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Assessment of Energy Use and Comfort in Buildings Utilizing Mixed-Mode Controls

with Radiant Cooling

by

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University of California, Berkeley

Abstract

Assessment of Energy Use and Comfort in Buildings Utilizing Mixed-Mode Controls

with Radiant Cooling

by

Samuel Dalton Borgeson

Master of Science in Architecture

University of California, Berkeley

Professor Gail Brager, Chair

This thesis describes the background, execution and results of a study of the feasibility of mixed-mode building cooling strategies involving radiant systems in California's 16 climate zones. Informed by case studies, building modeling and evaluation literature, detailed climate studies, and past experience, the research team created a parametric building simulation model in EnergyPlus. The simulation model was used in conjunction with Adaptive and Predicted Mean Vote occupant comfort models to evaluate the energy and comfort performance of mixed-mode buildings with radiant cooling by simulating a range of mechanical systems, control strategies, and physical building characteristics in each climate. Energy performance was quantified as $kBtu/ft^2$-yr and comfort was quantified using the percentage of occupant hours with more than 20% of occupants predicted to be dissatisfied, also known as the exceedance percentage. The cooling strategies simulated performed particularly well in moderate coastal climates, but were also able to meet comfort criteria when gains were controlled through building shell improvements and efficient equipment operation. In several climates, the chilled mass of a floor slab charged overnight by water from a cooling tower

was sufficient to preserve comfort throughout the day while using approximately 75% less pump, fan, and chiller energy than a comparable conventional HVAC system. In cases where a cooling tower was insufficient, a chiller was used to improve overnight cooling or to support the all day operation of the slab. The examination of model sensitivity to inputs, and the evaluation of discomfort predicted by the Adaptive Comfort model vs. the Predicted Mean Vote model indicate that site context and occupant expectations will play a significant role in determining the feasibility of mixed-mode cooling strategies. Results are presented graphically to allow comparisons across and within climates and in the form of regional maps that illustrate the geography of potential feasibility of mixed-mode cooling systems.

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Overview

Introduction

Persistent energy, comfort, and health concerns in sealed and mechanically conditioned buildings have led to renewed interest in building operation strategies that involve natural ventilation. However, it is very difficult, particularly in hot climates, to meet modern expectations of thermal comfort in purely naturally ventilated buildings. The idea of mixed-mode building operation is to take advantage of favorable conditions to make use of natural ventilation as often as possible, with scaled down mechanical systems used to preserve comfort under less favorable conditions. There are many possible strategies for choosing equipment and control strategies for mixed-mode building operation but one that has been attracting attention due to its favorable energy performance and occupant satisfaction is hydronic radiant cooling via chilled slabs, walls, or strategically placed panels. This work uses information gathered from existing buildings and simulation modeling to test the efficacy of mixed-mode strategies utilizing radiant cooling in California climates. Particular attention was paid to metrics of energy consumption and comfort designed to provide quantitative values for assessing performance.

Project objectives

The goal of this project has been to use building simulation to better characterize the energy and comfort implications of mixed-mode building operation with radiant cooling in California climates. The products of this work are intended to be accessible to building industry professionals, interested lay people, and decision makers at energy utilities and

regulatory agencies, but care has been taken to provide the methodological and technical details expected of academic work. Informed by these goals, the objectives were:

- To develop metrics to quantify and allow comparison of the energy and comfort performance of simulated or real mixed-mode buildings.

- To use lessons learned from successful mixed-mode buildings to inform the design and operation of the simulation models.

- To use simulation outcomes to quantify energy consumption and thermal comfort under varying building systems and control strategies across all 16 California climate zones.

- To provide design guidance via graphical summaries of simulation results.

Project outcomes

The high level outcome of this project is that mixed-mode strategies could save substantial energy over conventional air conditioning in many California climates without sacrificing occupant comfort or satisfaction. The basis for this statement comes from two different types of evaluation. Previous work assessing existing mixed-mode building performance has documented generally high levels of occupant satisfaction (Brager and Baker 2009) and substantial energy savings over comparable building utilizing conventional conditioning strategies. The simulation runs executed in support of this work demonstrate that well tuned mixed-mode strategies can deliver energy savings while preserving thermal comfort in coastal climate zones. Specifically, a mixed-mode system employing a cooling tower to charge a radiant slab overnight was found to use ~75% less cooling and ventilation energy than a conventional variable-air-volume air conditioning system in coastal climates. The strategy of cooling the slab overnight and free running during the day also promises near zero energy usage during periods of peak

electricity demand (late summer afternoons). However, comfort outcomes in warmer climates, which tend to be inland in California, range from probably acceptable to most likely unacceptable. On a state-wide basis, this yields a technical savings potential is ~30% of commercial building cooling.

Parametric sensitivity studies revealed that comfort in buildings in marginal climates is sensitive to internal and external heat gains, envelope performance, proper window operation, occupant behavior, and other site specific details. However, predicted comfort outcomes can also be extremely sensitive to the choice of comfort model applied. Of particular interest in this regard are the adaptive comfort model (de Dear and Brager 1998), which is derived from empirical data from naturally ventilated spaces, and the Fanger Predicted People Dissatisfied (PPD) model (Fanger 1970), which is more applicable to sealed conditioned spaces. Mixed-mode buildings strive to occupy the grey area between entirely naturally ventilated and completely sealed. Thus there is good reason to conclude that they have the potential to occupy the full range of outcomes bracketed by the adaptive comfort and PPD models. The above sensitivities underscore the significant contribution of competent low-energy and passive design and construction and occupant expectations and behavior in successful mixed-mode building operation.

This project required the development of novel tools and techniques to assess the potential of mixed-mode buildings, specifically those with radiant slab cooling and natural ventilation. Further development of such tools and techniques will be required to facilitate the predictable success of larger numbers of mixed-mode buildings.

Conclusions

- Many California climates are strong candidates for low energy cooling strategies, including mixed-mode operation with radiant cooling.

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- Predicted thermal comfort is very sensitive to both internal and external heat gains, so designers and occupants of mixed-mode buildings must take care to minimize gains.

- The sensitivity of modeled outcomes to bracketed climate and operational parameters underscores that higher performing buildings are more strongly influenced by environmental conditions than their sealed counterparts and that occupant expectations exert significant influence on the success or failure of mixed-mode buildings.

- Site-specific conditions influence the success of mixed-mode building strategies, and owners and occupants of such buildings must expect a more dynamic thermal environment. For a given indoor temperature, promotion of natural ventilation and occupant control, which statistically correlate with the adaptive comfort model, should help achieve greater thermal satisfaction.

Recommendations

- Mixed-mode building strategies with radiant cooling should be encouraged in California's mild climates. In the most favorable climates, air conditioning could be the exception rather than the rule for most types of commercial buildings.

- Mixed-model building designers should work first to minimize internal equipment gains, and external gains via well insulated and air tight building shells with shaded facades incorporating sensible window to wall ratios with windows designed to minimize solar heat gain.

- Better data on building energy performance and occupant expectations should be gathered over time to further characterize which strategies are working in the highly diverse building stock.

- The ability to model occupant behavior, particularly window operation, in simulation software should be prioritized when modeling high performance buildings with operable windows.

- Further research will be required to determine what conditions determine which comfort model is applicable to specific mixed-mode buildings.

Introduction

California has aggressive energy efficiency and climate mitigation targets. Solutions capable of dramatically reducing cooling and ventilation energy consumption are expected to be integral to future planning in the state. Cooling and ventilation together accounted for approximately 27% of California commercial building electricity consumption in the 2006 California Commercial End-Use Survey, also known as CEUS (Itron 2006). Ventilation fans account for 12% of consumption around 14% of peak demand. Cooling accounts for 15% of consumption and approximately 40% of peak demand. With a large coastal population, fairly modest humidity, and larger diurnal swings associated with its hotter climates, much of California is very well suited to control strategies that utilize thermal mass and radiant systems that take advantage of free or dramatically more efficient nighttime cooling to reduce cooling energy demand. Thus, buildings that are cooled by a combination of natural ventilation and radiant systems stand to play an important role in California's mitigation plans.

There are a number of documented benefits of operable windows, including thermal comfort over a wider acceptable range of indoor temperatures (de Dear and Brager 1998), and fewer Sick Building Syndrome symptoms (Seppanen and Fisk 2002). These benefits are being demonstrated in a number of new, naturally ventilated buildings in the coastal regions of California. But even with all these potential benefits, there are a variety of concerns and design challenges associated with operable windows. The ability to rely solely on natural ventilation for cooling is limited by loads and climate. Given modern-

day conditioning expectations, engineers, owners, and occupants are often uncomfortable with the lack of predictability and control over thermal conditions in naturally ventilated buildings. As a result, many innovative engineers are exploring "mixed-mode" buildings, which combine features of naturally ventilated and air-conditioned buildings to extend the range of climates in which operable windows are feasible.

Mixed-mode buildings that utilize radiant cooling are well suited to many California climates. Low humidity obviates the need for dehumidification of outside air and allows radiant cooling systems to operate with minimal risk of condensation. Generally moderate temperatures keep cooling loads manageable and cool nights support free cooling. When applicable, radiant cooling can provide a multitude of benefits while utilizing a fraction of the energy required for air conditioning. Radiant systems perform heat exchange across large surfaces (e.g. entire floors or ceilings), and are thus able to achieve the desired rates of heat exchange with relatively high surface temperatures. This in turn allows higher water supply temperatures, which can often be met by cooling towers, heat exchange with the night sky, ground coupled heat exchangers or other low energy, compressor-less cooling strategies. With operable vents and windows addressing ventilation requirements, radiant systems can eliminate the need for air handling equipment by meeting cooling loads without chilled air. Because radiant systems decrease the Mean Radiant Temperature (MRT) experienced by occupants, they can preserve thermal comfort for higher Dry Bulb Temperatures (a.k.a. air temperatures). Radiant cooling strategies often utilize the mass of a poured concrete slab or a water storage tank to store thermal energy over time. Thus, low overnight temperatures can be used to support daytime cooling. Two common approaches are night ventilation, which

utilizes outside air to cool radiant surfaces, and cooling towers that chill water to temperatures approaching the wet bulb that is either stored in a tank or used to cool or "charge" the slab. Mixed-mode buildings with radiant cooling can thus extend the energy and comfort benefits of natural ventilation to the warmer inland climates where air-conditioning is generally the norm.

However, there are also challenges associated with mixed-mode radiant systems. Successful utilization of thermal storage, which is characterized by time constants proportional to the heat capacity and mass of the storage material, requires some ability to predict cooling loads in advance. Misjudgments can lead to conditions that are either too hot or too cold as the temperature of the radiant system lags behind the optimal conditions. For example, on cool mornings, charged slabs can create conditions of cold discomfort even though they will later be used to offset heat discomfort, and inadequately chilled or undersized slabs can fail to maintain comfortable conditions, particularly on hot afternoons. Furthermore, the rate of heat exchange between a radiant surface and a building occupant is effectively limited by the temperature difference between the two. The difference in temperature is in turn limited by concerns over condensation forming on radiant surfaces, and occupant discomfort associated with radiant asymmetry. If the internal and external heat gains outpace the heat exchange with the slab, it can become very difficult to maintain comfortable conditions. Finally, like all radiant systems, radiant cooling systems rely on direct line of sight visibility between occupants cooling surfaces. This requirement can lead to hot or cold spots based on room geometry and impact furnishing options and room acoustics.

For all of the above reasons, there is a need for tools and information that support sound decision making on the design and operation of mixed-mode building utilizing radiant systems. In particular there is a need for improved simulation tools that can model the conditions under which such systems will tend to succeed or fail and climate calibrated guidelines to help designers and owners understand the factors that impact the viability of mixed-mode cooling. The overall goal of this project was to employ building energy modeling, based on real world case studies, to quantify the energy savings potential of natural ventilation and mixed-mode operational strategies in California's 16 climate zones and to present that information in tabular and graphical formats. This work is intended to support designers and building owners in their pursuit of high performance buildings, utility program planners, policy-makers as they contemplate energy reduction goals and future building standards, and building researchers in their search for appropriate metrics, modeling tools, and processes for the widespread delivery of successful mixed-mode buildings.

State of comfort metrics in industry

To better understand the nature of discussions leading building engineers are having with their clients about comfort and exceedance, we conducted an *informal* survey of professionals in our personal networks, affiliated with the Center for the Built Environment at UC Berkeley, or who have contributed to or benefitted from past research. The majority of the professionals we spoke to work in the US. While we are not prepared to present our findings as anything other than anecdotal, we were pleased to see consistency of experience across firms and project types. We asked:

1) How the topic of exceedance is approached with clients (it can be delicate to explain that comfort is not 100% guaranteed).

2) What metrics of exceedance are used during design and in communication with clients.

3) How comfort performance expectations are captured in agreements between designers and clients.

Conversations with clients

Exceedance is rarely discussed explicitly. The concept does come up, but via a wide range of metrics that get at the idea that some low energy spaces may not be equipped to meet setpoints under the most extreme weather conditions. Internally, several of the firms we contacted calculate metrics designed to capture the spirit of exceedance, but they note that there are not universally agreed 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[1].

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[1] It is tantalizing to consider the potential conflict between these assumptions and some of the mechanisms believed to be behind adaptive comfort outcomes.

Metrics of discomfort/exceedance

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

Agreements on delivered comfort performance

Based on our interviews, it is clear that contractual or other binding agreements on delivered comfort are rare. The consensus seems to be that these could appear over time, but many important aspects of the design and associated targets are not sufficiently fleshed out to support binding comfort targets at the time the contracts are signed. The acceptability of and risks associated with specific cooling strategies are hashed 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 designers consider in the course of designing low energy buildings.

Standards

The motivation for our investigation into the nature of exceedance in mixed-model buildings is that, largely due to concerns about energy use, such buildings are

increasingly common but it is unclear how they should approach the tradeoffs between energy and amenities like thermal comfort. We are not the first to make this observation. In a document on the development of European standards, Olesen 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" (Olesen 2007). Despite the need, the current ASHRAE Standard 55 does not offer much guidance on comfort in mixed-mode buildings. Its wording restricts the use of the adaptive comfort model to purely naturally ventilated buildings, which are rare in the U.S. In Europe, where the adaptive comfort applies to "free running" buildings, which can include mixed-model buildings not applying mechanical cooling, standards have recently begun to explicitly address exceedance. Namely, CEN EN15251 has exceedance calculations and recommendations on acceptance in its Annexes F and G (CEN 2007). However, this is not to say that it proposes a definitive standard. Annex F on the "long term evaluation of the general thermal comfort conditions" describes the following three exceedance metrics:

- **Percentage outside the range:** The percent of occupied hours (those during which the building is occupied) when the PMV of the operative temperature is outside a specified range.
- **Degree hours criteria:** The time during which the actual operative temperature exceeds the specified comfort range during occupied hours is weighted by a factor which is a function of the number of degrees beyond the range.
- **PPD weighted criteria:** The accumulated time outside the range is weighted by Fanger's percentage of people dissatisfied formula.

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The standard goes on to recommend appropriate exceedance values. "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" (Olesen, Seppanen et al. 2006). If anything, the diversity of calculations methods and the rough nature of the guidance on maximum exceedance underscore the rough nature of the state of long term comfort evaluation.

