfort models from ASHRAE Standard 55, EN 15251, and the Dutch NPR-CR 1752 frequently differed by 10 percentage points, often with 2–4 percentage points across the adaptive models. Yet, recommended exceedance limits often fall between 3% and 5% total. Exceedance predictions are also sensitive to uncertainties in predicted neutral comfort temperatures and variations in building envelope performance, solar heat gain, thermal mass, and control precision. Future work is needed to characterize comfort better in support of improved comfort modelling, exceedance targets, building design and building operation, and the development of related codes and standards.

Keywords: adaptive comfort, building standards, comfort models, cooling, exceedance, mixed-mode, occupants, sensitivity, thermal comfort

Les immeubles en mode mixte font intervenir un éventail de systèmes allant d'un chauffage, d'une ventilation et d'une climatisation étanches à une ventilation 100 % naturelle, mais l'on sait peu de choses sur ce qu'attendent et ressentent leurs occupants en matière de confort. La métrologie relative aux dépassements de seuils, qui quantifie le pourcentage de temps pendant lequel l'environnement d'un immeuble se situe hors d'une zone de confort thermique attendue, peut aider à traiter les compromis en matière de confort dans la conception et l'exploitation des immeubles. Des professionnels ont été interrogés par sondage sur l'utilisation des dépassements de seuils dans la pratique, et les modèles de confort comme la métrologie relative aux dépassements de seuils ont été analysés pour plusieurs normes de confort en utilisant les simulations EnergyPlus d'un immeuble en mode mixte équipé d'un système de refroidissement par panneaux dans les 16 zones climatiques de la Californie. Les résultats indiquent que le choix du modèle de confort influe considérablement sur les dépassements de seuils prévus. Les dépassements de seuils utilisant les indices PMV-PPD et les modèles de confort adaptatif de la norme ASHRAE 55, de la norme EN 15251 et de la norme néerlandaise NPR-CR 1752 différaient fréquemment de 10 points de pourcentage, avec souvent 2-4 points de pourcentage sur les modèles adaptatifs. Néanmoins, les limites de dépassement recommandées se situent souvent entre 3 % et 5 % du total. Les prévisions de dépassement de seuils sont également sensibles aux incertitudes relatives aux températures de confort neutres prévues et aux variations en termes de performances des enveloppes des

immeubles, d'apport de chaleur par insolation, de masse thermique et de précision des contrôles. Des travaux ultérieurs sont nécessaires pour mieux caractériser le confort afin d'appuyer les efforts d'amélioration de la modélisation du confort, des objectifs de dépassement de seuils, de la conception des immeubles et de l'exploitation des immeubles, ainsi que pour appuyer le développement des codes et des normes s'y rapportant.

Mots clés: confort adaptatif, normes de construction, modèles de confort, refroidissement, dépassement de seuils, mode mixte, occupants, sensibilité, confort thermique

Introduction

In standard sealed buildings, heating, ventilation and air-conditioning (HVAC) systems are often sized and operated to maintain indoor conditions within a narrow range of temperatures and humidity. In many places, comfort expectations have evolved to leave little margin for error in this regard. Building engineers are often asked (or compelled by codes and standards) to certify that their system designs will operate within these ranges. To do so, they typically use a model based on controlled laboratory experiments to predict the percentage of people dissatisfied (PPD) (Fanger, 1970). If, under the most extreme conditions, simulations or rules of thumb predict less than some PPD (often 20%), their systems are expected to provide acceptable performance once implemented. However, it is not uncommon for engineers to include an additional margin of error by over-sizing their systems and for building management systems to be configured to operate the equipment beyond occupied hours and despite temperate outdoor conditions.

Environmental, security and economic concerns about energy consumption are all growing and the profligate consumption within the built environment is coming under increasing scrutiny. This trend is leading to an increase in the popularity of passive and low-energy cooling strategies. Of particular note, due to their operational flexibility, are mixed-mode buildings that combine operable windows with some form of mechanical cooling. As mixed-mode strategies become more common, their sophistication and ability to save energy while preserving comfort is increasing. Even as they deliver less overall cooling and humidity control than sealed, conditioned buildings, naturally ventilated and mixed-mode buildings often get high marks from occupants on satisfaction with their thermal environment (Brager and Baker, 2009).

One reason such buildings can still meet comfort expectations is that occupants of buildings with operable windows tend to prefer slightly elevated indoor temperatures given elevated recent outdoor temperatures. Compared with occupants of sealed buildings they are more comfortable with warmer temperatures during the cooling season. Predicting these responses, however, requires newer models of comfort that go beyond the limits of PPD. This 'adaptive comfort'

effect has been quantified using regressions of surveyed thermal comfort data against outdoor temperature trends from hundreds of naturally ventilated buildings worldwide. In such buildings, the adaptive comfort model more accurately predicts measured comfort than the PPD model (de Dear and Brager, 1998; Humphreys and Nicol, 1998).

The adaptive comfort effect has only been measured extensively in naturally ventilated (or free running) buildings. When the weather is hot, these buildings can and do exceed comfortable conditions from time to time. The same can be true of mixed-mode spaces. For example, radiant cooling systems, which offer many advantages as part of a mixed-mode strategy, cannot always keep pace with heat gains. Such systems drive radiative thermal exchange by cooling room surfaces. However, surface temperatures, and therefore heat-removal rates, are limited by practical concerns about discomfort and condensation. If, under extreme conditions gains exceed their maximum rate of heat removal, such systems will fail to maintain their set-points. The question, then, is when such excursions are acceptable and when they become unacceptable.

As building engineers increasingly look to mixed-mode strategies to improve comfort performance and expand the climatic range of naturally ventilated buildings, it is becoming all the more important to predict and characterize the severity and duration of episodes of discomfort. This information helps properly set expectations about occupants' comfort experiences, plan alternate strategies and ensure the overall success of such buildings. There are many potential metrics for such characterization, almost all of which account for the accumulated time indoor conditions exceed comfort conditions. In other words, they quantify the level of comfort *exceedance*, typically as a percentage of hours outside the expected occupant comfort range over time, with or without weighting factors to account for severity. However, there is not yet consensus on how to apply various comfort models, and associated exceedance metrics, to mixed-mode buildings. Since they feature natural ventilation, it is a reasonable assumption that adaptive comfort is at least partially applicable. The observed adaptive comfort effect is most likely attributable to some

combination of adaptive behaviours, physiological effects, and a psychological 'forgiveness factor' that comes from altered expectations and increased feelings of control. Yet, it is not known how large a contribution each of these elements makes to the total effect, even in the naturally ventilated buildings that have been studied extensively. It is therefore difficult to extrapolate from the data set used to develop the adaptive comfort model to the much wider range of operating conditions present in mixed-mode buildings.

The objective of this research is to improve understanding of the use of exceedance metrics in practice, and, through simulation, examine the sensitivity of exceedance values to the choice of comfort model used to predict thermal dissatisfaction, uncertainties in simulated outcomes, and reasonable variations in loads caused by occupant behavior, equipment, and building thermal performance. A discussion is included on the practical consequences of such uncertainty.

Standards and exceedance metrics

Despite their growing popularity, it is still unclear how mixed-mode buildings can best address the trade-offs between energy and amenities like thermal comfort, and what impact their rising popularity should have on building standards. The current authors are not the first to make this observation. In a document on the development of European standards, Olesen (2007, p. 740) recently observed that:

> … the energy consumption of buildings depends significantly on the criteria used for the indoor environment, which also affect health, productivity and comfort of the occupants. An energy declaration without a declaration related to the indoor environment makes no sense.