Methods

This study utilized a hybrid project approach that drew upon simulation outcomes as well as case studies of existing buildings to better understand the performance and limitations of mixed-mode buildings that utilize radiant cooling. The project team used case study buildings for background research, and custom built models in EnergyPlus for parametric studies. The simulation strategy itself was informed by several sources. There has been steady progress modeling mixed-mode and radiant systems through recent work (Henze, Felsmann et al. 2008; Spindler and Norford 2009; Spindler and Norford 2009) and there are a handful of sources that offer design guidance on mixed-mode and naturally ventilated buildings (Jaunzens 2000; Heiselberg 2002; CIBSE 2005). The main EnergyPlus simulation model for this work is based on the Kirsch Center at DeAnza College in Cupertino, CA. It is a two story, 20,000 ft^2 (1,800 m^2) building designed from the ground up to be mixed-mode that has many features, including orientation, massing, shading, window placement, and floor plate dimensions that enhance natural ventilation and minimize heat gains.

Using various permutations of configuration options for the model, project team members ran a set of parametric studies that spanned all 16 official CA climate zones[2] with system sizing and operational and control strategies tuned to each climate. The outputs of these runs (which are large spread sheets) were then distilled into climate specific performance metrics and regional advice for the design of mixed-mode buildings. The results were also compared to rules of thumb used in industry and to the known performance of case study buildings. Simulation data were also used to color maps of California based on the climatic feasibility of mixed-mode strategies. Finally, the simulation data were used to calculate the energy savings and emissions mitigation potentially associated with mixed-mode strategies compared to purely mechanical cooling systems in California.

Best practice case studies

Sources of information for best practice case studies included a variety of building databases, including:

- CBE database of mixed-mode buildings (http://cbesurvey.org/mixedmode/database.asp)

- New Buildings Institute buildings database for high-performance buildings that have typically met or exceeded a 50% beyond code requirement for the energy use. http://www.advancedbuildings.net)

- US DOE Buildings Database (http://eere.buildinggreen.com/)

- USGBC LEED Project Lists (http://www.usgbc.org/DisplayPage.aspx?CMSPageID=1452)

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[2] As defined by the California Energy Commission to support the Title 24 building code and standardized through typical meteorological year weather data files available for each zone.

- NRDC Case Studies (http://www.nrdc.org/buildinggreen/casestudies/default.asp)

- NREL Building Research (http://www.nrel.gov/buildings/projects.html)

- AIA/COTE Top Green Projects (http://www.aiatopten.org/hpb/)

- Betterbricks Success Stories
  (http://www.betterbricks.com/default.aspx?pid=successstories)

In addition to the databases described above, additional sources of information for this more specific data included literature review, building documentation such as design and operations specifications, and interviews with architects, design engineers, building operations engineers, and facility managers. Actual control sequences and algorithms for existing buildings are not typically published, and often can only be obtained directly from the building engineer – a task that was much more difficult than originally anticipated.

Project team members discussed mixed-mode building operation in general and specific modeling and evaluations tasks with many academics, engineers, building owners, and occupants. Depending on the relevant experience of the professional interviewed, questions addressed topics such as building energy use, thermal storage and predictive control, humidity risks, industry practice and rules of thumb, thermal comfort, indoor environmental quality, costs (first vs. life-cycle), ease and quality of manual control, ease and quality of automatic control, variable seasonal requirements, impact of operable windows on acoustics, security, etc.

The project team identified the Kirsch Building at De Anza College in Cupertino as the most suitable case study building to use as the basis for the building simulation model. The building was designed from the ground up to support mixed-mode operation

with radiant cooling, has an excellent record of occupant comfort, and both design team members and occupants were available to provide additional information as needed. A site visit was conducted along with initial occupant interviews, and building stakeholders provided a full set of drawings and mechanical system documentation. Efforts to find a retrofit case study generated a list of 30 non-residential renovation projects, including 17 in California, in which there was a deliberate decision to retain or re-introduce natural ventilation in the retrofit. Office buildings were listed into categories of pre-1940's/historic preservation, non-historic modernization, and more significant re-design or adaptive reuse. Unfortunately, none of the case studies were sufficiently prototypical to be useful as the basis for simulation. Examples of buildings investigated closely but dismissed as case studies included a building that will not be retrofit until it is leased, a building whose occupants declined to participate in the study, and a building too early in its retrofit planning to have settled on a retrofit strategy. The alternate approach was explored in a preliminary manner using a modified (sub-optimal shading, glazing, massing) version of the Kirsch Center model with an actively cooled low mass panel system.

Measured performance assessments

Post-occupancy evaluations (POE), conducted prior to the work described in this thesis, utilized the CBE web-based Indoor Environmental Quality survey. In addition to basic questions about demographics and workspace descriptions, the core CBE survey measures occupant satisfaction and self-reported productivity related to nine environmental categories: office layout, office furnishings, thermal comfort, air quality, lighting, acoustics, cleanliness and maintenance, overall satisfaction with the building,

and with the workspace. Satisfaction questions use a consistent 7-point scale ranging from "very satisfied" (coded as 3) to "very dissatisfied" (-3), with a neutral midpoint (0). Outside the scope of this thesis, the survey was conducted in 12 mixed-mode buildings, and the results were compared to overall benchmarking survey database of 370 buildings, with over 43,000 individual responses (Brager and Baker 2009).

Based on a review of literature and interviews with other researchers and professionals involved with mixed-mode buildings, the project team identified systems for classifying mixed-mode buildings based on their operation strategies. These systems typically differentiate operating strategies using temporal and spatial criteria. For example, natural ventilation and mechanical cooling can operate in the same or different spaces, or at the same or different times. This work led to a more nuanced classification system based on the design decision-making process and the reality that many well-designed systems simultaneously draw upon multiple categories from the traditionally used taxonomy. See the separate publication, "Control Strategies for Mixed-Mode Buildings"(Brager, Borgeson et al. 2007)[3], from the Center for the Built Environment for a detailed analysis based on this work.

Performance metrics for simulation outcomes

Compared to their conventional counterparts, well-designed mixed-mode buildings can deliver similar or improved occupant comfort while using less energy. The process for identifying performance metrics therefore focused on energy and comfort.

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[3]Available at the time of writing at
http://www.cbe.berkeley.edu/research/pdf_files/SR_MixedModeControls2007.pdf

Energy metrics

Energy metrics were directly quantifiable as kBtu/ft^2-yr of cooling energy. This metric was defined as the annual amount of cooling energy demanded (the sum of energy use reported in the simulation output files for the fans, pumps, and equipment used to cool the building), divided by the total building floor space. This value is also known as the *cooling energy intensity* and is what was used for comparisons between simulation runs.

There is a caveat to this use of the energy intensity metric. The thermal storage associated with a slab radiant system can transfer cooling energy expended over night for use in daytime cooling. However, with large diurnal swings, it is possible that charging the slab overnight will result in conditions that are too cool in the morning. In this case, one would expect some form of heating to be used for part of the morning to offset the chilling effect of the slab. Researchers did not attempt to quantify this effect in this study, but it does merit further investigation. Preliminary investigation into discomfort in modeled outcomes indicates that slabs chilled overnight do indeed increase the frequency of instances of morning chill.

Comfort metrics

Comfort is an inherently subjective criterion, but studies of building occupants have derived durable empirical relationships between environmental conditions and self reported comfort. Two obvious candidates for the work were the Fanger model of thermal comfort (Fanger 1970), which was derived from controlled studies in environmental chambers, and the adaptive comfort model (de Dear and Brager 1998), which was derived from statistical analysis of comfort survey results from naturally ventilated

buildings and continues to be verified by independent research (Moujalled, Cantin et al. 2008).

Both the PMV model and the adaptive comfort model describe a comfort zone outside of which occupants will tend to be increasingly dissatisfied. The project team looked at how these models and their comfort zones were being applied in the design and operation of buildings in practice and adopted the idea of hours of exceedance (occupied hours outside of the comfort zone) as the primary comfort metric used on the project. For this work, the percentage of occupied hours where conditions exceed the 20% dissatisfied threshold (on the warm side), weighted by occupancy (which depends on time of day) was used. More precisely, the following formula was used to calculate exceedance:

$$Exceedance_M = \sum_{t=0}^{all\ hours} \begin{matrix} n_t \ if \ discomfort_M > 20\% \\ 0 \ if \ discomfort_M \le 20\% \end{matrix} \Bigg/ \sum_{t=0}^{all\ hours} n_t$$

Where n_t = 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 cutoff at 20% percent dissatisfied can create a particular sensitivity to values that just happen to be on one side or the other of the threshold.

For $Exceedance_{PPD}$, we used the standard PMV/PPD calculations to determine the percentage of occupants dissatisfied as originally described by Fanger in 1970 and implemented in EnergyPlus. For $Exceedance_{adaptive}$ we used the adaptive comfort calculation methodology used by ASHRAE Standard 55:

$$T_{comf} = 0.31\ T_{a,out} + 17.8°C$$

Where T_{comf} is the "optimum comfort temperature" and $T_{a,out}$ is the mean outdoor dry

bulb temperature for the previous month. T_{comf} has an envelope of ±2.5C around it that

defines 90% acceptability and ±3.5C for 80% acceptability (de Dear and Brager 2002).

This is similar to, but slightly different from the calculation used in the European

EN15251 standard (Nicol and Humphreys 2010).

Figure 1 below presents the adaptive comfort zone and provides a scatter plot of

indoor temperature vs. a 10 day running average of outdoor temperature for every

occupied hour from May to September for climate zone 6. Areas represent neutral

comfort (white/middle) and predicted hot (red/top) and cold (blue/bottom) conditions.

The scattered points represent hourly indoor conditions during occupied periods between

May and September and the bars at the bottom tabulate the percentage of time the model

spent in each comfort category, with the bar furthest to the right serving as the "hot

exceedance" percentage, similar to Exceedance$_{adaptive}$ described above (except for the

weighting by occupancy).
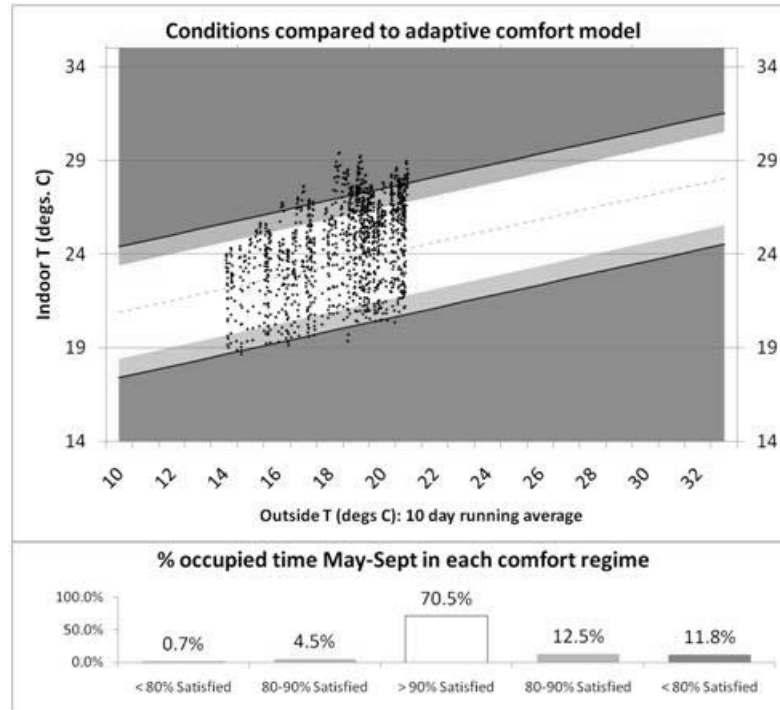
Figure 1: Adaptive comfort summary for the natural ventilation case for climate zone six.

The adaptive comfort model uses an "optimum comfort temperature", T_{comf} (represented as a dashed grey line running down the center of the white zone) described by the regression formula: $T_{comf} = 0.31\ T_{a,out} + 17.8$ °C and thresholds at ±2.5°C for 10% of people dissatisfied and ±3.5°C for 20% of people dissatisfied. On the hot side, the light red band is between 10% and 20% or people dissatisfied, and the darker red area is >20% of people dissatisfied. Each data point plotted represents an hour of simulated time, but only the occupied hours (which are illustrated in Figure 3) between the beginning of May and the end of September are represented. The percentage of points in the neutral band, the 10-20% band for both hot and cold, and the > 20% for both hot and cold are tabulated and presented across the bottom of each chart. This study has been focused on percentage of points in the dark red > 20% too hot area. That percentage is also known as the exceedance percentage, which is used extensively in the results section of this thesis.

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Appendix C provides similar adaptive comfort visualizations for several system

configurations across all climates.

Climate analysis

Cooling loads and mechanical system performance are strongly influenced by

weather conditions and climate in general. This is especially true for systems that

incorporate natural ventilation and radiant cooling. Because they have a lower overall

cooling capacity, comfort in mixed-mode buildings with radiant cooling will tend to be

more sensitive to external heat gains. Because they often rely on free cooling (facilitated

by evaporative chillers or cooling towers) and/or night cooling, and risk condensation on

their chiller surfaces, their energy consumption and control strategies are also particularly

sensitive to climate conditions (including dew point and overnight temperatures in

addition to the more obvious air temperature and solar intensity). It should therefore be

possible to develop "rule of thumb" metrics based on simplified calculations to aid the

process of determining the suitability of mixed-mode strategies in a given climate and to

support the design process and operations of mixed-mode buildings. Some practitioners

have already highlighted several candidate metrics. In an article title "Finding the Right

Mix" in the ASHRAE Journal, Erin McConahey documented a set of 10 "Feasibility

Questions" that can be used to determine the likely feasibility of natural ventilation and

mixed-mode operating strategies (McConahey 2008). Of these, six were related directly

to climate. Inspired by these rules of thumb, the project team undertook an analysis of

TMY2 weather data files for each climate zone with a focus on characterizing the

climatic compatibility with natural ventilation and low energy cooling strategies.

Model construction

After initial prototyping exercises, technical team members used the Open Studio EnergyPlus plug-in for SketchUp to develop a detailed 24-zone model of the Kirsch Center, including its mechanical systems. This model was found to be unnecessarily complex to configure and slow to run, so it was simplified into a fast running 6-zone model with little observed change in the annual and monthly summary statistics related to energy, comfort, and system performance that the project called for. The model consists of six thermal zones with 3 on each floor. Two zones on each floor are 336 m^2 (3600 ft^2) and one is 234 m^2 (2500 ft^2), for a total of approximately 1,800 m^2 (20,000 ft^2).
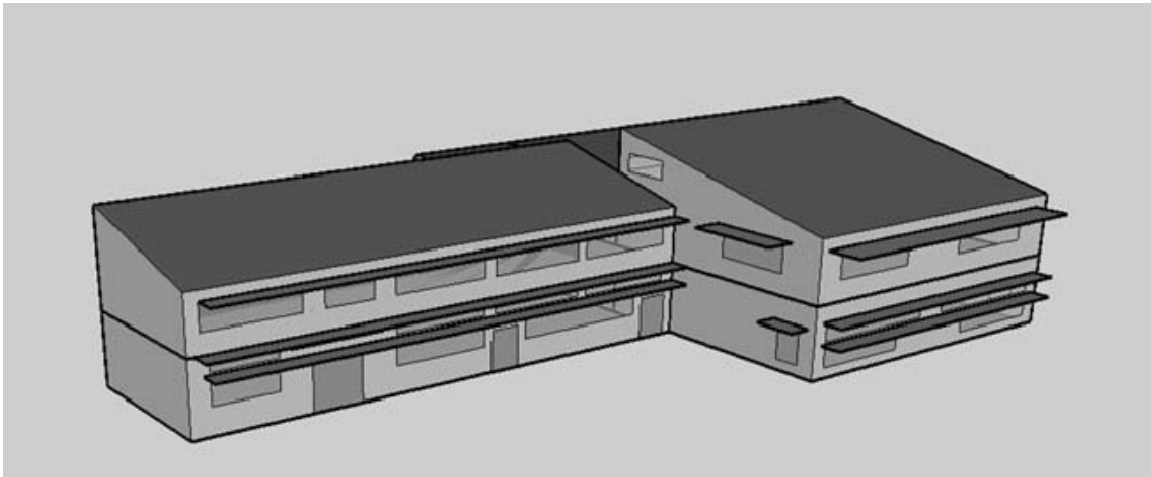
Figure 2: Rendering of six zone EnergyPlus model in Sketch-Up. The two zones to the left are considered "wings", the two in the front right side are "classrooms" and the two mostly out of view in the back right are "office". The names come from the usage of the case study building, but all zones are configured with typical office loads and occupancy.

The simulation model uses include files ("imf" file extension), conditional logic, and a set of centralized configuration parameters to support operation using natural ventilation only, mechanical only, or mixed-mode conditioning strategies. Table 1 below provides a summary of the range of simulated cooling strategies.

Cooling strategy	Characteristics	Comments
VAV	Sealed windows; variable air volume (VAV) air conditioning (AC) "autosized" as appropriate to each climate	Best case for "standard" AC based design
NV	Fully operable windows; night ventilation; no mechanical systems involved in cooling	Poor comfort performance in most climates
MM	Base mixed-mode case; radiant slab; manual operable windows; cooling tower charges slab to 18˚C overnight (10pm to 10am)	Risk of over cooling in the mornings; approximately 75% energy reduction over VAV
MM Chiller	Same as above, except cooling tower assisted by chiller; no active daytime conditioning	More energy use and hard to algorithmically prioritize free cooling, but guaranteed slab performance; good for hot nights
MM All Day Chiller	Same as above, except chiller is actively maintaining slab setpoint all day	Most energy use of MM options, but allows for more flexibility, including time varying slab setpoints and holding setpoint even on hot days; most complex control

Table 1: Summary of cooling strategy options available as configuration options in the simulation model. The names used here are consistent with those used in later discussion.

The model features internal gains, infiltration rates, R-values, window characteristics, and mechanical system performance assumptions that represent best practice performance for mechanical systems, lighting, windows, insulation, and internal gains (except when variations of the above were being studied). For example, both lighting and equipment power density default to 10 W/m^2 (which is lower than average). Ventilation rates were modeled using both scheduled infiltration rates (for simplicity) and a more complex AirFlow Network, which is a bulk air flow model built into EnergyPlus. The "realism" achieved by the airflow network did not alter comfort results sufficiently to offset its computational costs in the comparative parametric studies that form the basis of this paper (see the discussion surrounding Figure 4 below), so infiltration rates (scaled proportional to outdoor temperature) were scheduled to provide a proxy for window operation.

The variable definition, function definition, and file-include features of the macro language in EnergyPlus were used to allow natural ventilation, radiant cooling, variable-air-volume HVAC, and many other physical and operational parameters to be individually activated and controlled in each zone. Variations of the values of those parameters were in turn used to support parametric studies of the effects of key model inputs, including internal gains, shell performance, ventilation performance, operating control strategies, mechanical systems, and thermal mass on occupant comfort and energy consumption. Standard and CSV file based schedules for EnergyPlus were used to specify building and equipment control timing. Figure 3 below presents a visualization of the simple equipment, lighting, and occupancy schedules used for weekdays.
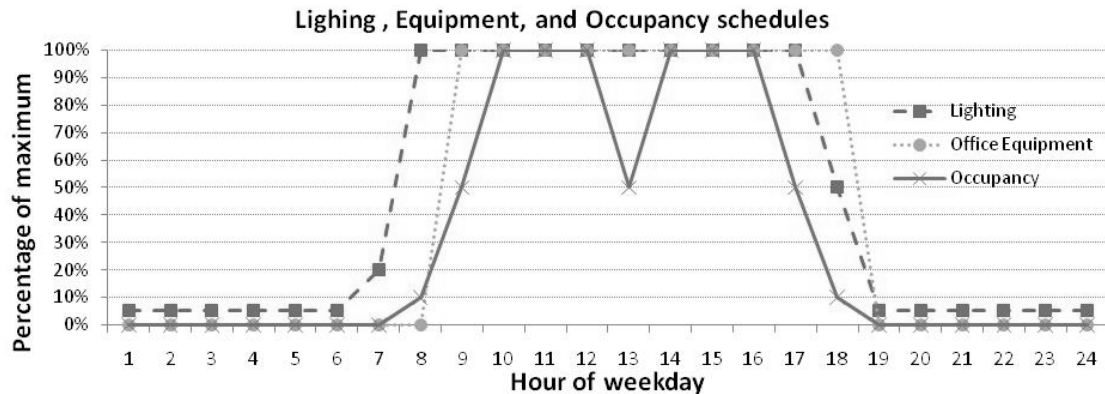
Figure 3: Schedules for lighting and equipment gains and occupancy for weekdays. For reference, the first to peak is lighting, second to peak is office equipment, and the third is occupancy. Typical buildings will have more lighting and equipment activity over night, but the simulation model assumes very aggressive load curtailment.

To cool the floor slab overnight, a cooling tower was configured with a maximum air flow rate on 9.45 m^3/s producing max chilled water flow rates of 1.8 to 17.3 l/h-m^2 or 0.04 to 0.42 gallons/h-ft^2 with the specific value required determined by the cooling load created by simulated climate conditions.

Natural ventilation

One of the biggest challenges in conducting simulations was how to address the air movement that is essential to the performance of naturally ventilated buildings. For a basic overview of the fluid dynamics and bulk flow equations behind both wind and stack driven ventilation drawn in large part from ASHRAE's Handbook of Fundamentals, see Appendix B of this thesis. Simulation outcomes for natural ventilation are highly sensitive to model inputs because of the non-linear nature of air movement and the prevalence of transient wind conditions. This is especially true for the pressure coefficients used to determine how wind pressure translates into airflow through windows (Good, Frisque et al. 2008). The consensus among many experts is that the best results for determining pressure coefficients are achieved through wind tunnel studies of building models. In some cases, CFD models are called for, but they are sensitively dependent on their inputs and time consuming to configure and execute. For the model used in this study, which is intended to offer generalizable results, neither wind tunnel nor CFD models were realistic options. The pressure coefficient inputs into the air flow model in EnergyPlus were generated using a web-based tool called Cp Generator made available for free by TNO[4], a research firm in the Netherlands. Cp Generator is widely regarded as the best available system for determining pressure coefficients (abbreviated as C_p) starting from simple building geometry and is itself based on wind tunnel test results. It has also been validated against other methods in several papers in the literature (Knoll, Phaff et al. 1996; De Wit 1999; Heijmans and Wouters 2002). However, it is by no means infallible.

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[4] Cp Generator was located at http://cpgen.bouw.tno.nl/cp/ at the time of this writing.

Cp Generator coefficients were used on this project as inputs into the EnergyPlus

AirFlow Network features. Due to the inherent uncertainty associated with C_p estimates,

Medium, High and Low values of C_p's, defined as 1x, 2x, and 0.5x the coefficients from

Cp Generator were used to conduct a simple parametric study of the sensitivity of

comfort outcomes to coefficient magnitude. Despite the sensitivity of the details of air

flow to initial conditions, building and window geometry, room furnishings, and wind

speed and direction, the annual values for our calculated comfort metrics were robust to

variation. Figure 4 below illustrates the results of the test of the effect of C_p strength on

exceedance.
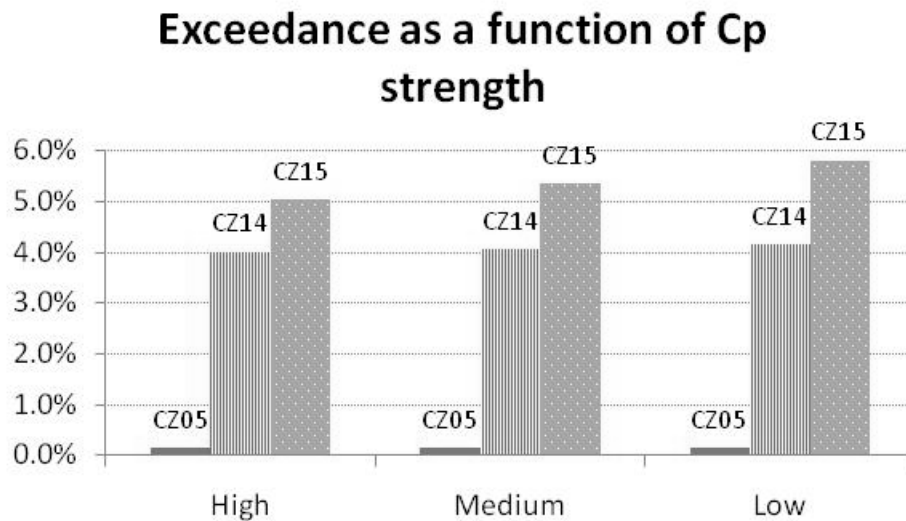
Figure 4: Exceedance values from a mixed-mode simulation for three exemplary climate zones: 5, 14, and 15. "High" values are double the values from Cp Generator, "Medium" are the unaltered values, and "Low" are one half the values.

This result justifies the use of admittedly approximate C_p values, but also supports the

substitution of a simplified (and dramatically faster) approach to simulating ventilation

using a schedule of infiltration rates for time sensitive parametric model runs. The

substitution options are discussed further in the Window Control section that follows.

Window control

Even though the simulation model was found to be insensitive to the pressure coefficients that determine the flow rates in AirFlow Networks in EnergyPlus, the questions of how windows are controlled is of central importance to the design and operation of naturally ventilated spaces with ramifications for comfort, energy use, and system control strategies. As the modeling efforts progressed, it became increasingly clear that manual controls, particularly occupant decisions to open and close windows, are poorly represented in standard simulation tools, including EnergyPlus. A literature review of occupant behavior with respect to operable windows identified many recent journal articles (Nicol 2001; Raja, Nicol et al. 2001; Nicol and Humphreys 2004; Pfafferott and Herkel 2007; Rijal, Nicol et al. 2007; Rijal, Tuohy et al. 2007; Yun and Steemers 2008; Rijal, Tuohy et al. 2008a) and several pieces of grey literature that directly addressed the question of improving models of occupant control over windows. Based on the literature, the research team identified models of both probabilistic and time dependent window operation strategies that take various environmental conditions (e.g. inside and outside temperature, humidity, wind speed, time of day, etc.) as their inputs. The volume of recent publications on window control, particularly those from European sources, indicates a high level of interest in better understanding window operation within the research community. There are now several models to choose from, but human behavior is quite complex and there is no clear consensus on which approaches can be most reliably generalized.

The key points of *overlap* in the literature that are particularly relevant to this project are:

- Human behavior is not *deterministic*, but aggregate tendencies are recognizable in the data that has been collected. Models based on the *probability* of observed phenomena (like window opening and closing actions) are best suited to capturing such behavior.

- *Stochastic* (i.e. probabilistic) modeling can take several forms. Some can be simple functions that spit out the probability of a window being open given a set of environmental conditions as inputs, while others like Markov chains[5] and survival analysis[6] can use the current state of the window or other time varying factors to influence the outcome.

- People do not typically manage their windows actively or regularly throughout the day. Thus, most opening and closing behavior is associated with arrival and departure from the office. It can also be seen that windows tend to be left in the state they are already in. These facts introduce a time dimension into models and suggest that different times of day or different window states might require their own probability functions.

- Temperature is still the most important driver in most models, but context really does matter. For example, there is substantial seasonal variation of window control probabilities at the same outdoor temperature and behavior is demonstrably different when window access is shared and on windy days.

The key points of *difference* in the literature are:

- Interestingly, there is not consensus about whether indoor temperature or outdoor temperature is dominant in determining behavior. They tend to co-vary in naturally ventilated buildings, and even as indoor temperature produces the discomfort that triggers window opening, the acceptability of the open window will be determined by the conditions outside. Models using either or both can produce good results.

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[5] Markov chains describe mathematically processes where the probability of transitioning into the next state depends only on the current state.
[6] Survival analysis involves looking at how long and under what conditions a system is likely to remain in the same state. It give a sense of the "inertia" of a given state.

- Some models focus on the temporal aspects of window control (occupant arrival and departure, and evolution given a particular window state), others focus on the thermal comfort aspects (T_{in}, T_{out}, adaptive comfort modeling, etc.), and some account for both. While they are not mutually exclusive, polite disagreement over the importance of each is evident.

- The data underlying each research project seems to influence what type of model is viable. Studies with good temporal resolution are the ones that spot temporal patterns and try to account for them. Studies with data from many buildings can tease out site specific variation. Studies with detailed information on indoor environmental conditions can model comfort and air quality related behavior.

The *key take away* messages relevant to modeling and building controls are:

- Further development of simulation and control software based on stochastic models of occupant behavior is needed to support the delivery of comfortable and usable low energy buildings. Specifically, work needs to be done in EnergyPlus to incorporate runtime building temperatures into stochastic models of occupant window control based on the models from recent publications (Pfafferott and Herkel 2007; Haldi and Robinson 2008; Hellwig, Antretter et al. 2008; Herkel, Knapp et al. 2008; Humphreys, Nicol et al. 2008; Yun and Steemers 2008).

- Empirical studies of mixed-mode and natural ventilated buildings are needed to better understand the energy and comfort consequences of building control strategies that interact with human behaviors. Specifically, work must be undertaken to better characterize the relationship between comfort and manual controls in existing mixed-mode buildings. There is, presumably, a transition between adaptive and static comfort models as buildings move along a mixed-mode gradient from free running natural ventilation to completely sealed. If this transition can be better understood, building designers and engineers ought to be able to take advantage of the flexibility of adaptive comfort to deliver low energy cooling strategies in increasingly hot and humid climates.

The results of the literature review on the subject of window control that includes the above findings can be found in the 2008 Center for the Built Environment publication "Occupant Control of Windows: Accounting for Human Behavior in Building Simulation" (Borgeson 2008)[7].

Window control in EnergyPlus

The window control simulation capabilities of EnergyPlus do not extend to the type of stochastic models being developed at the leading edge of window behavior research. For this reason, the model used for this project contained simplified controls that were within the current capabilities of EnergyPlus but based on insights drawn from the window control literature. When using the AirFlow Network[8], the "Ventilation Control Mode" was set to temperature[9]. The "Vent Temperature Schedule", which provides an hourly schedule of minimum window operating temperatures, was based on calculated minimum adaptive comfort thresholds (meaning $T_{comf} - 3.5°C$). The "Minimum Venting Opening Factor" was set to 0.05, the "Lower Limit For Maximum Venting Open Factor", which is the number of degrees above the scheduled minimum temperature at which the windows begin to be closed, was 5°C and the "Upper Limit for Minimun Venting Open Factor", which is the number of degrees above the scheduled minimum temperature at which the window is closed all the way to its minimum opening value, was set to 10°C.

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[7] The paper can be found at http://www.cbe.berkeley.edu/research/pdf_files/Borgeson2008-OperableWindowSimulation.pdf at the time of this writing.
[8] See the EnergyPlus Input-Output reference on AirflowNetwork:Multizone:Zone for more details on the configuration of temperature dependant window control. For the EnergyPlus 3.0 version of the reference, this is pp. 709-714.
[9] This is where the degree of the window opening is determined by the indoor and outdoor temperatures. The other options are no ventilation, constant flow, or enthalpy controlled, which takes into account both temperature and humidity.