Despite the need, the current ASHRAE Standard 55 does not offer much guidance on comfort in mixed-mode buildings. Its current wording seems to restrict the use of the adaptive comfort model to purely naturally ventilated buildings, which are rare in the US. In Europe, where the adaptive comfort has been applied to 'free-running' buildings, which can include mixed-mode buildings during times they are not employing mechanical cooling, standards have recently begun explicitly to address exceedance. For example, EN 15251 has exceedance calculations and recommendations on acceptance in its Annexes F and G (Comitè Eurpoéen de Normalization (CEN), 2007). However, this is not to say that it proposes a definitive method (Nicol and Wilson, 2011). Annex F on the 'long term evaluation of the general thermal comfort conditions' describes three approaches to calculating exceedance metrics based on the following different criteria:

- '*Percentage outside the range*': per cent of occupied hours (hours during which the building is occupied) when the PMV or the operative temperature is outside a specified range.

- '*Degree-hours criteria*': time during which the operative temperature exceeds the specified comfort range during occupied hours weighted by some function of the number of degrees beyond the range.

- '*PPD weighted criteria*': accumulated time indoor temperatures are outside the expected comfort range weighted by some function of PPD.

The standard goes on to recommend acceptable 'length of deviation' values for indoor environmental conditions, including thermal discomfort, as '3% (or 5%) of occupied hours a day, a week, a month and a year'. In an associated journal article explaining philosophy behind EN15251, Olesen (2007, p. 747) explains:

> As the criteria are based on instantaneous values, values outside the recommended range should be acceptable for short periods during a day. Therefore it is recommended that for 3–5% of the time (working hours) the calculated or measured values can be outside the range.

Note that it is unclear whether or how the 3–5% of the time rules of thumb should be applied to the weighted calculations. Although the standard is breaking new ground by including exceedance criteria, the diversity of calculations methods and the rough nature of the guidance on maximum exceedance underscore the preliminary nature of even the most thoughtful exceedance guidance and suggest that further clarification will be required before widespread use. Nevertheless, the provided range offers a concrete starting point for comparative analysis and is included for reference in two of the figures and some discussion of this work. In this work, all exceedance values are calculated on an annual basis.

Methods

State of the industry

To understand better the nature of discussions that leading building engineers are having with their clients about comfort and exceedance, the authors conducted an informal survey of professionals in our personal networks.[1] These professionals were selected from those who are either affiliated with the Center for the Built Environment at the University of California at Berkeley, or who have contributed to or benefitted from past research. The majority of the contacted professionals work in the US. This brief investigation

was never intended to be comprehensive, but rather to give at least an anecdotal sense of the patterns of experience across firms and project types. The questions asked were:

- How is the topic of exceedance approached with clients (*i.e.*, can it be delicate to explain that comfort is not 100% guaranteed)?

- What metrics of exceedance are used during design and in communication with clients?

- How are comfort performance expectations captured in agreements between designers and clients?

Adaptive comfort models

Mixed-mode buildings can fall anywhere along the continuum between purely naturally ventilated to mechanically conditioned. As such, it is likely that mixed-mode comfort and exceedance will lie somewhere along a spectrum between the values predicted using the adaptive comfort model(s) and PPD, respectively. To provide a more precise comfort estimate will require further insight into the nature of and interactions between the individual factors that contribute to the adaptive effect. Leaman and Bordass (2007) have offered valuable (and cautionary) guidance along these lines through their observations on the origin of occupant dissatisfaction and satisfaction and development of a quantitative 'forgiveness score'. For the current analysis, the authors bracketed the likely comfort outcomes between predictions from the PMV-PPD model (ISO 7730) and the adaptive comfort models employed by ASHRAE 55 in the US, EN 15251 in Europe, and the Dutch code of practice NPR-CR 1752. Table 1 summarizes the calculation of the ideal comfort temperature, T_{comf}, in each standard. In all cases, T_{comf} corresponds to the neutral operative temperature, where the lowest total percentage of people are expected to be either too hot or too cold. Using each of these, a series of simulations was performed which was designed to establish the magnitude of the resulting range of comfort that might be achieved in mixed-mode buildings.

Exceedance metrics

For this work, the authors developed an exceedance metric that weights the hours of exceedance by their occupancy. This metric ignores out-of-range operating conditions during unoccupied periods and can be calculated using outputs from PMV/PPD and adaptive comfort models. Specifically, it is the percentage of occupied hours where conditions exceed the 20% dissatisfied threshold (on the warm side), weighted by the

Table 1 Details of comfort temperature calculations for all four comfort models: summary of T_{comf} (also known as comfort temperature or neutral operative temperature where the lowest total percentage of people are expected to be either too hot or too cold) calculations with 90% and 80% of people-satisfied thresholds from the various standards examined in this study

Standard	Description of comfort temperature (T_{comf}) calculation and range for 10−20% acceptability
PPD-PMV ISO 7730	T_{comf} is 22°C in winter and 24°C in summer. Summer days are defined by a daily maximum temperature of 25°C. A total of 90% and 80% of people satisfied are calculated using the PPD model, but come at approximately $T_{comf} \pm$ 2.5 and 3.5°C, respectively
ASHRAE 55 Adaptive	Derived from a global comfort database, T_{comf} is 22°C in winter and 17.8°C + 0.31 × T_m in summer, where T_m is the monthly average of the daily average outdoor dry bulb temperatures. A total of 90% and 80% of people satisfied are assumed to fall at $T_{comf} \pm$ 2.5 and 3.5°C, respectively
EN 15251	Derived from a European comfort database, T_{comf} is 18.8°C + 0.33 × T_{rm7} in summer, where T_{rm7} is the exponentially weighted running mean of the daily outdoor temperature, approximated using the previous week's temperatures as: $T_{rm7} = (T_{-1} + 0.8T_{-2} + 0.6T_{-3} + 0.5T_{-4} + 0.4T_{-5} + 0.3T_{-6} + 0.2T_{-7})/3.8$, where T_{-n} is the average outdoor temperature n days before the day in question. A total of 90% and 80% of people satisfied are assumed to fall at $T_{comf} \pm$ 2.0 and 3.0°C, respectively
NPR-CR 1752	Dutch code of practice. T_{comf} is 17.8°C + 0.31 × T_{rm3} for type 'beta' buildings in cooling mode, where T_{rm3} is calculated from the averages of the maximum and minimum outdoor temperature of the day under study and the three preceding days as: $T_{rm3} = (T_0 + 0.8T_{-2} + 0.4T_{-3} + 0.2T_{-4})/2.4$, where T_{-n} is the average outdoor temperature n days before the day in question. A total of 90% and 80% of people are assumed to be not uncomfortably hot at T_{comf} +2.5 and 3.5°C, respectively (there is a separate calculation for the lower bounds of comfort)

Note: References include: PPD-PMV ISO 7730 (Fanger, 1970; Olesen and Parsons, 2002), ASHRAE 55 (de Dear and Brager, 2002; ASHRAE, 2004), EN 15251 (Comitè Eurpoéen de Normalization (CEN), 2007; Nicol and Humphreys, 2010); and NPR-CR 1752 (van der Linden et al., 2006).

time varying occupancy. The units of the metric are percentage of occupant-hours:[2]

$$Exceedance_M = \sum_{i=0}^{allhours} \frac{n_i \, if \, discomfort_M > 20\%}{0 \, if \, discomfort_M \leq 20\%} \Big/ \sum_{i=0}^{allhours} n_i$$

where n_i is the number of occupants present for a given hour; and $discomfort_M$ is the estimated percentage of

people dissatisfied according to comfort model *M*. Note that the hard cut-off at 20% dissatisfied can create a particular sensitivity to values that just happen to be on one side or the other of the threshold.

For *Exceedance*$_{PPD}$, the authors used the standard PMV/PPD comfort calculations as originally described by Fanger and implemented in EnergyPlus. For each adaptive model, comfort calculations using the operative temperature values output by the simulation were performed as described in Table 1.[3]

Simulation

EnergyPlus models were built to support the parametric studies of the trade-offs between comfort and energy use in the context of varying climate conditions and a range of passive performance attributes and internal gains. The modelling approach itself was informed by a selection of prior work. There has been steady progress on approaches to modelling mixed-mode and radiant systems (Strand and Pedersen, 2002; Henze *et al.*, 2008; Spindler and Norford, 2009a, 2009b) and there are a handful of written sources that offer design guidance on mixed-mode and naturally ventilated buildings (Heiselberg, 2002; Chartered Institution of Building Services Engineers (CIBSE), 2000, 2005).