Because simulations using the full AirflowNetwork were far more time intensive and did not typically produce dramatically different comfort outcomes, the feature was not used for the majority of parametric simulation runs. Instead, it was sufficient to use infiltration rates that were scheduled using occupancy and outdoor temperature values to roughly match expected air flow. Based on the insight that people tend to enjoy the feeling of having a window open, the infiltration rate was scaled on the assumption that windows would be open if outdoor temperatures were moderate and scaled back otherwise. Maximum infiltration rates were set to 5 ACH. Wind driven ventilation can dramatically exceed this value, but this was deemed an appropriate proxy for sub-optimal/average conditions. Minimum infiltration rates were set to 0.2 ACH, which assumes very tight construction. Both a binary open/closed and a linear ramp infiltration multiplier were calculated hourly using weather file data, and they were included in a schedule CSV file compatible with the "Schedule:File" feature of EnergyPlus. For simplicity, the binary option was used for most simulation runs. Figure 5 below illustrates the relationship between outside temperature and scheduled window operation. Note how windows are closed down as temperatures get too hot each day and closed when they are more moderate.
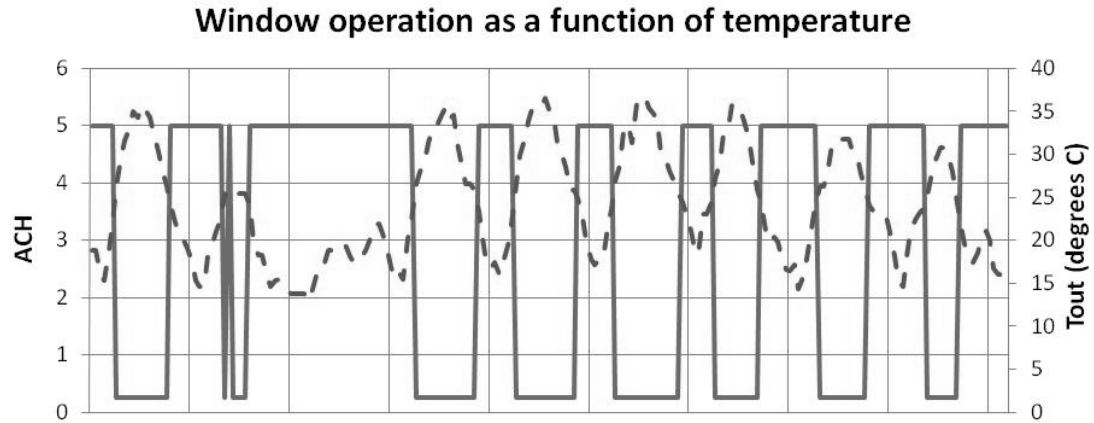
Figure 5: Temperature-responsive scheduled infiltration rates that mimic window operation. Windows (square wave shap) are open with 5 ACH if the outdoor temperature (smoothly varying) is "temperate" between 12 and 25°C and closed to their minimum position otherwise. In the case shown, this rule leads to night ventilation.

Parametric simulation

There are many factors that impact the energy and comfort performance of mixed-mode buildings. They include weather and climate conditions, mechanical system setup and controls, levels of insulation, window type, orientation and size, shading, occupant behavior and preferences, the distribution and amount of building thermal mass, etc. A detailed assessment of all the permutations would require many thousands individual simulation runs and an enormous data analysis effort. To reign in the complexity of the simulation tasks and focus the project work on the most important issues of practical concern, the project team directed its attention to factors surfaced by case study buildings, industry professionals, past mixed-mode research, and the iterative explorations of simulation results. In some cases, the team's areas of interest were further constrained by the limitations of existing modeling tools. The resulting simulation plan, which attempts to cover all topics of interest while minimizing the inevitable complexity, is detailed below.

Project team members used the simulation plan to determine modeling priorities and guide the model features as they were implemented. The simulation framework developed for this project was used to configure, execute, and analyze the parametric runs based on the plan. Additional model tests and analysis were done on an ad-hoc basis using the standard controls available in EnergyPlus.

Climate analysis		
For each climate zone:		
	Quantitative climate analysis displaying climate metrics that are expected to influence cooling loads and radiant/NV system performance	
		Monthly average maximum and minimum temperatures
		Percentage breakdown of time with outside conditions comfortable, cold, hot, or humid
		Cumulative hours with dewpoint at or above 65F or 18C
		Cumulative hours with outdoor temperatures at or above 80F or 27C
		Total number of nights with less than 8 hours below 65F or 18C
Across all climate zones:		
	Quantitative analysis displaying climate metrics that are expected to influence cooling loads and radiant/NV system performance allowing direct comparison of climate zones.	
		Count of temperate months with average max temp. < 80F or 27C and > 32F or 0C
		Fraction of temperate hours between 60-80F or 15.5-27C with rh < 70%
		Total number of hours annually at or above 80F or 27C
		Total number of nights anually that have less than 8 hours below 65F or 18C
		Total number of hours annually with a dew point at or above 65F or 18C
Building simulation		
Using the Kirsch Center model in each climate:		
	Adaptive comfort chart with scatter plot of conditions during occupied hours	
	Design week time series chart with hourly temperatures, energy demand, and comfort	
	Monthly and annual energy consumption calculations	
Using the Kirsch Center model across all climates (n=16):		
	Graphical comparison of energy and comfort values, with bracketed uncertainties	
	Map of California with climat zones shaded according to expected percentage of time indoor conditions exceed comfort criteria	
Sensitivity analysis for representative subset of climates (n=6 for CZ 1, 3, 7, 12, 13, and 15):		
	Comfort and NV effectiveness with high and low pressure coefficients	
	Energy consumption and cooling strategy across:	
	Energy consumption and control strategy	
	Comfort, energy, and humidity	
	Comfort and comfort model	

Table 2: Simulation and analysis plan for EnergyPlus modeling tasks

Simulation framework

The process of developing and running the EnergyPlus building models and interpreting their results included many manual computing tasks that were highly repetitive. Furthermore, the objectives of comparisons across climate zones and between

various operating conditions and inputs required the accurate repetition of hundreds of parametric simulations. To improve the efficiency of model development, support the expedited definition of parametric simulation runs, and standardize the execution and analysis of those runs, the author developed purpose built software tools that augment the EnergyPlus modeling, simulation, and analysis processes. Care was taken to ensure that these tools could be accessible to others and adapted to support future work.

A software toolkit for supporting the setup and execution of EnergyPlus models and the analysis of their outputs was developed using the open source programming language Python. This toolkit is available to others, and is a significant product of this research. The features of the toolkit include the following:

- Weather data analysis
    - A parser for EPW formatted weather files.
    - Data structure and algorithms to compute daily, monthly, and annual summary data from EPW data.
    - Implementation of natural ventilation and mixed-mode metrics.
    - Excel output using metrics for temporal and cross climate comparisons.
- Support for configuring IDF files generated using the SketchUp Open Studio Plugin
    - A parser for IDF formatted EnergyPlus input files.
    - Support for hierarchical renaming to update zone, surface, window, and shade names to be human readable and meaningful (e.g. "afda243" to "Office1_wall1_window1)
- Generation of custom hourly schedules based on climate and other inputs
    - Ability to derive values of interest from a variety of sources (e.g. calculate adaptive comfort thresholds using weather data).

- o Output a CSV format data file readable as an hourly EnergyPlus schedule (e.g. to enforce adaptive comfort set points or specify window control parameters based on changing weather conditions).
- Setup and execution of batches of related simulation tasks
  - o Implementation of templating system (based on the templates used by the Python project Django) and template files for IDFs.
  - o Batch run configuration, including model parameters, climate zones to run in, and post processing options.
  - o EnergyPlus process invocation with error handling in Python.
  - o Input and output file management.
- Automated analysis of individual model runs and aggregation of results into summaries
  - o Configuration and implementation of data "aggregators" and "post processors" to calculate and write out derived values (e.g. number of occupants present when conditions exceed adaptive comfort standards).
  - o Ability to plug CSV data directly into an Excel XLS file "templates" with existing formulas, charts, and graphs to facilitate analysis.

This framework allowed a handful of configuration files to describe the hundreds of parametric runs required to support this work and cut back on the repetitive analysis tasks associated with processing and interpreting such a large volume of data.

Results

The results summarized below are compiled from hundreds of distinct parametric model runs across all 16 of California's climate zones[10], with varying cooling strategies, gains, and comfort criteria. For context, Figure 6 below provides a map of California's climate zones and Table 3 provides the locations of the weather stations whose data has

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[10] As defined by the California Energy Commission for Title 24

been selected to represent each climate in the official weather data files published by the California Energy Commission. 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 in no way warmer than Climate Zone 15, with includes Death Valley, the hottest place in North America.

Figure 6: Map from PG&E's "Guide to California Climate Zones" illustrating California's 16 climate zones. Note that 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 north eastern part of the state.

Zone	Lat. / Long.	Nearest City
CZ 01	N 40° 47' W 124° 11'	Eureka
CZ 02	N 38° 24' W 122° 41'	Santa Rosa
CZ 03	N 37° 42' W 122° 11'	Oakland
CZ 04	N 37° 24' W 122° 24'	Half Moon Bay
CZ 05	N 34° 54' W 120° 24'	San Luis Obispo
CZ 06	N 33° 54' W 118° 30'	Los Angeles
CZ 07	N 32° 42' W 117° 11'	San Diego
CZ 08	N 33° 35' W 117° 41'	Mission Viejo
CZ 09	N 34° 9' W 118° 9'	Pasadena
CZ 10	N 33° 52' W 117° 16'	Riverside
CZ 11	N 40° 12' W 122° 11'	Red Bluff (South of Redding)
CZ 12	N 38° 30' W 121° 30'	Sacramento
CZ 13	N 36° 47' W 119° 41'	Fresno
CZ 14	N 35° 42' W 117° 41'	Ridgecrest (W of Bakersfield)
CZ 15	N 32° 47' W 115° 35'	El Centro (South of the Salton Sea)
CZ 16	N 41° 17' W 122° 18'	Mt. Shasta

Table 3 Location (latitude and longitude and nearest city) of weather stations used to gather climate data for each of the official climate zones in California.

Climate analysis

Considering that California spans about 1200km (800 miles) from north to south, with elevations ranging from below sea level[11] to 4,400m (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 humid climates, it provides a very good laboratory for examining a wide range of climate driven cooling loads and comfort in buildings.

An obvious driver of cooling loads and corresponding natural ventilation and radiant cooling potential is the outdoor temperature. Figure 7 shows the total number of months found in the CEC standard weather files for each California climate zone with "moderate" outdoor temperatures, which are defined as having an average daily maximum temperature less than 80˚F (27˚C) and an average daily minimum temperature

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[11] Death Valley is actually nearly 100m (296ft) below sea level

above freezing, or 32˚F (0˚C). In "Finding the Right Mix", McConahey suggests a conservative threshold of at least 6 months with such conditions before considering natural ventilation (McConahey 2008). This threshold is presented as a dashed line on the graph, and suggests that projects in 13 of the 16 climates (counting borderline cases) should consider the use natural ventilation.

Count of months with average
Tmax < 80˚F (27˚C) and Tmin > 32˚F (0˚C)
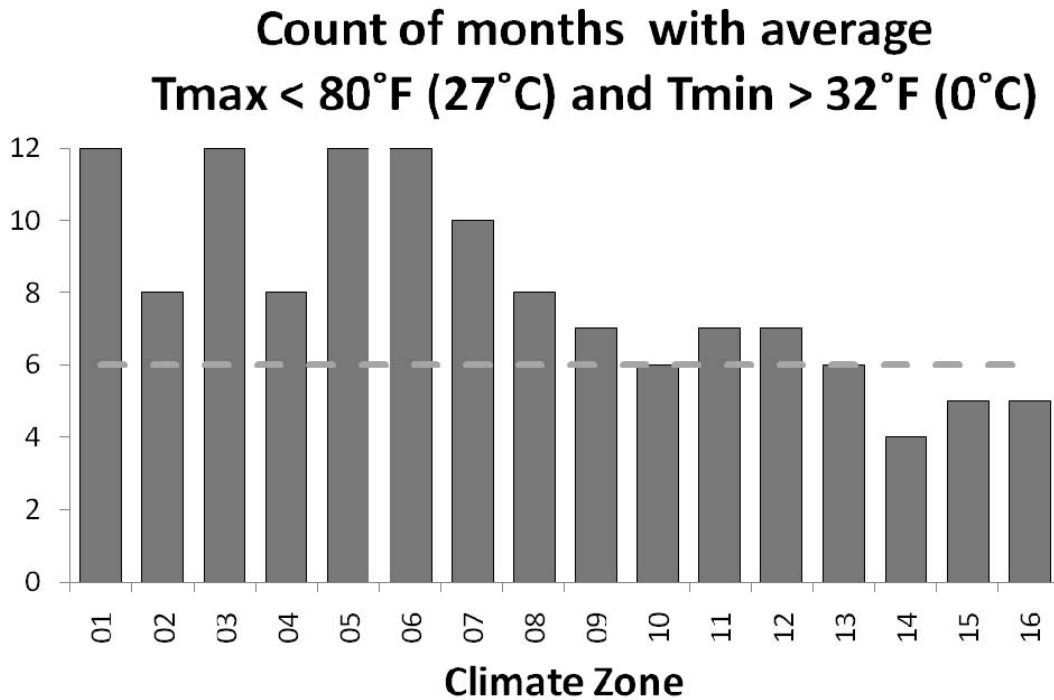
Figure 7: Number of months in each climate zone that feature average daily minimum temperatures above freezing and average daily maximum temperatures below 80˚F (27˚C). Higher bars correspond to greater potential. A rule of thumb threshold is that a mixed-mode strategy may be worth pursuing in climates with 6 or more months in this range.

A more specific metric of conditions conducive to natural ventilation can be used to determine the fraction of all hours annually that are ideally suited to natural ventilation. Figure 8 documents in dark bars the fraction of hours in each climate annually with temperatures between 60-80˚F (15-27˚C) and relative humidity < 70%. McConahey's suggested threshold of 0.3 (30%) is indicated as a dashed line. Lighter shaded bars stacked on top of the base indicate the fraction of hours considered too hot, too cold, or

too humid for natural ventilation. This hourly analysis provides a more favorable

assessment, suggesting that all but one climate zone feature temperatures and humidity

levels conducive to natural ventilation for at least 3/10ths of their hours.

Fraction of hours between 60°F (15°C) and 80°F (27°C) with rh < 70%
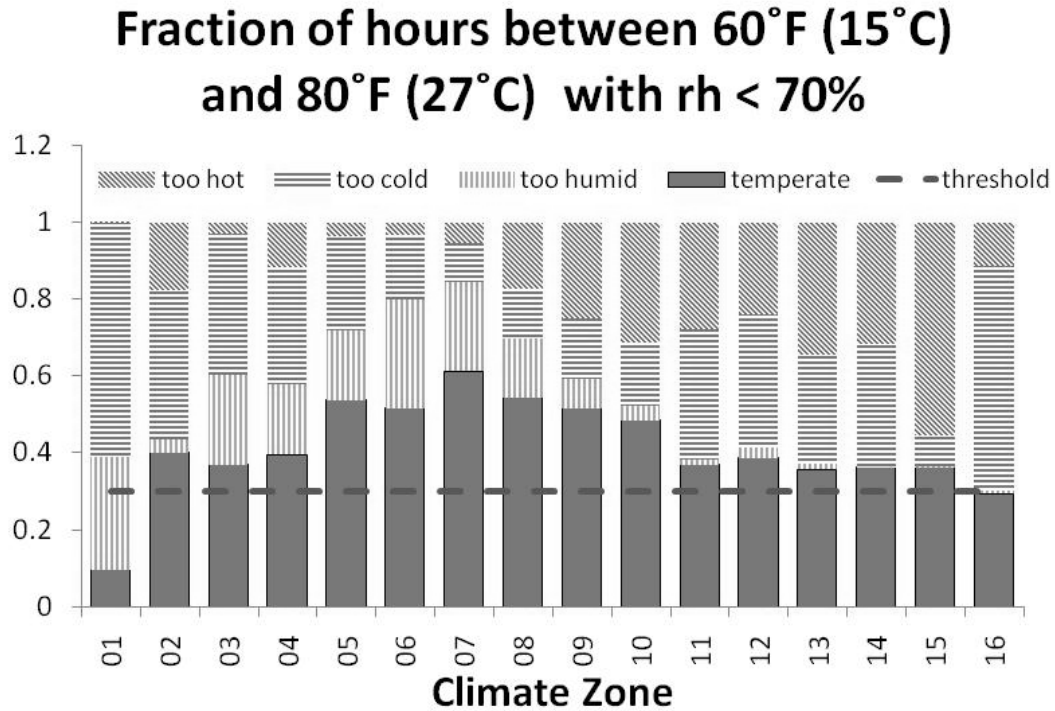
Figure 8: Fraction of hours annually with outside conditions conducive to natural ventilation, defined as temperature between 60-80°F (15-27°C) and relative humidity < 70%. Taller bars are better candidates for NV. The portion of hours cooler than the range are labeled "too cold", those that are hotter are labeled "too hot", and the remainder "too humid".