Technical modelling concerns and real-world best practices were used to inform a simulation model that was based loosely on the Kirsch Center, a well-performing two-story 2000 m^2 (21 500 ft^2) building in Northern California that hosts an academic environmental studies programme. The Kirsch Center was designed for mixed-mode operation and has many features, including orientation, massing, shading, radiant cooling, window placement, and floor plate dimensions that enhance natural ventilation and minimize heat gains and energy use. Along these lines the EnergyPlus model was parameterized to support operation using different cooling strategies: natural ventilation only (including night ventilation), mechanical only (sealed VAV) or mixed-mode (daytime ventilation through operable windows and night charging of radiant floors slabs using a cooling tower). The model was configured with infiltration rates, insulation levels, exterior shading, low-e glazing, coefficients of performance, etc. consistent with the best practice design and performance of mechanical systems, lighting, windows, insulation, and internal gains in California climates (except when variations of the above were being studied).[4] For example, both lighting and equipment power density default to approximately 10 W/m^2. Ventilation rates were modelled using both scheduled infiltration rates (for simplicity) and a more complex AirFlow Network, which is a bulk air flow model built into EnergyPlus. However, a sensitivity analysis of a fourfold increase in the strength of the pressure coefficients, which are used by the AirFlow Network to translate outdoor conditions to indoor air flow, found minimal impacts on exceedance percentages (well less than 1 percentage point for all climates). It was concluded that the AirFlow Network calculations did not alter comfort results sufficiently to offset their computational costs in the comparative parametric studies that form the basis of this paper. Instead, infiltration rates were scheduled to provide a proxy for window operation. Windows were 'open', providing infiltration of five air changes per hour, between 12 and 25°C; infiltration rates were otherwise set to 0.2 air changes per hour. Wind-driven ventilation can dramatically exceed five air changes per hour, but this was deemed an appropriate proxy for suboptimal/average conditions.

The Kirsch model was further parameterized for studies of internal gains, shell performance, ventilation performance, operating control strategies, mechanical systems, and thermal mass with respect to occupant comfort and energy consumption. Using various permutations of the model configuration, parametric studies were run using TMY2 weather data that spanned all 16 California climate zones, as provided and described by the California Energy Commission,[5] with system sizing and operational and control strategies tuned to each climate. Specifically, the radiant floor slabs were cooled through heat exchange with a cooling tower overnight to an 18°C surface temperature set-point and allowed to float during the day. Tower size and flow rates were iteratively tuned to minimize energy consumption given the cooling loads for each climate. The extensive outputs of these runs have been distilled into climate specific performance metrics, including exceedance derived from average conditions across all rooms using both PPD and adaptive comfort as described above. For this paper, a representative subset consisting of six climate zones was used in place of the full set of 16 for some of the analyses to produce more easily read and digested figures.

For the 100% naturally ventilated simulation runs, only the ASHRAE 55 adaptive comfort model was used to calculate exceedance. For the sealed HVAC cases, only Fanger's PPD calculation was used. For all of the mixed-mode cases, a range of expected comfort conditions were bracketed using the PPD and all three adaptive comfort models described in Table 1.

Results
State of the industry
The interviews with building professionals revealed that, traditionally, the concept of exceedance has not been discussed explicitly with clients. The concept

does arise, but via a wide range of metrics. These metrics suggest that some low-energy spaces may not be equipped to meet set-points under the most extreme weather conditions. Internally, several of the contacted firms calculate metrics designed to capture the spirit of exceedance, but they note that there are not universally agreed upon metrics, and lament the lack of tools they can use to do such calculations.

For clients, energy is often a driving factor. Thus, the conversation is often steered towards energy performance with comfort left to professional judgment. The most thoughtful conversations about comfort tend to be on owner-occupied projects, where the client invests more time and effort in the outcome. However, for many clients planning hybrid systems, comfort is not much of a concern. They expect the mechanical system to serve as a reliable backup to the lower energy strategies.[6]

When exceedance is discussed with clients, relevant metrics tend to be simplified. Analyses that predict the number of hours at or beyond a certain per cent dissatisfied are common, as are those that predict the number of hours beyond ASHRAE 55 or beyond specific set-points. Some analyses are presented in terms of thresholds. Others use histograms with bins for per cent dissatisfied ranges. Clients who want low-energy designs that do not compromise the ability to maintain set-points do not have exceedance metrics on their minds at all (at the outset).

Based on the undertaken interviews, it is clear that contractual or other binding agreements on delivered comfort are rare in the US. The consensus seems to be that these could appear over time, but many important aspects of the design and associated targets are not sufficiently developed to support binding comfort targets at the time the contracts are signed. The acceptability of, and risks associated with, specific cooling strategies are worked out in less formal settings during the course of projects. In fact, more than one professional mentioned that performance standards and contractual agreements increase the likelihood of legal wrangling and can actually impede creative problem solving. Comfort concerns play only a small role in the complex set of factors that designers consider in the course of designing low-energy buildings.

In spite of traditional practice, the interviews with industry practitioners clearly demonstrated that conversations about exceedance or 'exceedance-like' metrics are becoming increasingly common and that all parties are searching for a standard set of metrics, assumptions, and calculation tools to help them better navigate the trade-offs between energy, comfort and other amenities. This finding confirms industry demand for comfort models and exceedance metrics that have been better studied, improved and made replicable.

Climate characterization

The results culled from the simulations are compiled from hundreds of distinct parametric model runs across all 16 of California's climate zones, with varying cooling strategies, gains and comfort criteria. For context, Figure 1 provides a map of California's climate zones. The climate zone numbers in California start in the coastal north and proceed south and inland as their assigned numbers increase. Thus, the general trend is towards hotter and dryer, leading to increased cooling energy and/or decreased thermal comfort as the zone numbers increase. A notable exception to this trend is Climate Zone 16, which covers a large mountainous region and is not warmer than Climate Zone 15, with includes Death Valley, the hottest place in North America.

Figure 2 provides some sense of the diversity of climates involved, and also allows one to identify which of the California zones is comparable with other climates that may be of interest. It disaggregates the portion of hours in each climate where conditions are temperate (defined as air temperature between 60 and 80°F, or 15–27°C, and relative humidity < 70%), too hot, too cold or too humid. Considering that California
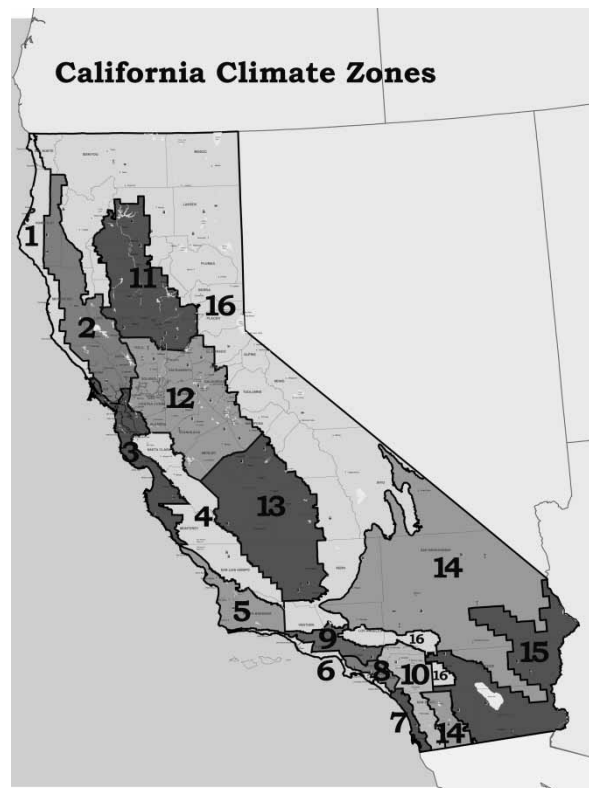
Figure 1 California's 16 climate zones, as defined by the California Energy Commission. The numbering runs from north to south along the coast, then north to south again along the central valley all the way through to Death Valley, and finally the eastern part of the state
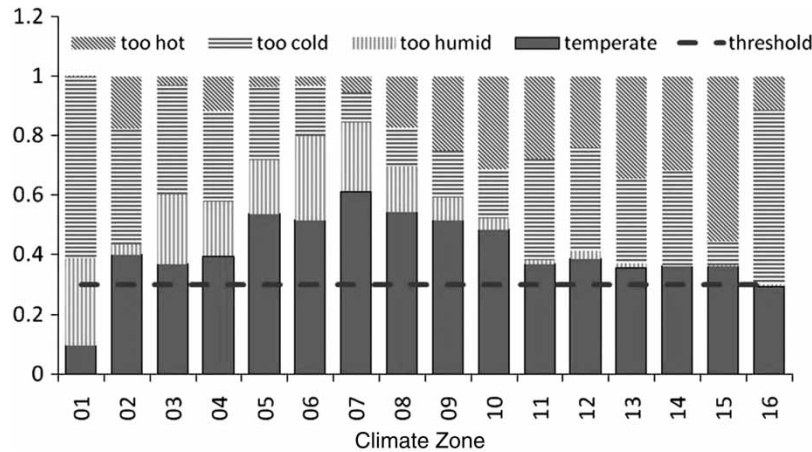
Figure 2 Fraction of hours annually with outside conditions conducive to natural ventilation, defined as temperature between 60 and 80°F (15–27°C) and relative humidity less than 70%. Taller solid (temperate) bars are better candidates for natural ventilation and mixed-mode operation. The portion of hours cooler than the range are labelled 'too cold', those that are hotter are labelled 'too hot', and the remainder 'too humid'

spans about 1200 km (800 miles) from north to south, with elevations ranging from below sea level[7] to 4400 m (14 500 ft) above sea level, it should come as no surprise that temperatures (and climates) in California vary substantially. With the notable exception of truly hot *and* humid climates, it provides a very good laboratory for examining a wide range of climate-driven loads and comfort in buildings.
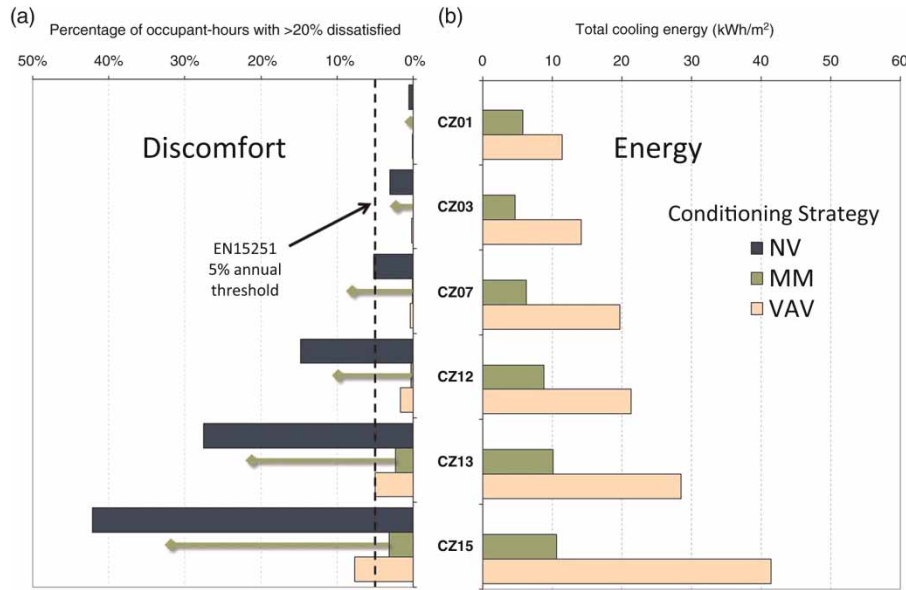
Simulation

The main findings from the simulation modelling are detailed below, focusing on the role of comfort metrics and the concept of exceedance. It is important to note that there are limits to the accuracy of simulation-based approaches and that all such work is coloured by the assumptions and expert judgments made by the simulation team. Computer simulations are most valuable when they are examining the *relative* performance of one configuration to another to help inform design decisions. There is mixed evidence on the extent to which they are accurate in predicting *absolute* energy consumption (Turner and Frankel 2007). For this reason, the results are presented in a form that encourages comparison and emphasizes the sensitivity of findings to model inputs.

Influence of conditioning strategy

Figure 3 uses the per cent exceedance and cooling energy-intensity metrics adopted for this project as two axes extending in opposite directions. Each of the six exemplary climate zones has the modelled results of three variants of conditioning strategies plotted on these two axes. The data can thus be read across climate zones and across conditioning method to understand the energy and comfort trade-offs each approach makes.

Proceeding from top to bottom, the data for each climate zone start with the pure natural ventilation scenario (labelled 'NV'). Natural ventilation uses no cooling energy, so the right-hand side has no bar. The left-hand side displays the percentage of occupant hours in exceedance of the ASHRAE 55 adaptive comfort standard. The next scenario (labelled simply 'MM') is mixed-mode operation with a radiant slab that is cooled using a cooling tower that only operates overnight. The left-hand side features a bar that corresponds to the percentage of exceedance for the ASHRAE 55 adaptive comfort model. To account for the uncertainty in comfort outcomes associated with mixed-mode buildings, the bar is extended out to a point that corresponds to the percentage of exceedance using PPD. Finally, the last model variant for each climate zone (labelled 'VAV') is the performance of a variable-air-volume forced air system. The left-hand side shows the percentage of exceedance using PPD only, since adaptive comfort does not apply to buildings without operable windows.

When examining the left side of Figure 3, note how sensitive the comfort results are to both the conditioning strategy and the comfort model being applied in the mixed-mode scenario. For the building modelled, in the milder climates (three of the six representative climate zones), natural ventilation alone was sufficient for maintaining comfort a significant amount of the time, with exceedance near or below 5%. For the other climates, however, the analysis suggests that some form of supplemental conditioning is required. Assuming that the ASHRAE 55 adaptive comfort model applies, the analysis shows that the mixed-mode strategy would imply acceptable comfort conditions (less than 5% exceedance) in all six of these representative climate zones. Such a conclusion would be quite different if one had to apply the PPD

Figure 3 Simulation results displaying the trade-offs between comfort (a) and energy consumption (b). For the mixed-mode case, comfort exceedance predictions are bracketed using both the ASHRAE 55 adaptive model (base bar) and the PPD model (line extension)

metric to the mixed-mode buildings (the extended bars in the left side of Figure 3). Using PPD, predicted exceedance levels imply that this mixed-mode building could deliver exceedance below 5% in only two of the six representative climates zones.

Clearly, the choice of comfort metric used in a mixed-mode building significantly changes the conclusions one might reach, with stark difference between PMV-PPD and adaptive comfort. Regarding the most extreme climate zone represented below, it should be noted that even the sealed building with a VAV system was being challenged to maintain comfort levels within acceptable exceedance limits, and significant amounts of energy were required to do so. Under these extreme weather conditions, the mechanical system hit its set-point for air temperature, but the mean radiant temperature of the walls was sufficiently high to cause discomfort.

Influence of internal gains
Climate and conditioning strategies are not the only factors driving thermal comfort of buildings. In particular, heat gains, whether coming from outside (mediated by the shell) or generated internally, are the factors that shape cooling loads most directly. Gains should therefore be minimized very carefully before a cooling strategy is established and equipment is sized in a low-energy building. Thus, the geometry, orientation, shading, massing, glazing, and insulation can all be part of a strategy to support low-energy cooling. These features are represented in the Energy-Plus model used for this study. However, at the level

of granularity of the exceedance analysis being explored here, all gains are roughly equivalent in terms of predicted comfort.