High outdoor temperatures are major drivers of cooling loads (and prevent window

operation). Figure 9 shows the total number of hours annually that the outside dry bulb

temperature exceeds 27C (80F). It is a clear indication of the large diversity of conditions

in California climates and gives a sense of the magnitude of the expected cooling loads.

There is not a recommended threshold for this chart because the high daytime

temperatures can be accompanied by cool temperatures overnight, so there is not a simple

rule of thumb that applies to this metric. Still, it is obvious that climate zone 15 presents

supreme cooling challenges and several other climates feature hot conditions for a

significant number of hours per year.
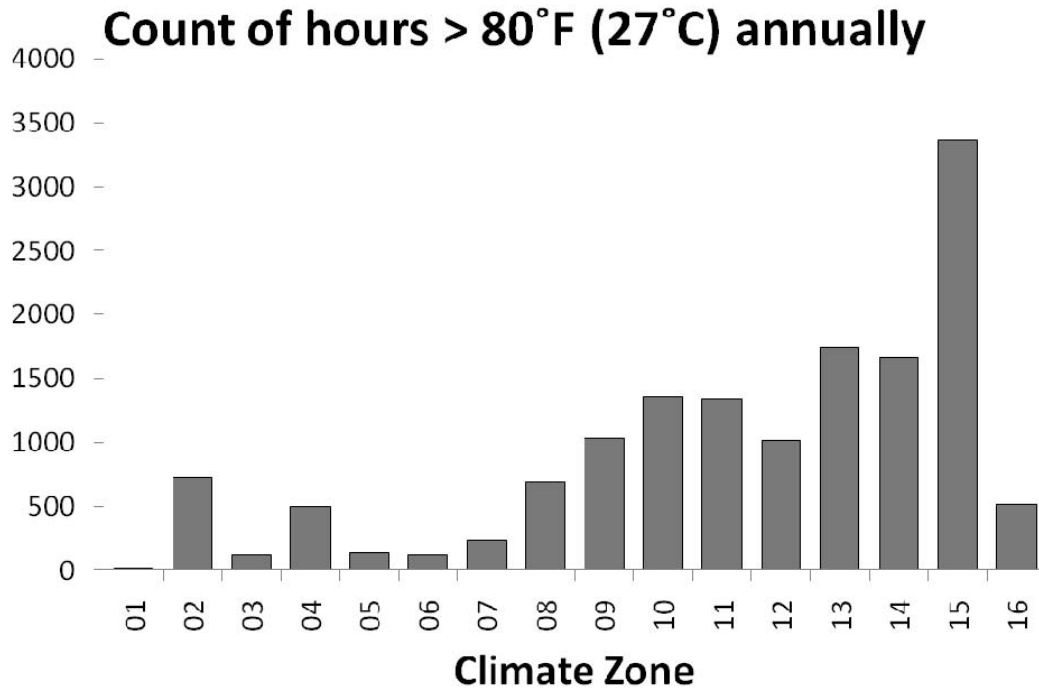
Figure 9: The total number of hours above 80°F (27°C) annually. Taller bars are bad for low-energy cooling strategies.

Systems that rely on free cooling, can be assessed in terms of the cooling resource

available to them. Failing site specific opportunities for heat exchange with cool bodies

of water or the ground, the air around the building presents the best option for exchange.

To be effective, such processes must involve temperature differences of several degrees

for a prolonged period of time. For every night that such conditions are not met, there is a

corresponding risk of not being able to provide adequate cooling the following day. In

this spirit, Figure 10 counts the number of nights in each climate annually where drybulb

temperatures do not dip below 65°F (18°C) for at least 8 hours. Note that the desert

climate of climate zone 15 stands out again as a very poor fit for this strategy and that

several of the remaining hot climates have poor overnight cooling resources 1/4 to 1/3 of

the time. Finally, it is also worth noting that all 5 coastal climate zones north of Los

Angeles have plentiful overnight cooling.

Count of nights with fewer than 8 hrs below 65˚F (18˚C)
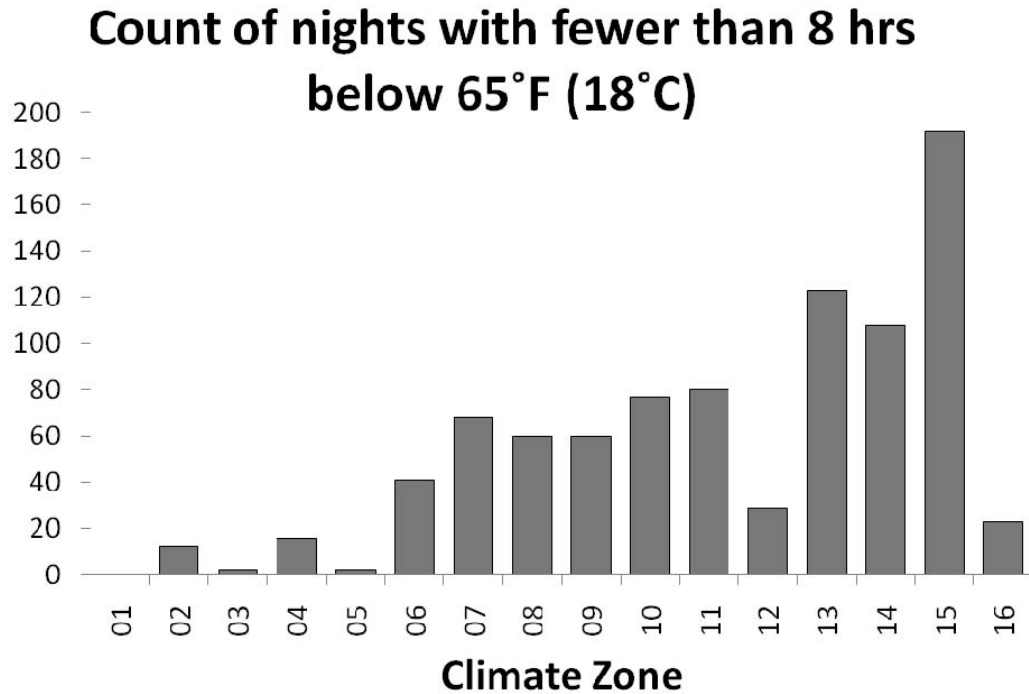
Figure 10: The number of nights annually in each climate zone that fail to maintain temperatures below 65˚F (18˚C) for at least 8 hours. Taller bars are worse for free and low energy overnight cooling.

Humidity can complicate the operation of both cooling towers (which cannot cool

beyond the wet bulb) and radiant surfaces (which must avoid condensation). Thus

humidity can play a major role in limiting the operation of radiant cooling systems.

Specifically, high dew points require that radiant systems increase their operating

temperature and diminish the ability of cooling towers to provide cool water. Figure 11

tabulates the total number of hours annually in each climate where the dew point is

higher than 64˚F (18˚C). This temperature is typical of slab operating temperatures

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(radiant panels are often even cooler) in radiant cooling systems. Note that dew point is a concern primarily in southern coastal climates.
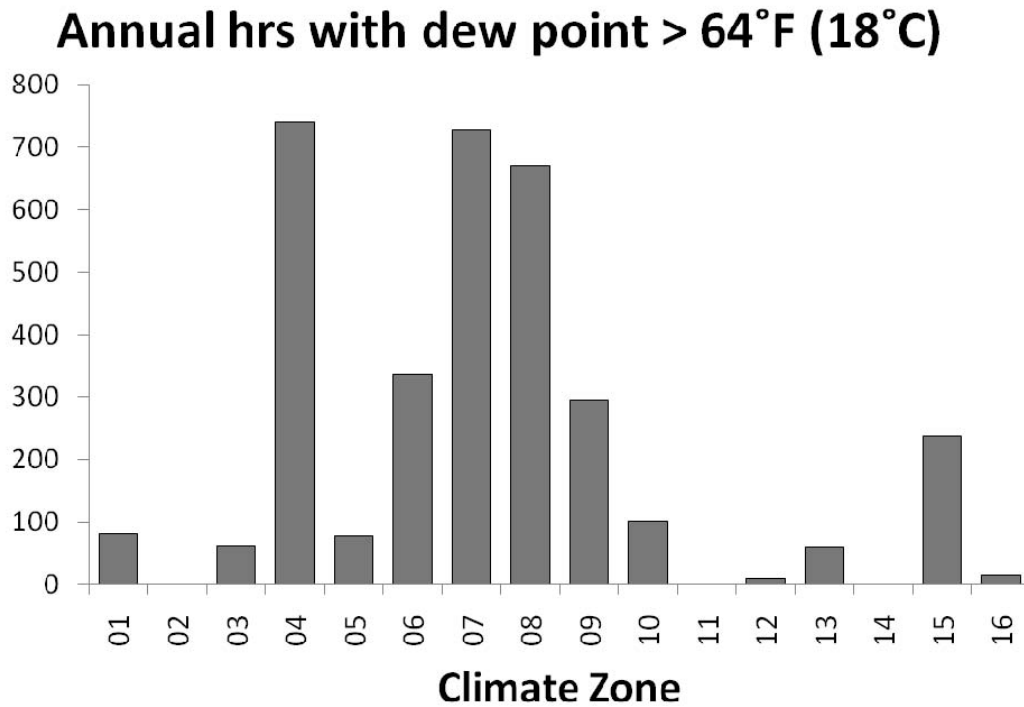
Figure 11: The number of hours annually in each climate zone with dew point above 64˚F (18˚C). Taller bars represent worse risk of condensation for radiant cooling systems.

Based on a qualitative analysis the above climate metrics taken in aggregate, it is possible to produce a conceptual map of the climate zones where mixed-mode strategies are likely to work well. The northern coastal zones offer the best conditions, with the southern coastal climates and a handful of inland zones meriting further examination. Figure 12 provides a map based on these rough guidelines. Simulation outcomes examined later in this report further refine and better quantify the "geography of discomfort".
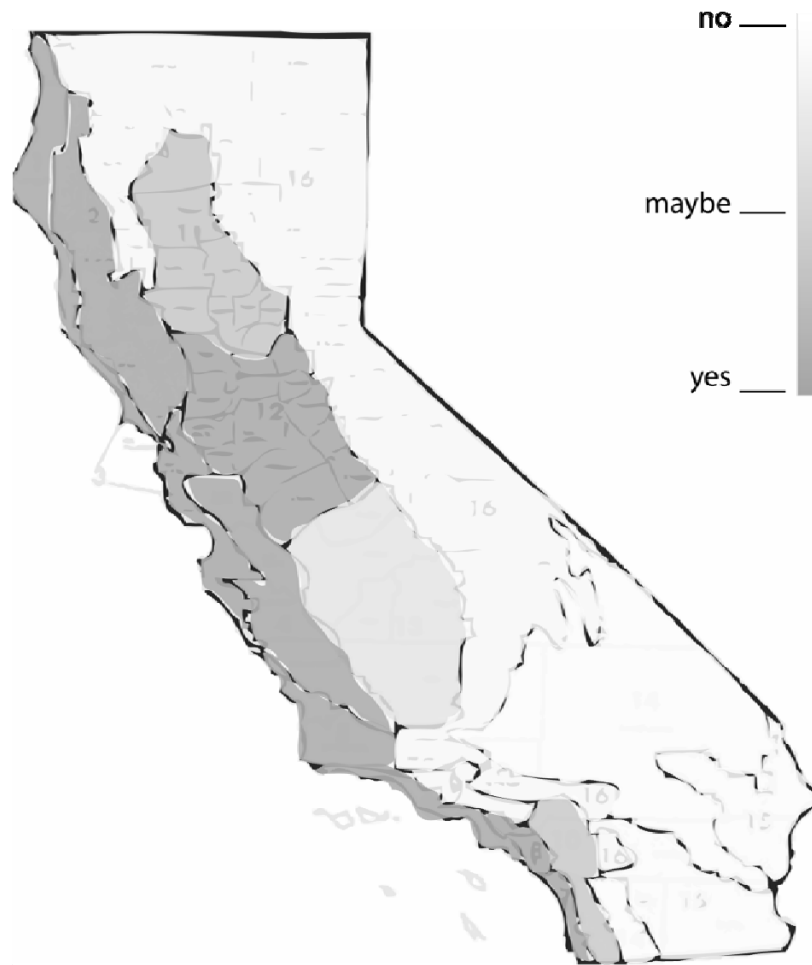
Figure 12: Qualitative map of favorable climate zones based on climate analysis.

Simulation

This section provides a summary of the main findings from the simulation modeling, focusing on the role of comfort metrics and the concept of exceedance. See the sub-sections "Comfort metrics", "Model construction", and "Parametric simulation" of the Methods section for details on our exceedance calculations and simulation approach.