Figure 4 illustrates the effect of changing internal gains on exceedance in the mixed-mode configuration, but it could also be interpreted as a more generic summary of how gains of any type affect comfort. As in Figure 3, the solid bars represent calculations using the adaptive ASHRAE 55 model, and the line extensions represent the PPD model. The high, medium, and low lighting and equipment power density values were drawn from ASHRAE guidance and expert opinion on typical ranges of intensities for such gains in buildings.

The rates of internal gains clearly have a significant effect on the exceedance, regardless of calculation method. However the applicability (or lack thereof) of adaptive comfort is decisive in determining acceptability in seven of the 18 configurations shown, pushing exceedance from below 5% if adaptive comfort applies (solid bar), to well beyond if it does not (line extension). In five of 18 cases conditions are acceptable regardless of comfort standard. In four of 18 configurations the choice of comfort model pushes exceedance from between 5 and 10% to above 10%. In the remaining two of 18 configurations exceedance is over 10% regardless of comfort standard.

Influence of uncertainties in ideal comfort temperature
Adaptive comfort models are all developed as regression models of ideal comfort temperature,

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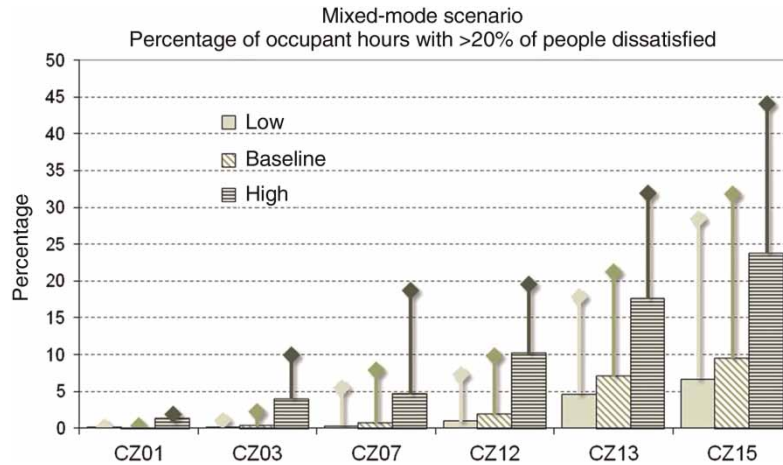
Figure 4 Comparison between high, medium and low internal gains scenarios with radiant cooling (only). Bars represent ASHRAE 55 adaptive comfort exceedance. Bar extenders represent PPD comfort exceedance: lighting power density (W/m^2): low = 7.53, baseline = 9.68, ASHRAE 'high' = 11.83; and equipment power density (W/m^2): low = 5.4, baseline = 10.75 and high = 28.0

based on field-based data. But as with all regression models there is a margin of error, or degree of uncertainty, associated with the estimated ideal temperatures, and there is also the potential for divergence due to uncertainties in model inputs or structure. Figure 5 illustrates the variation in exceedance assuming ± 1 and $\pm 2°$C deviations from the comfort temperature calculated using the ASHRAE 55 adaptive comfort model. Because exceedance here is calculated using a comfort threshold, it is very sensitive to the exact location of the threshold. As the assumed comfort temperature, T_{comf}, is decreased (leading to more people presumed to be too hot, but perhaps fewer feeling too cold) exceedance increases dramatically, often by over 10 percentage points. This is not surprising since in these buildings it is *warm* discomfort that is a primary concern. As T_{comf} is increased (leading to fewer people presumed to be too hot) the expected exceedance quickly drops to values well below the 3–5% recommended threshold in most climates. Thus, within a safe margin of error of 2°C above or below the predicted T_{comf}, it is possible to find reason to reject or accept a building's thermal performance. The sensitivity of exceedance to small changes in T_{comf}, as illustrated by Figure 5, strongly suggests that its continued development will require practitioners to employ methodologies and tools that properly account for and communicate the statistical and structural uncertainties inherent in comfort models as well as the uncertainties inherent in temperature data from simulation models.

Influence of climate and comfort theory
Collectively, Figures 3–5 reveal the sensitivity of exceedance predictions both to comfort model assumptions (*i.e.*, is adaptive comfort theory applicable), and

to rates of heat gains. The effect of climate on this sensitivity is summarized in Figure 6, which compares predicted exceedance from applying the ASHRAE 55 adaptive comfort model versus PPD for the mixed-mode case with baseline gains in every climate zone in California. The magnitude of the gap between the two metrics is significant in most climates. In 14 out of the 16 climates adaptive comfort predicts less than 5% exceedance (as recommended in Annex G of EN 15251), but PPD predicts exceedance below this threshold in only four. Using adaptive comfort standards, exceedance is less than 5% in 14 of the climate zones. Using PPD, this is the case in only four. This analysis underscores the need to understand better how comfort models apply to mixed-mode buildings. All too often the choice of the model will make the difference between whether one predicts thermal success or failure.

Influence of comfort standards
Figure 7 compares exceedance values calculated using the occupant-hours method described in the methods section across T_{comf} values determined using the adaptive comfort models found in three different standards, whose T_{comf} calculations are detailed in Table 1. ASHRAE 55 and NPR CR 1752 use the same formula for T_{comf}, except NPR CP 1752 uses a four-day (the current day and the three before) running average outdoor temperature and the ASHRAE 55 model uses a monthly average temperature as its inputs. The fact that calculated exceedance values for identical conditions are consistently lower for NPR CP 1752 confirms that a short-term running mean temperature is more 'adaptive' than a monthly average. The exceedance values using comfort calculations from EN 15251 are even lower than those using NPR CP 1752. EN 15251 uses an exponentially
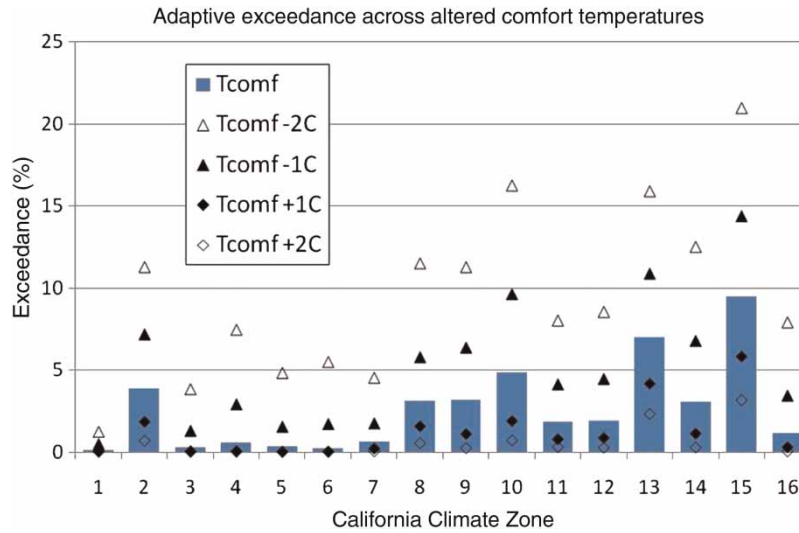
Figure 5 Comparison of exceedance using ASHRAE 55's adaptive comfort calculation of T_{comf} and variations of $\pm$ 1 and $\pm$ 2°C, representing potential divergence due to uncertainties in model inputs or structure. Note the magnitude of the increase in exceedance, depicted by the shaded and open triangles, as the assumed T_{comf} is decreased (a lower comfort temperature leads to an increased percentage of people predicted to be too hot under the same conditions) and the corresponding decrease in exceedance depicted by closed and open diamonds, as the assumed T_{comf} is decreased. With $\pm$ 2°C uncertainty in T_{comf} the total range of predicted exceedance straddles the 5% threshold in 14 of the 16 climates
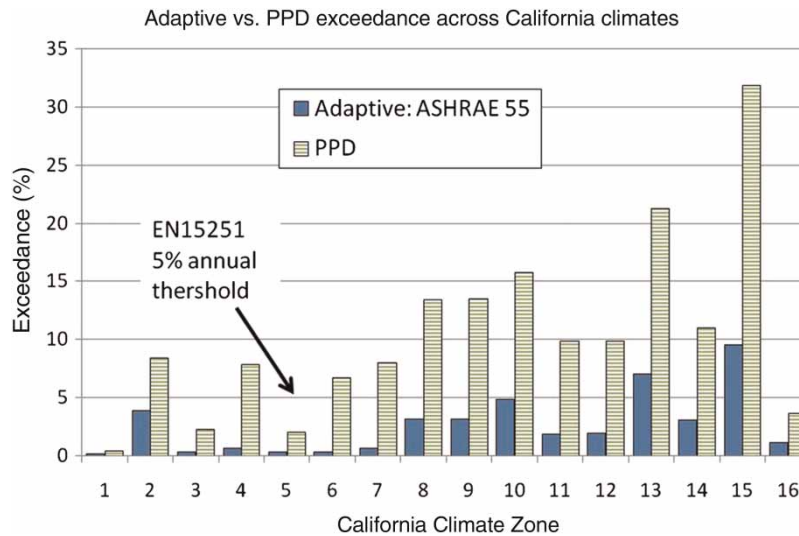
Figure 6 Exceedance predictions in the mixed-mode scenario with baseline gains using the ASHRAE 55 adaptive comfort model and the PPD model across all 16 climate zones in California

weighted running mean outdoor temperature and is based on a different formula for T_{comf} derived from a more narrowly focused set of building data (*e.g.* strictly European) than the ASHRAE 55 and NPR CR 1752 models (Nicol and Humphreys, 2010). Comfort temperatures are consistently higher when calculated using this formula and even with their tighter 90% and 80% comfort ranges (2.0 and 3.0°C respectively rather than 2.5 and 3.5°C), the exceedance threshold is crossed less frequently. This is consistent with the analysis presented in Figure 5, where a higher

comfort temperature will inherently lead to lower exceedance values.

Influence of outdoor temperature metric

As indicated above, ASHRAE 55 and EN 15251 feature adaptive comfort models derived from different sets of data. Thus their comfort temperature calculations, based on regression outcomes, are numerically different. However, the only difference between ASHRAE 55 and NPR CR 1752 is that the Dutch
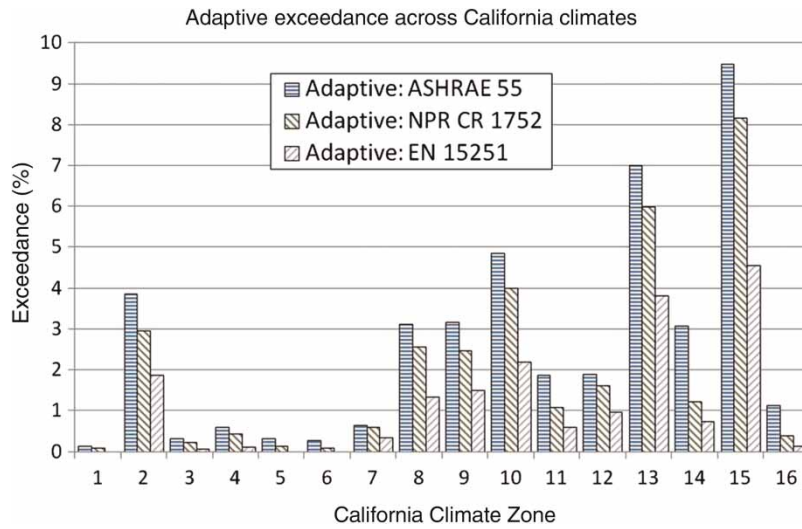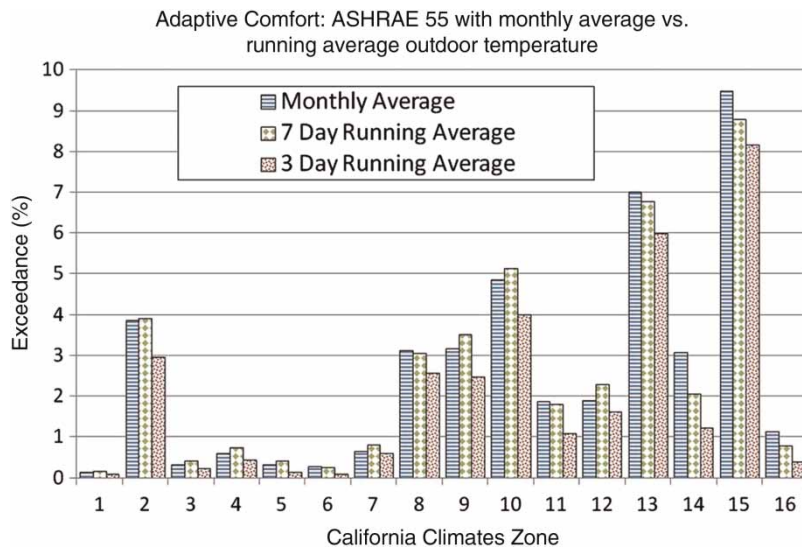
Figure 7 Exceedance predictions in the mixed-mode scenario with baseline gains comparing the ASHRAE 55 adaptive comfort model with EN 15251 and NPR CR 1752

standard employs a three-day running average outdoor temperature instead of a monthly average. Inspired by the observation that the averaging algorithm can impact calculated exceedance values, Figure 8 presents data from three variations of the ASHRAE 55 comfort calculation: monthly averages (as currently used in ASHRAE 55), weekly weighted running averages (an approximation for exponential weighting allowed by EN 15251), and three-day weighted running averages (as used in NPR CR 1752). This is more than a speculative exercise because the original adaptive comfort research that became part of the ASHRAE 55 standard used a running average to characterize the outdoor

temperature, but was later simplified to a monthly average for ease of calculation in the standard. Now that computer analysis is the norm and typical meteorological year weather data is widely available for nearly all US locations, the more precise model may be adopted by future versions of the standard.

As seen in Figure 8, the seven-day running average outdoor temperature produces exceedance values both greater and less than those using the monthly average, depending on the climate zone. In contrast, the three-day running average produces exceedance values consistently below the monthly average, often

Figure 8 Exceedance predictions in the mixed-mode scenario with baseline gains comparing the ASHRAE 55 adaptive comfort model with different methods of calculating the average outdoor air temperature. Note that the seven-day running average can produce exceedance either greater or less than the monthly average, depending on recent weather conditions but that exceedance using the three day average is consistently lower

shaving off 1 percentage point or more from the total exceedance percentage.

Discussion

The exceedance outcomes from these simulations, including the climates with best and worst performance and the relative performance across climates, correlated well with common sense evaluation of climate attributes and the observed geography of successful naturally ventilated and mixed-mode buildings in California. The temperate coastal climates allowed our mixed-mode configuration to deliver low exceedance values. The warmer the climate, the higher the exceedance predicted by the simulations.

Despite this correlation, the results show that methods of comfort prediction (using exceedance) are quite sensitive to variations in building envelope quality, internal gains, and insolation and particularly sensitive to which comfort standard is assumed. Because comfort standards are themselves subject to fairly large uncertainties, the authors must conclude that quantitative exceedance results must be interpreted very carefully.

Benefits and challenges with exceedance calculations

Informed by the trend towards lower-energy buildings, the ongoing development and evaluations of standards, and the increasing frequency heat storm weather events (like the long, brutally hot summer of 2003 in Europe), it is becoming clear that a comfort metric that allows scrutiny of the trade-off between energy consumption and comfort would be valuable to building designers, owners and other stakeholders. To this end, exceedance metrics are extremely useful for encapsulating time-varying comfort into a single number. They can often be calculated independent of building type and can even be used to compare different comfort standards, as done here. Many building researchers are quite logically pursuing work on comfort exceedance intended to benefit comfort standards and their associated guidance.