Exceedance calculations require the use of a comfort model to determine whether enough people (typically 20% or more) are uncomfortable to classify the conditions as unacceptable (in real world comfort surveys and experiments there is never a condition

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where all people are comfortable). However, mixed-mode buildings operate in the grey

area between Fanger's lab-based PMV/PPD comfort model, which applies best to sealed

buildings, and the field-based adaptive comfort model, which applies to naturally

ventilated buildings. The difference between predicted exceedance from applying the

adaptive comfort model vs. PPD to mixed-mode simulation results for every climate zone

in California is illustrated in Figure 13. Note the magnitude of the gap between the two

metrics in most climates and the large number of cases where adaptive comfort predicts

less than 5% exceedance (a typical upper limit: for example it is the limit used in the

European standard CEN EN15251), but PPD does not. Using adaptive comfort standards,

exceedance is less than 5% in 12 of the climate zones. Using PPD, this is the case in only

4. This analysis underscores the need to better understand how comfort models apply to

mixed-mode buildings. All too often they straddle the line between thermal success and

failure, depending on which comfort model is being used.
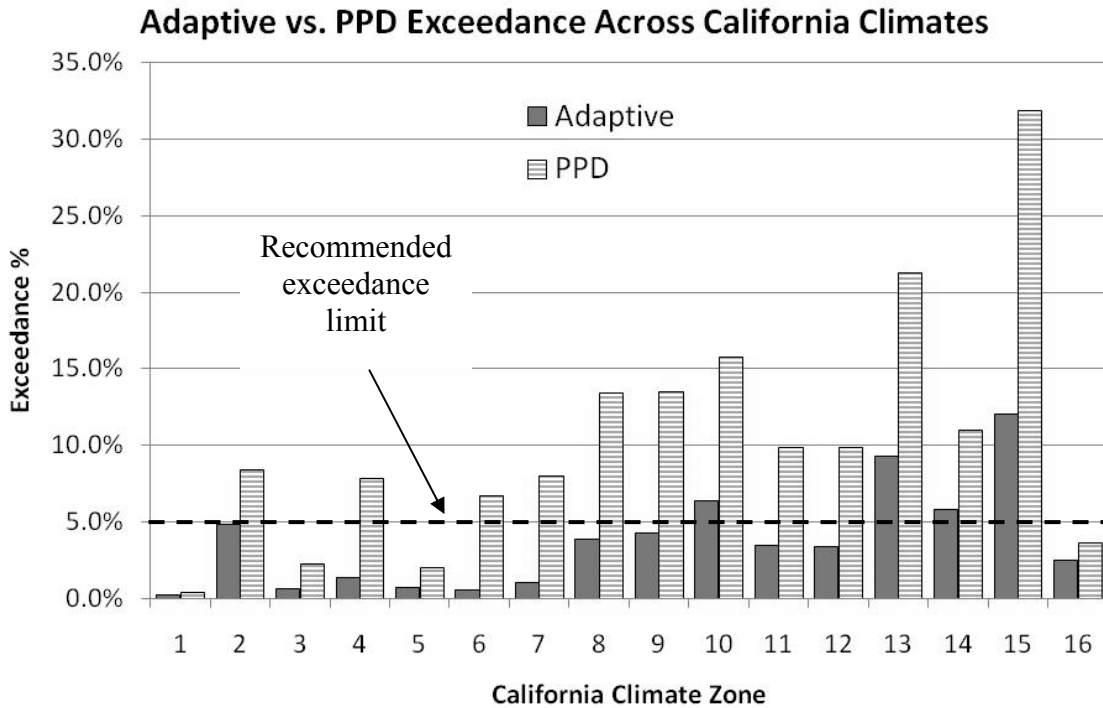
Figure 13: Exceedance predictions in mixed-mode scenario with baseline gains using the adaptive comfort model and the PPD model across all 16 climate zones in California.

Figure 14 below goes one step beyond the annual analysis of Figure 13 to tabulate the monthly hours of exceedance using both adaptive and PPD comfort models for each climate zone. It may be possible to use monthly data to plan a seasonal mixed-mode strategy applicable to even hot climates. The metrics tend to be closest to each other during the spring shoulder season, where individual days may be hot, but the monthly mean temperature used for adaptive comfort calculations can still be rather chilly. Finally notice that the difference in magnitude between adaptive comfort and PPD exceedance is particularly large for CZ 4, CZ 6, and CZ 7 (mid and southern coastal regions) and even CZ 9, CZ 11, CZ 12, and CZ 14 (central valley and inland regions). These climates tend to be the ones for which the comfort standard choice makes or breaks acceptability. Empirical comfort data from such climates could provide further differentiation of the factors that determine the degree of adaptive effects on comfort.

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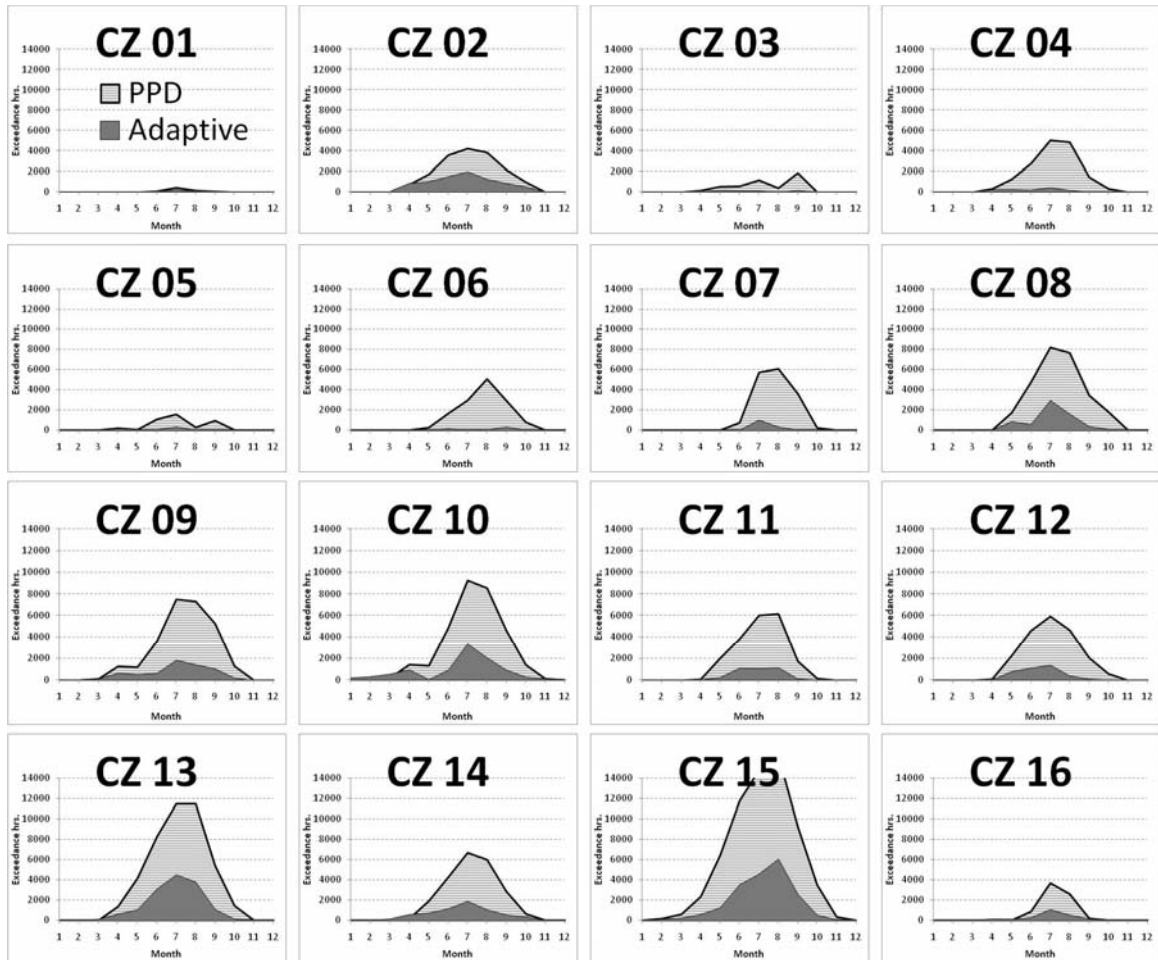
Figure 14: Comparison of adaptive vs. PPD monthly hours with > 20% of people dissatisfied for each climate zone, for the mixed-mode scenarios. The area between adaptive comfort and PPD results (the visible portion of the green background area) represents the discrepancy in predicted hours of exceedance between the two comfort standards.

Taking the difference between exceedance outcomes and turning it into an "extender" on the adaptive case, we can show both adaptive (base bar) and PPD (extender) results in a single column. The length of the extender corresponds to the degree of uncertainty in comfort outcomes determined by comfort model choice. Figure 15 below applies this technique to the simulation results of all mixed-mode configurations (with and without a supplemental chiller). The dashed line represents the recommended 5% exceedance level. Note that the choice of comfort model determines acceptability in many cases. Note also that exceedance with the active chiller is notably lower in hot climates, but it rarely

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makes the difference between acceptable and unacceptable conditions. In cooler climates, all mixed-mode configurations perform well.
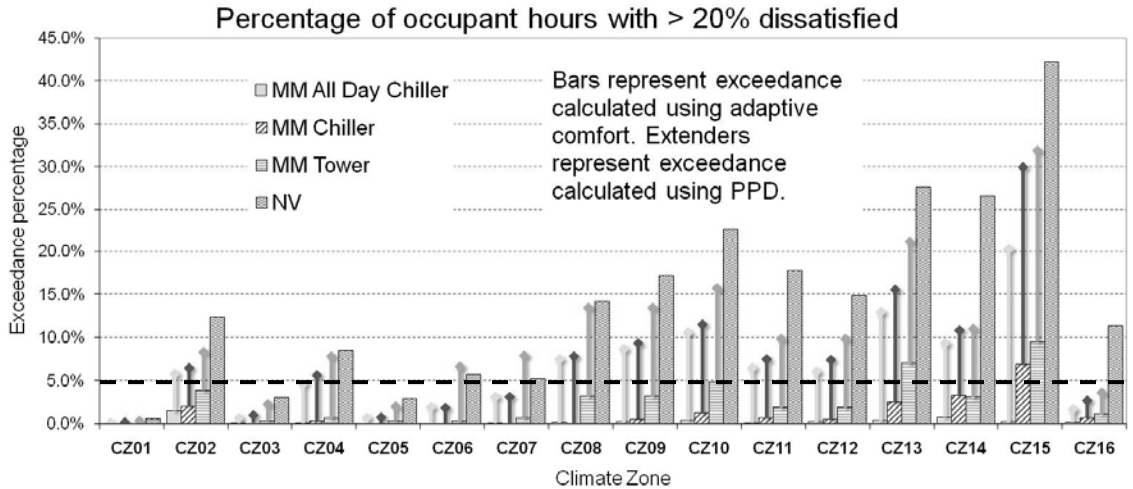
Figure 15: Comfort summary for all MM and NV configurations across all climates. Bars represent exceedance calculated using the adaptive comfort model. Extenders reach up to exceedance levels calculated using PPD. Note that only adaptive exceedance was calculated for the NV case because there is no ambiguity about its applicability.

More active cooling strategies come with an associated cost in energy use. Figure 16 below illustrates the cooling energy use for all the mixed-mode strategies and the VAV case across all climate zones. The cooling tower only strategy (MM Tower) has relatively consistent energy use regardless of climate zone. This is due to the fact that the cooling is free, so only the pumps and fans, which operate in virtually the same manner across climates, consume energy. The addition of a chiller led to unnecessary (but hard to avoid) operation of the chiller overnight where the cooling tower would have cooled the slab on its own if given until morning. It is conceivable that a real world control strategy that accurately predicts the outcome of cooling tower operation could avoid the use of the chiller more of the time, but a simple setpoint control algorithm (as is standard in EnergyPlus) leads to concurrent operation of the cooling tower and chiller. A predictive algorithm capable of avoiding this condition was beyond the capabilities of our model and is likely beyond most ordinary control systems as well. Nevertheless, the energy

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difference between the tower only (MM Tower) and tower with chiller (MM Chiller)

configuration is striking. When both systems are used, and especially if the chiller is

allowed to operate during the day as well (MM All Day Chiller), energy use is on par

with or beyond the VAV base case consumption. It is likely that the two chiller cases

could be tuned to lower their energy use further, but these results provide a cautionary

lesson on the energy costs of compressor driven cooling.
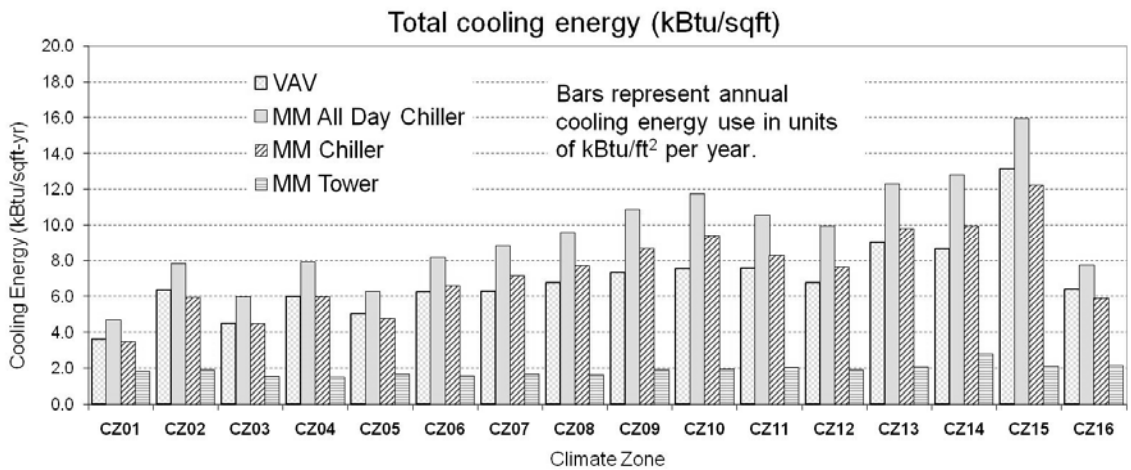
Figure 16: Cooling energy use summary for VAV and all MM configurations across all climates.

To draw conclusions about the tradeoffs being made between energy use and comfort,

it is useful to combine the two previous figures into a single visualization. Figure 17

below rotates Figure 15 and Figure 16 90 degrees and places them back to back to use the

exceedance % and cooling energy intensity metrics adopted for this project as two axes

extending in opposite directions. The data can thus be read across climate zones and

across variants of mechanical systems, to understand the energy and comfort tradeoffs

each approach makes. As with most computer simulations of buildings, the performance

of one configuration relative to another is more likely to parallel real world situations

than the absolute performance of any individual run. Proceeding from top to bottom, the

data for each climate zone starts with the pure natural ventilation scenario (labeled

"NV"). Natural ventilation uses no cooling energy, so the right hand side is zeroed out.
The left hand side displays the percentage of occupant hours in exceedance of the
adaptive comfort standard. The next scenario (labeled simply "MM Tower") 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 adaptive comfort model. To account for the uncertainty in comfort
outcomes associated with mixed-mode buildings, a line extends the bar out to a point that
corresponds to the percentage of exceedance using PPD. Finally, the last model variant
for each climate zone (labeled "VAV") is the performance of a variable-air-volume
forced air system. The left hand side shows the percentage of exceedance using PPD
since the adaptive comfort model does not apply to buildings without operable windows.