However, it is also becoming clear from the diversity of definitions in practice, standards and academia that there is no consensus on how best to define or apply exceedance metrics. For example, EN 15251 provides three different calculation methods (one in percentages and two in weighted hours) and reasonable sounding, but arbitrarily determined, guidance on what levels of exceedance should be acceptable in buildings (3–5% of occupied time per day, week, month and year). This parallels the similarly arbitrary nature of the thresholds of acceptability that define the traditional comfort zones (*i.e.*, 20% discomfort or dissatisfied).

Unfortunately, exceedance values are highly sensitive to small variations in the comfort models or assumptions underlying them, including the details of the calculation of recent average temperatures, the uncertainties in the assumptions and inputs of the models used to simulate indoor conditions, the preferred regression model used to calculate comfort temperatures, and the applicability or lack thereof of adaptive comfort in buildings that are neither free running nor fully sealed and automated. In many scenarios, this means that predicted exceedance values are likely to exaggerate any shortcomings of their underlying comfort models and produce results so sensitive to their uncertain inputs that they carry much less information, and therefore predictive power, than they appear to.

This finding from the present analysis is consistent with previous studies. For example, Pfafferott *et al.* (2007) used measured data spanning several years from 12 buildings to analyse comfort outcomes by applying four different standards: the international PMV-PPD standard ISO 7730,[8] the preliminary European standard prEN15251, now EN 15251 (CEN, 2007),[9] the former German standard DIN 1946-2,[10] and the proposed Dutch code of practice NPR-CR 1752[11] (Pfafferott *et al.*, 2007). In their findings, both the *total predicted exceedance* and the *performance of buildings relative to one another* varied from one metric to the next: *neither magnitude nor order were preserved*. This result held even between prEN15251 and NPR-CR 1752 where the main difference in the comfort calculation was using the average monthly outdoor temperature (a simplification made by ASHRAE 55) versus using a running average of the previous three days. The authors concluded that the overall character of the values was sufficient to make the *qualitative* judgment that many of the buildings they examined were successful based on the range of exceedance values they calculated. But there is not a singular accepted measure of exceedance that would have allowed them to make a more reliable *quantitative* judgment.

The present work corroborates the sensitivity of exceedance to comfort model features and small variations in comfort temperature (as well as variations in internal gains, shell performance, and insolation, which are also uncertain at design time), and further supports the value of characterizing a plausible range of exceedance values rather than calculating single values. This finding has relevance for all of the standards we investigated, and is an important consideration for their future development and application.

Comfort/energy trade-off

In the optimistic spirit of pursuing building energy goals, there is sometimes a reluctance to recognize inevitable interactions between energy use and comfort expectations. In the European Union directive on building efficiency

it is stated for example that energy saving measures should not lead to *sacrifices* in comfort and health of building occupants. (Boestra, 2006, p. 1, emphasis added)

This seems like a reasonable sentiment at first glance, but the process of building design by its very nature involves artful compromises and the balancing of priorities. It is inevitable that there will be trade-offs in many circumstances. Should such trade-offs be labelled as '*sacrifices*'? The directive is silent on the nature of the sacrifices it refers to and how to avoid them. This is not merely a semantic point. There is an emerging school of thought that holds that there is nothing sacred about our current comfort standards. *Building Research & Information* dedicated an entire special edition to 'Comfort in a Lower Carbon Society' in 2008. The issue contains some stern warnings for people taking comfort metrics too seriously. In their opening editorial, Shove *et al.* (2008) argue, based on the contents of the issue, that codes and standards will not be enough to address climate change properly and that the real question lies in how well we exploit the observation that 'definitions of comfort are not set in stone' (Shove *et al.* 2008).

In cases of over-conditioning, lower energy use can actually improve thermal comfort. In all other situations, perhaps the question should be how the necessary reductions in energy consumption can be made as comfortable as possible. The current research addressed both energy use and comfort performance in variously configured buildings. It clearly shows that the sealed buildings with HVAC systems reliably minimize exceedance, and by this measure can be assumed to be providing higher levels of comfort. However, they also use more than three times as much energy as their mixed-mode counterparts to do so. On the other hand, the mixed-mode configurations we simulated simply do not have the cooling capacity to maintain their set-points under all circumstances. Can some nominal amount of comfort be traded off for large energy savings? This is where exceedance can become a very useful metric. When a long term comfort performance expectation can be articulated (*e.g.* 5% exceedance annually), then the compromise that mixed-mode buildings might make on comfort can be compared to the energy benefits they yield. As a general principle, the greater the occupants' tolerance for higher levels of exceedance, the more energy can be saved. However there is more to the story. Specific circumstances can contribute to the comfort or discomfort of building occupants, which is ultimately a subjective assessment based on complex, contextual factors. An exceedance-based goal leaves room for enhanced comfort achieved in part through energy-neutral mechanisms, like providing for increased occupant control and creating expectations and even preferences for a more variable thermal environment.

Recommendations for the future of exceedance metrics

As already observed, exceedance metrics, particularly those that count the number of hours on one side or the other of a given per cent dissatisfied, are quite sensitive to uncertainties in the comfort calculations they rely upon. There are several potential strategies for addressing this sensitivity. Each has its own strengths and weaknesses, and all deserve further thought.

- *Bracketing* This technique can use the distinct assumptions that lead to low and high estimates of exceedance to put bounds around the range of probable exceedance outcomes. This approach, used in the presented work, acknowledges the uncertainties inherent in these metrics and the resulting wisdom of calculating some range of exceedances rather than single values. It also tends to better support qualitative or comparative interpretations. This technique can be particularly useful when addressing sensitivities across comfort models or specified ranges of operating conditions, but requires interpretation by users.

- *Weighting* Discomfort values that contribute to exceedance can be weighted by various factors to ensure that the contribution of more extreme thermal conditions is larger, and to moderate the arbitrary nature of counting measurements just above but not just below a comfort zone limit defined by a per cent dissatisfied threshold. As indicated by the options laid out in EN 15251 Annex F, examples of factors used to weight the count of uncomfortable hours can include the number of degrees above the comfort temperature, or the magnitude of per cent dissatisfied. The resulting exceedance metric can then take the form of total degree-hours or per cent dissatisfied-hours (PD-hours) of deviation from comfort conditions. Note that some comfort models, including adaptive comfort models, cannot directly predict per cent dissatisfied (as Fanger's PPD does), so the degree-hours approach would be the most generalizable. This technique will tend to produce results that may not be as intuitive as an unweighted percentage of exceedance, but because the largest deviations are emphasized, the results will be more robust to uncertainties in the comfort estimates.

- *Histograms/distributions* If results can be presented as histograms of exceedance metrics, with the count of the number of hours in specific binned ranges of per cent dissatisfied (or degrees above the comfort temperature) along the *x*-axis, it is then possible to judge not just the exceedance for > 20% dissatisfied, but for other acceptability threshold values and ranges of uncertain T_{comf} values as well. For example, in work explaining

the development and use of NPR-CR 1752, van der Linden *et al.* (2006) have provided a graphical depiction of the NPR-CR 1752 comfort zone that includes a histogram of per cent dissatisfied. Such distributions make visible the additional discomfort that would be included or lost if assumptions about the association of 'acceptability' with 'percent dissatisfied' values shifted up or down in response to comfort model uncertainties. However, interpreting distributions is not always intuitive. For example, it can be confusing to say that the exceedance is the area under the histogram beyond 20% dissatisfied. Yet the interviewed practitioners do report success in using binning methods with non-technical clients to show how comfort will be expected to be distributed over time in their buildings.

Conclusions

The design and operation of every low-energy building requires striking a careful balance between energy use and the amenities delivered using that energy, which often directly impact the health, productivity and comfort of occupants. A focus on amenities without concern for consumption often leads to the profligate waste that characterizes too much of the existing building stock. A focus on energy without concern for amenities can lead to unacceptable indoor conditions and buildings that are ultimately seen as failures. Thus, it is the trade-offs between the two that must be the focus of attention as researchers and practitioners seek to reduce energy use in buildings.

It is encouraging that an increasing number of buildings are being designed and operated with energy goals in mind. But it is clear from observed performance and anecdotal evidence from industry that conversations about the energy/comfort trade-offs and opportunities inherent in such efforts are limited, and when they do exist they proceed in an *ad hoc* manner. This is precisely why metrics like exceedance, which quantify expected comfort levels over time and allow correlation to the energy used to deliver that comfort, should be further studied, refined and standardized. Consensus on the use and meaning of exceedance calculations would ensure increased industry awareness, improve the likelihood that conversations and strategizing around energy/comfort trade-offs are taking place, and help decrease the number of surprises in the outcomes. However, as this work has demonstrated, exceedance calculations are very sensitive to small uncertainties in their inputs and should be presented and interpreted with care.

Addressing uncertainty in exceedance metrics

The process of developing codes and standards is very often the mechanism for formalizing metrics and methodologies, so it is encouraging to see standards bodies taking up work on exceedance at this time. The European standard EN 15251 and the associated documentation of its development provides an excellent example of recent efforts to do this. In particular, its Annexes F and G provide guidance on five methods of exceedance calculation and rules of thumb for what should be viewed as acceptable levels of exceedance. However, there are some important caveats that must be applied to any quantitative approach to predicting exceedance.

Exceedance metrics are calculated as deviations from comfort limits, which in turn are derived using assumptions about the relationship between indoor (and sometimes outdoor) conditions and occupant comfort. These assumptions can be direct (*e.g.* the degrees above a fixed comfort temperature can be used as a proxy for occupant sentiment) or embedded in a comfort model (*e.g.* PPD or adaptive comfort calculations). The current research work joins the work of others, particularly Pfafferott *et al.* (2007), in demonstrating that exceedance is sensitive to these underlying comfort assumptions. Where two justifiable sets of assumptions can lead to dramatically different outcomes, there is a problem of reliability that needs to be addressed.

An initial step towards a remedy was made by running the exceedance calculations for mixed-mode buildings through both PPD and adaptive comfort (the ASHRAE 55 version) models to bracket exceedance results, and by examining exceedance outcomes for identical indoor conditions across varying adaptive comfort models, perturbed T_{comf} values, and varying methods of accounting for the time-averaged effect of outdoor temperatures. In the many cases where the range of predicted outcomes straddles the threshold of acceptable levels of exceedance, the results suggest that acceptable comfort should be possible but is by no means guaranteed. Designers, owners and occupants should proceed with caution in such circumstances by doing everything they can to cultivate an adaptive comfort outcome (*e.g.* maximizing the 'adaptive opportunity' through operable windows, emphasizing occupant control, and choosing heating and cooling systems that compliment natural ventilation) while mitigating against the possibility that there will be periods of discomfort (*e.g.* designing cooling systems that can handle expected loads while allowing for some level of exceedance).

They may not be as simple to manage or easy to interpret, but distributions and/or ranges of exceedance metrics are a more honest representation of what is known about the actual dynamics of thermal conditions in buildings. Standards bodies in pursuit of practical guidance and tangible progress towards better buildings should recognize the limits and uncertainties of both simulation and comfort models, and

the sensitivity that exceedance calculations have to these uncertainties, by emphasizing exceedance ranges, distributions, and probabilities rather than exact numbers, and elaborating on the qualitative implications of their outcomes (*e.g.* that trade-offs may be necessary to achieve comfort and amenity goals). There is also a danger that 'energy only' optimization can go too far and lead to failures in other categories of building performance, so it would be significant progress for more substantial conversations and analyses of the trade-offs to emerge, facilitated by performance metrics like exceedance.

Setting an exceedance research agenda

It is clear that more work can and should be done to improve quantitative models of comfort and exceedance and to evaluate exceedance outcomes in real-world situations. This is particularly needed in mixed-mode buildings where there is no consensus on the relative applicability of the PMV/PPD versus adaptive comfort standards. The field studies that formed the basis of adaptive comfort models in naturally ventilated buildings should be repeated in mixed-mode buildings using methods designed to support comparisons with existing data. A first step towards this goal would be to develop a standard set of 'building characteristic/adaptive opportunity' information that should be collected for all studied buildings, in addition to the standard existing protocols for field-based studies of thermal comfort. A critical goal of this work should be to develop guidance on when and how components of adaptive comfort (*e.g.* behavioural and physiological adaptation, the effect of expectations and environmental preferences on occupant experiences of conditions, etc.) and related models might apply to mixed-mode spaces.

Another important goal of such fieldwork should be to correlate long-term measures of occupant satisfaction with 'right now' comfort surveys, physical measurements and comfort model predictions. Such work would form the basis of a more empirical evaluation of the relationship between short-term comfort and long-term satisfaction and the efficacy of exceedance calculations in predicting the success or failure of buildings.

The urgency behind efforts to reduce building energy consumption demands that architects and engineers, their institutions and standards organizations, and the supporting research community collectively learn to deliver buildings that dramatically reduce their energy use without pushing beyond the acceptable comfort limits of their occupants. In many cases there are opportunities to improve indoor environmental conditions while simultaneously reducing energy consumption dramatically. However, there are also cases where the required reductions risk producing failures of thermal comfort unless they are accompanied by

shifts in expectations or societal values. Across this entire spectrum, metrics like exceedance that facilitate discussion about the trade-offs between comfort and energy should be used to inform policy, design and operational decisions. As imperfect as they are, such metrics have a critically important role to play in moving the industry towards well-performing low-energy buildings. Researchers and practitioners can make important contributions to this process of improvement by applying such metrics thoughtfully, understanding their limitations, and contributing to the improvement of the comfort models and methods of calculation behind them.

Acknowledgements

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Endnotes

[1] There were six respondents, with five primarily employed as senior engineers or managers at leading mechanical engineering firms, and one primarily employed as a building researcher focused on the evaluation of building performance.

[2] The use of occupancy weighting, or 'occupant-hours', in this work's exceedance calculations was designed to account for the fact that there can be no discomfort in unoccupied buildings. EN15251 Annex F Method A suggests a calculation of the percentage of 'occupied hours'. Thus, the calculation method developed here will produce exceedance values identical to Method A for fully occupied periods and lower values for partially occupied periods. The occupancy schedule used for the calculations presented here includes hours of partial occupancy at the beginning, lunch hour and end of a nine-hour work day, so the exceedance percentages presented in this work are slightly lower than Method A would produce.

[3] Although the comfort conditions were calculated using separate comfort models from specific standards, the exceedance calculation algorithm used was identical across standards. Thus, even though EN 15251 has five recommended methods of calculating exceedance, the method used was the author's own, but it is very nearly the same and the 'percentage outside the range' method it describes.

[4] This paper is primarily concerned with comparisons between model configurations, rather than with the absolute calibration of system performance, so full technical description of the modelling approach and input parameters is beyond its scope. Such details can be found in the final research report for this project, 'Low Energy Cooling for California Climates'.

[5] California climates were selected because the modelling work used to inform this study was originally commissioned by the California Energy Commission as part of its Public Interest Energy Research grant programme. Now that the foundation has been laid, the simulation approach described here can be extended to other regions.

[6] It is worth noting here the potential conflict between the assumption of mechanical backup ensuring zero exceedance and the observed role of expectations of more dynamic thermal environments in achieving adaptive comfort outcomes. This strongly suggests future research opportunities.

[7] Death Valley is nearly 100 m (296 ft) below sea level.

[8] Fixes T_{comf} at 24°C.

[9] $T_{\text{comf}} = 17.8°C + 0.31 \times T_{\text{rm}}$, where T_{comf} is the comfort temperature; and T_{rm} is the running mean outdoor temperature. Note that the formula used by Pfafferott *et al.* differs from the official EN 15251 standard, which uses $T_{\text{comf}} = 18.8°C + 0.33 \times T_{\text{rm}}$.

[10] $T_{\text{comf}} = 23.5°C + T_{\text{h}}/3$, where T_{h} is the hourly ambient temperature.

[11] $T_{\text{comf}} = 17.8°C + 0.31 \times T_{\text{rm}}$, where T_{rm} is the running mean ambient air temperature of the last three days (as opposed to the monthly average).