% of occupant hours with > 20% dissatisfied

Total cooling energy (kBtu/sqft)
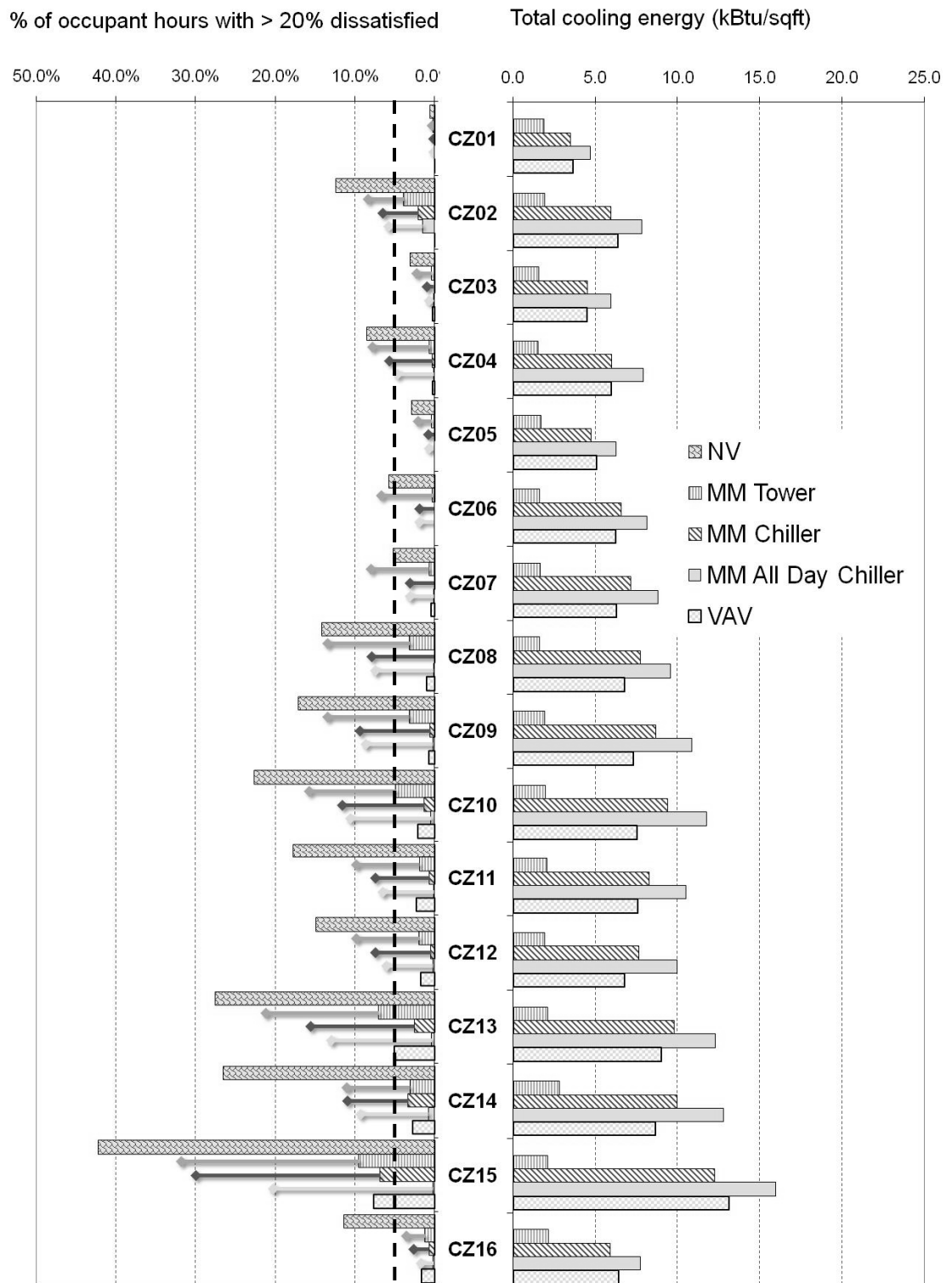
Figure 17: Comprehensive comparison between Simulation results for NV, VAV, and the 3 main permutations of MM (tower only, tower with chiller overnight, tower with chiller active all day)

When examining the left side of Figure 17, note how sensitive the comfort results are to both the conditioning strategy (the difference between the left facing bars within the same climate zone) and the comfort model being applied in the mixed-mode scenario (the length in the extension lines). For the building modeled, natural ventilation alone was sufficient for maintaining comfort exceedance near or below 5% in the milder climates (4 of the 16 representative climate zones). This suggests that some form of supplemental conditioning is required for the other climates. Assuming that the adaptive comfort model applies, the analysis shows that the mixed-mode strategy extends the range of climate zones (to 13 of the 16) in which comfort can be maintained with exceedance levels below 5%. Such a conclusion would be quite different if one had to apply the exceedance results represented by the PPD extended bars to the mixed-mode buildings. Applying PPD to the simulated mixed-mode building with a cooling tower delivers exceedance below 5% in only 4 of the 6 representative climates zones. Regarding the most extreme climate zone represented, 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 clearly significant amounts of energy were required to do so. Under these extreme weather conditions, the mechanical system hit its setpoint for air temperature, but the mean radiant temperature of the walls was sufficiently high to cause discomfort.

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 have roughly the same effect. Figure 18 below 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. 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 gains labeled "Baseline" (a.k.a. Medium) are 9.68 W/m^2 for lighting and

10.75 W/m^2 for equipment. These levels were used to obtain the previous results and

typical of buildings aggressively conserving energy. However, the "Low" case (7.53

W/m^2 for lighting and 5.4 W/m^2 for equipment) pushes them even lower. The "High"

case uses 11.83 W/m^2 for lighting and 28 W/m^2 for equipment. 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 plays a make or break

role (pushing exceedance from below 5% to beyond) in 7 of the 18 configurations shown.

In 5 of 18 cases, conditions are acceptable regardless of comfort standard. In 4 of 18

configurations, the choice of comfort model pushes exceedance from between 5-10% to

above 10%. In the remaining 2 of 18 configurations, exceedance is over 10% regardless

of comfort standard.

% of occupant hours with > 20% of people dissatisfied

Lighting power density in W/m2:   low=7.53, baseline= 9.68, ASHRAE high=11.83
Equipment power density in W/m2: low=5.4,   baseline=10.75,   high=28.0
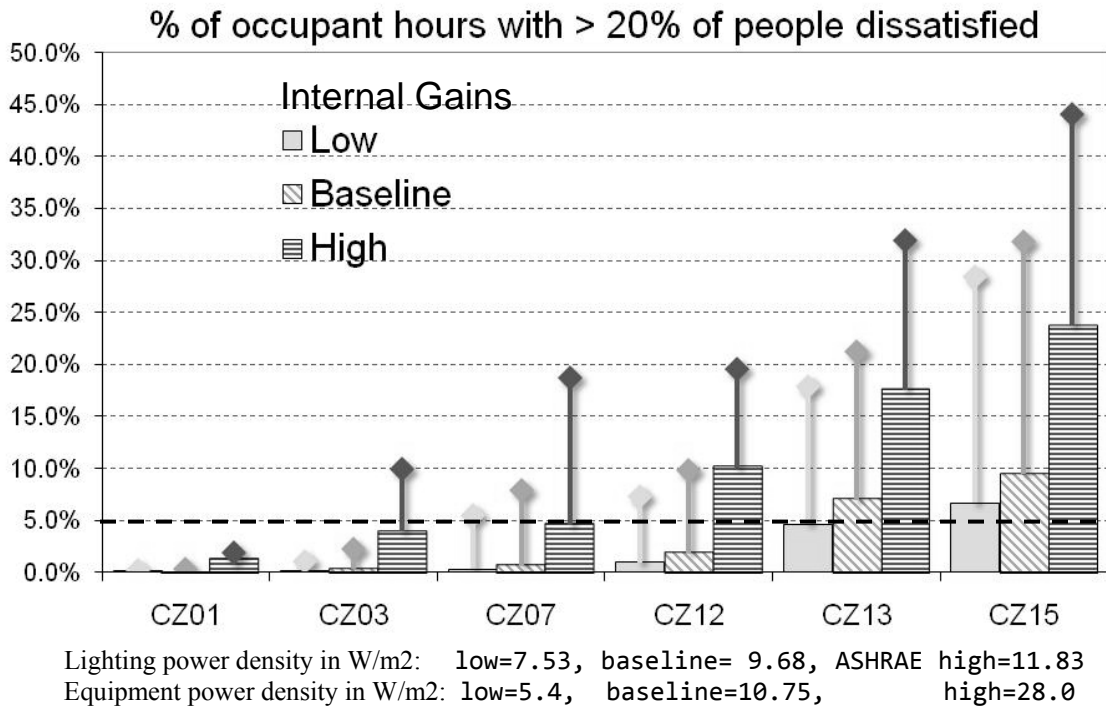
Figure 18: Comparison between high, medium and low internal gains scenarios with radiant cooling (only). Bars represent adaptive comfort exceedance. Bar extenders represent PPD comfort exceedance.

Insights into climate effects on exceedance can be improved by correlating the exceedance results with the actual geography of California's climate zones. The following three figures present overlays of exceedance predictions from the NV and MM Tower cases onto maps of the climate zones. For all the maps presented, the exceedance percentages calculated from simulation runs have been mapped to a color scale that is darkest when the model spends no time outside of the comfort zone during a full year simulation to white when the model spends over 8-10% of the time outside of the comfort zone. Figure 19 maps exceedance for the NV case using adaptive comfort. Note the clear message that coastal climates have the best comfort outcomes. This pattern of the coasts being the easiest targets is similar to the qualitative results from the climate analysis.

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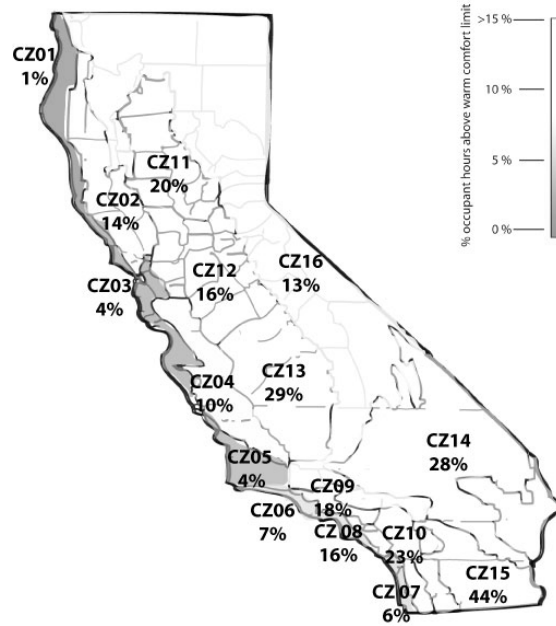
Figure 19: Map of California's climate zones with exceedance predictions from NV only simulations using daptive comfort. As one might expect, the simulation results predict the best results in the more temerate coastal regions.

Figure 20 maps the exceedance outcomes of the cooling tower only scenario using "baseline" internal gains. The map on the left applies the adaptive comfort model and the map on the right applies the PPD model. Again the coasts emerge as the easiest targets for mixed-mode strategies, but the effect of the chilled slab has improved comfort results compared to the NV case in a large land area inland and further south. Almost as striking as the increased coverage of acceptable exceedance levels over NV (e.g. the difference between figures 19 and 20) is the difference in results between the comfort models (Figure 20 left and right). Because mixed-mode buildings occupy the grey area between comfort models, site specific resources and design decisions that affect occupant perceptions of indoor environment and control (e.g. does the building feel connected to the environment and allow for direct control) are likely to determine whether specific outcomes tend towards one end or the other of the range.
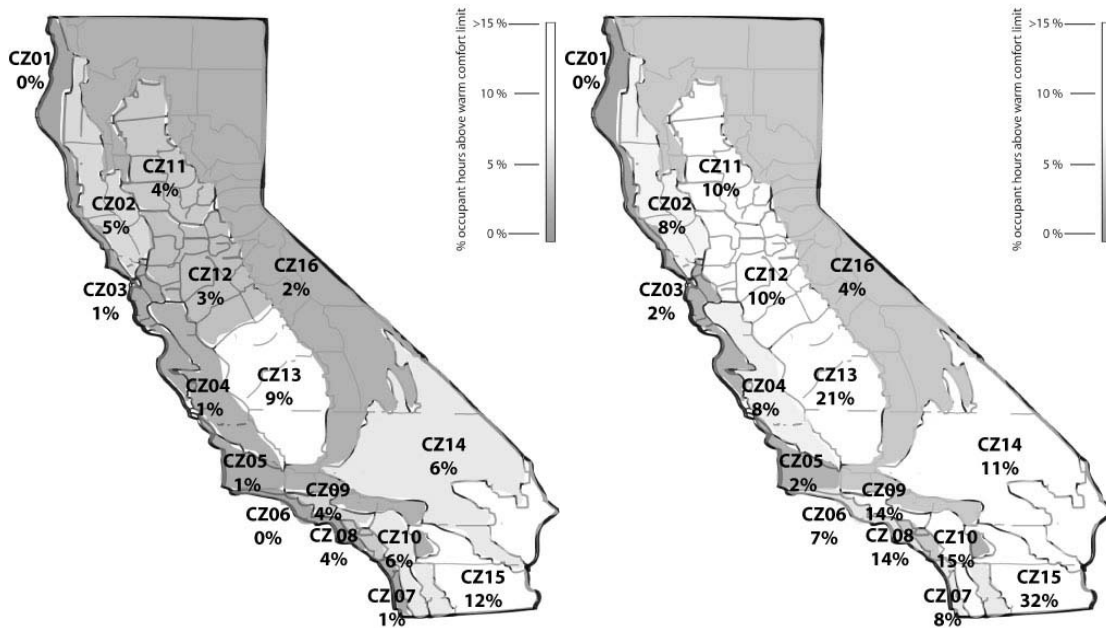
Figure 20: Map of California's climate zones with exceedance predictions from MM simulations comparing adaptive comfort on the left to PPD on the right.

Finally, it is possible to make a rough estimate of the energy savings potential that would be associated with the successful deployment of mixed-mode cooling strategies where they are predicted to succeed. Table 4 shows the predicted energy performance of mixed-mode buildings with cooling towers and no chillers and the corresponding savings potential compared to the current stock performance as estimated from 2005 CEUS data (Itron 2006). The data are presented for seven regions rather than sixteen climate zones because those were the only ones for which the CEUS data were available to the research team. The technical savings predictions are optimistic in that they apply the savings predictions obtained from simulation to all types of commercial buildings with 100% market penetration. However, mixed-mode buildings with cooling towers and no chillers have been assumed to be only viable in the coastal regions and so the savings derived from simulations for the other climate zones have been discounted. Based on inspection of the simulation results, it appears that reducing cooling loads by improving building envelope performance over and above the relatively high level of performance modeled

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in the study (recall the correlation between exceedance and internal gains in Figure 18) could possibly enable acceptable comfort in a number of inland climate zones. This is a potential topic for further work.

	Climate Zones	Current Stock Vent Energy (GWh/yr)	Current Stock Cooling Energy (GWh/yr)	Current Stock Vent + Cooling (GWh/yr)	MM Savings Potential (%)	Vent Energy for 100% MM Stock (GWh/yr)	Cooling Energy for 100% MM Stock (GWh/yr)	Vent + Cooling Energy for 100% MM Stock (GWh/yr)
Central Coast	3, 4, 5	1600	1410	3010	74	400	353	753
Central Valley	11- 13	1610	2080	3690	[0]	1610	2080	3690
Desert	14, 15	182	379	561	[0]	182	379	561
Mountains	16	61	87	148	[0]	61	87	148
Northern Coast	1, (2)	183	177	360	67	46	44	90
Southern Coast	6, 7	1560	2070	3630	78	390	518	908
Southern Inland	9, 10	2200	329	5490	[0]	2200	3290	5490
Total		**7390**	**9490**	**16900**		**4890**	**6750**	**11600**
Savings						34%	29%	**31%**

Table 4: Predicted Performance and Savings Potential for Mixed-Mode Buildings with Cooling Towers and no Chillers assuming that the performance achieved in the simulated buildings can be achieved throughout the building stock.

Discussion

The comfort / energy tradeoff

This research addresses both the energy use and comfort performance of variously configured buildings. It clearly shows that the sealed buildings with HVAC systems reliably minimize exceedance. 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 do not have the cooling capacity to maintain their setpoints

under all circumstances. Can some nominal amount of comfort be traded off for large energy savings?

Having woken up to the magnitude of waste in buildings, the industry is now enthusiastically pursuing low energy buildings, but not always with the associated opportunities and tradeoffs in mind. There is a danger that "energy only" optimization can go too far and lead to failures in other categories of building performance. In the EU directive on building efficiency "it is stated for example that energy saving measures should not lead to *sacrifices* [emphasis added] in comfort and health of building occupants" (Boestra 2006). 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 tradeoffs in many circumstances. Should we label such tradeoffs 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 and 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 properly address climate change and that the real question lies in how well we exploit the observation that "definitions of comfort are not set in stone" (Shove, Chappells et al. 2008).

Perhaps the question should be how we can make the necessary reductions in energy consumption as comfortable as possible. 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 rule of thumb, the greater the tolerance for 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. An exceedance-based goal leaves room for comfort achieved in part through energy neutral mechanisms, like providing for increased occupant control and creating expectations of a more changeable thermal environment.

Simulation outcomes

The qualitative outcomes of our simulations, including the climates with best and worst performance as well as the relative performance across climates, correlated well with conventional wisdom, rules of thumb from practitioners, and the observed success of 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, our results show that comfort prediction (using exceedance) is quite sensitive to variation in shell quality, internal gains, and insolation and particularly sensitive to which comfort standard is assumed. Because comfort standards are themselves subject to fairy large uncertainties, we must conclude that quantitative exceedance results must be interpreted very carefully.

Problems with exceedance

Informed by the trend towards lower energy buildings, the ongoing development and evaluations of standards, and specific weather events, like the long hot summer of 2003 (during which comfort conditions were exceeded for unacceptable periods of time in many European buildings), it is becoming clear that a comfort metric that allows scrutiny of the tradeoff 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 we have 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, EN15251 provides three difference calculation methods (one in percentages and two in weighted hours) and a common sense, but otherwise arbitrary, rule of thumb 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. In many scenarios, this means that

predicted exceedance values will likely exaggerate any shortcomings of their underlying

comfort models and produce results so sensitive to their uncertain inputs that they carry

much less information than they appear to. For example, Pfafferott et al. (2007) used

measured data spanning several years from 12 buildings, to analyze comfort outcomes by

applying four different standards: the international standard ISO 7730[12], the preliminary

European standard prEN15251, now CEN EN15251 (CEN 2007)[13], the German standard

DIN 1946[14], and the proposed Dutch code of practice NPR-CR 1752[15] (Pfafferott, Herkel

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 only difference in the comfort calculation was using the average monthly

outdoor temperature (a simplification made by both ASHRAE 55 and EN15251) vs.

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 generally accepted measure of exceedance that would

have allowed them to make a more reliable *quantitative* judgment.

Our 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

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[12] fixes T_{comf} at 24˚C

[13] $T_{comf} = 17.8°C + 0.31 * T_{m,out}$ where T_{comf} is the comfort temperature and $T_{m,out}$ is the monthly mean outdoor temperature. This is the same formula used for T_{comf} in ASHRAE 55.

[14] $T_{comf} = 23.5°C + T_h/3$ with T_h as the hourly ambient temperature.

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

supports the value of bracketing exceedance outputs with high and low bounds rather than calculating single values.

The need for predictive control

Systems that store energy by heating or cooling thermal mass benefit from the "inertia" of the mass. The slow response to change can moderate otherwise uncomfortable conditions. However, their slow response time can be a liability as well. To take the edge off a hot afternoon, a radiant slab will often need to be pre-cooled through the morning. It may be colder than desired on a cool morning to ensure comfort later in the day (indeed, this condition is quite evident in our simulation results). Similarly, radiant slabs may lack the ability to respond adequately to rapidly changing conditions, which can result in conditions that are either too hot or too cold, the formation of condensation, and wasted energy. Such changes can be driven by occupancy (e.g. heating due to a large gathering) or changing weather conditions (e.g. an incoming weather front). In such cases, outcomes can be improved by controlling the slab with some expectation about what future conditions are going to be. Doing so is an example of "predictive control", which can involve sophisticated simulation driven decision making, the incorporation of past performance data, the use of weather forecasts, or the use of targeted forms of manual overrides. Whatever the mechanism, the use of predictive controls is a relatively unexplored strategy that is certain to improve energy and comfort outcomes and is therefore worthy of further exploration in practice and academia.

The role of occupants

In mixed-mode buildings, occupants are often given a greater degree of control over windows and other building amenities. At the same time, high performance buildings tend to be more sensitive to climate conditions than their sealed counterparts. Taken together, these conditions elevate the stakes of occupant behavior in mixed-mode buildings. From a systems engineering perspective, occupants can be viewed as an obstacle to optimal control. Their behavior is unpredictable, they are not usually aware of the motivations and tradeoffs behind system control strategies, and they can make individual decisions that degrade the performance of the whole. For this reason, strategies designed to deliver optimized outcomes often include steps to minimize the influence that occupants can exert on control outcomes. Taken to the extreme, we might assume that the highest performing buildings with the most sophisticated controls should have the least occupant control.

However, performance is a subjective term. Occupants are the reason buildings are conditioned in the first place and their degree of control impacts their subjective experience of comfort and attitudes about their environment and building. Some very sophisticated systems and control strategies have successfully been deployed in mixed-mode buildings without preempting the occupant control and there appears to be a trend towards control strategies that are robust to (or better yet, responsive to) occupant control decisions. Examples include systems that separate heat transfer for cooling from air movement (as radiant systems do), indicate when it will be counterproductive to open windows (often with colored lights), or turn back air conditioning when windows are open (via window "lockouts"). The future of mixed-mode controls may very well lie in

the artful accommodation of occupant control decisions and enlisting them in the process of balancing their comfort with energy use.

Extrapolating to specific projects

By its very nature, simulation requires simplifying assumptions and rules of thumb, averaging, and professional judgment. Even the weather data most commonly used in simulations is edited to represent a "typical meteorological year" with extreme weather conditions filtered out. Given this background, it is natural to wonder how well the simulation based results presented in this thesis will correspond to results in practice. Because buildings and site conditions vary widely, it is easy to conclude that the results will not match the simulated results exactly. However, this is not to say that simulation results cannot be used profitably in the assessment of the likely performance of mixed-mode projects. In this work, we have taken pains to explore the sensitivity of the model to varying climate conditions, cooling strategies, comfort assumptions, and thermal loads and to explain the logic behind our conclusions so readers have the data and information required to develop intuition about what factors may impact the performance of the buildings they are interested in. Using the data and references provided here, skeptical or curious readers are encouraged to draw their own conclusions about the climate conditions and building features they are interested in.

All good designs will take advantage of the microclimate conditions provided by local topography, landscape, and other site local resources that can provide conditioning benefits beyond the generic expectations from their "climate". In some cases, the site local conditions will create more problems than they solve. It is recommended that anyone reading this information for the purposes of planning a specific project pays a

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great deal of attention to the climate analysis presented in the results section and Appendix C as well as the simulation outcomes. Readers should look at the results across several climate zones with plausible similarity to a specific site to try to identify risks and opportunities. The ranges of latitudes, elevation, rain fall, and temperatures in California are extremely broad and at least one of the climates (but not necessarily the "official" one) is likely to provide an approximate fit.

For readers outside California, similar logic applies. However, it would be misleading to claim that the range of California's climates is as broad as the full range of conditions elsewhere. In particular, California is in an arid region and does not feature rainfall totals or humidity levels as high as other areas. Because humidity can increase discomfort levels and is related to the risk of condensation on radiant surfaces, it must be said that the simulations undertaken for this study are unlikely to fully address the role that humidity plays in moderating the viability of mixed-mode radiant designs. Radiant systems are still worthy of consideration in humid climates because there are effective control strategies for addressing condensation and the fact that they decouple conditioning from air flow allows for more flexibility in planning for energy efficient dehumidification.

Finally, it is important to note that this work clearly demonstrates that comfort outcomes can be highly sensitive to gains and the applicability of adaptive comfort. This result places a burden of responsibility on designers hoping to deliver well received mixed-mode buildings. Best practices in massing, shading, glazing, insulation, and air tightness (along with equipment intensity) can be critical to keeping loads within the cooling capacity of radiant systems. Furthermore, cues to occupants that they have

control over their environment (particularly windows) and that the indoor environment will be responsive to outdoor conditions are both believed to contribute to the adaptive response that can make or break exceedance outcomes.

Conclusions

Simulation outcomes

The research team executed hundreds of distinct parametric model runs. In aggregate the simulation outputs predicted lower cooling energy use and greater occupant comfort in mixed-mode buildings found in the coastal climate zones of California, with increasing energy use and increasing discomfort further inland and further south, except in mountainous areas. When applying adaptive comfort criteria, mixed-mode buildings were found to be comfortable and therefore acceptable in a far greater number of cases than when the Predicted Mean Vote criteria were applied. Since it is generally believed that actual comfort in mixed-mode building should lie somewhere between these two extremes, the differences in predicted outcomes deserve further study.

Even within the variations of predicted comfort, both the simulation analysis and the assessment of existing buildings indicated that natural ventilation alone can provide satisfactory comfort in suitably designed buildings with low cooling loads in the north and central coastal regions of California. The addition of a radiant slab cooled at night by a relatively large cooling tower can extend this region of applicability to the south coastal region of the state. Based on a comparison of simulated energy use between the pure HVAC case and the mixed-mode case, the cooling energy savings associated with this

configuration in the south coastal region could approach ~75%. In addition, significant first cost savings would be expected to result from avoiding the cost of a chiller and a duct system. In the Central Valley, however, the nocturnally-cooled radiant slab system appears to have insufficient thermal capacity to deal with the cooling loads resulting from the envelope characteristics and lighting and miscellaneous heat gains assumed in the model used here.

When subjected to focused study, heat gains (internal from equipment and people and external passed from the external environment via windows, walls, and roof) were found to have a large impact on predicted comfort performance. It follows that gains (both internal equipment gains and external gains mediated by shell characteristics) should be very carefully controlled in mixed-mode buildings to ensure their success, especially in warmer climates.

Mixed-mode system classification

Mixed-mode conditioning strategies span the entire spectrum between 100% natural ventilation and sealed HVAC. The term therefore applies to a great diversity of strategies. Various researchers have proposed a series of increasingly refined taxonomies for classifying mixed-mode strategies. Classifications tend to emphasize spatial and temporal attributes as key differentiators between strategies. Owners and designers should note that climatic, programmatic, code, and even logistical and financial concerns can all interact to determine appropriate mixed-mode strategies.

Standardizing metrics in support of design objectives

The design and operation of each 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 our existing building stock. A focus on energy without concern for amenities can lead to unacceptable indoor conditions and buildings that are seen as failures. Thus, it is the tradeoffs between design constraints that must be the focus of attention as we seek to reduce energy use in buildings.

That an increasing number of buildings are being designed and operated with energy goals in mind is encouraging, but it is clear from observed outcomes and anecdotal evidence from industry that conversations about the tradeoffs 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 energy intensity and exceedance, which quantify expected building performance over time and allow correlation between energy use and delivered amenities should be further developed. Consensus on the use and meaning of such calculations would ensure increased industry awareness, improve the likelihood that conversations and strategizing around energy/amenity tradeoffs are taking place, and help decrease the number of surprises in the outcomes.

However, there are some important caveats that must be applied to any quantitative approach to predicting comfort. 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. that we can use the degrees above a fixed comfort temperature as a proxy for occupant sentiment) or embedded in a comfort model (e.g. PPD or adaptive comfort calculations). Our 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.

We took an initial step towards a remedy by running our exceedance calculations for mixed-mode buildings using both PPD and adaptive comfort (the ASHRAE 55 version) models. We used these outcomes to bracket our exceedance results. Our results are thus reported using likely ranges of exceedance rather than point estimates. In the many cases where our range straddles the threshold of acceptable levels of exceedance, our results suggest that acceptable comfort outcomes should be possible but are 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 and other forms of occupant control 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 preparing for the possibility of 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 we know about

the actual dynamics of thermal conditions in buildings, and in some ways may be more useful in fostering a working understanding of design and operational tradeoffs than point estimates. Standards bodies in pursuit of practical guidance and tangible progress towards better buildings should recognize the limits and uncertainties of comfort models, and the sensitivity that exceedance calculations have to these uncertainties, by emphasizing exceedance ranges rather than exact numbers, and elaborating on the qualitative implications of their outcomes (e.g. that tradeoffs may be necessary to achieve comfort and amenity goals).

Recommendations for exceedance metrics

As we've seen, exceedance metrics, particularly those that count the number of hours on one side or the other of a given percent 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, but all deserve further thought.

1. **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 our work, acknowledges that there should be some range of exceedances calculated given the uncertainties inherent in the system. It also tends to 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.

2. **Weighting:** Discomfort values that contribute to exceedance can be weighted 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 percent dissatisfied threshold. As indicated by the options laid out in EN15251 Annex F, these metrics can use the number of degrees above the comfort temperature or the magnitude of percent dissatisfied to weight the count of uncomfortable hours. These can come in the form of total degree-hours or percent-dissatisfied-hours (PD-hours) of deviation from comfort conditions. Note that some comfort models, including the adaptive comfort model cannot directly predict percent dissatisfied (as Fanger's PPD does), so the degree-hours approach would be the most generalizable. This technique will tend to produce results that are not 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.

3. **Histograms/Distributions:** If results can be presented as histograms with the count of the number of hours of percent dissatisfied (or degrees above the comfort temperature) in specific binned ranges along the x-axis, it is be possible to judge not just the exceedance for > 20% dissatisfied, but for other threshold values as well. 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 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.

Future work on comfort

It is clear that more work can and should be done to improve quantitative models of comfort and exceedance and to evaluate 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 vs. 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. A critical goal of this work should be to develop guidance on when and

how adaptive comfort might apply to mixed-mode spaces. This will likely require teasing

apart the various factors that contribute to the overall adaptive opportunity and

determining the extent to which they can be individually controlled in a mixed-mode

context.

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 (which we typically quantify

using the percentage of occupants outside of an acceptable comfort range) and long term

satisfaction (which is beginning to be quantified using exceedance metrics) and could

eventually be used to provide valuable insights into the design and operation of low

energy cooling system in buildings.

The urgency behind efforts to reduce building energy consumption demands that we

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 energy

intensity and exceedance that facilitates discussion about the tradeoffs 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, their relationship to real world

outcomes, and contributing to the improvement of the simulation techniques, comfort

models, and methods of calculation behind them.

References

ASHRAE, E. (2005). "ASHRAE Handbook-Fundamentals." <u>American Society of Heating Refrigerating and Air-Conditioning Engineers, Atlanta</u>.

Boestra, A. (2006). "The adaptive thermal comfort criterion in the new EPBD IEQ Standard." <u>BBA Indoor Environmental Consultancy, The Netherlands (bba@ binnenmilieu. nl)</u>.

Borgeson, S., Brager, G. (2008). Occupant Control of Windows: Accounting for Human Behavior in Building Simulation, UC Berkeley Center for the Built Environment.

Brager, G. and L. Baker (2009). "Occupant satisfaction in mixed-mode buildings." <u>Building Research & Information</u> **37**(4): 369-380.

Brager, G., S. Borgeson, et al. (2007). Control Strategies for Mixed-Mode Buildings, UC Berkeley Center for the Built Environment.

CEN (2007). EN15251. <u>Indoor Environmental Parameters for Assessment of Energy Performance of Buildings–Addressing Indoor Air Quality, Thermal Environment, Lighting and Acoustic</u>. Bruxelles, Comitè Eurpoéen de Normalization.

CIBSE, A. (2005). Natural ventilation in non-domestic buildings. London, UK, The Chartered Institution of Building Services Engineers.

de Dear, R. and G. Brager (1998). "Developing an adaptive model of thermal comfort and preference." <u>ASHRAE Transactions</u> **104**(1): 145–167.

de Dear, R. J. and G. S. Brager (2002). "Thermal comfort in naturally ventilated buildings: revisions to ASHRAE Standard 55." <u>Energy and buildings</u> **34**(6): 549-561.

De Wit, M. (1999). "Uncertainty in wind pressure coefficients for low-rise buildings." <u>Heron- English Edition</u> **44**: 45-59.

Emmerich, S. J. (2003). <u>Impact of Natural Ventilation Strategies and Design Issues for California Applications, Including Input to ASHRAE Standard 62 and California Title 24</u>, US Dept. of Commerce, Technology Administration, National Institute of Standards and Technology.

Fanger, P. (1970). <u>Thermal comfort: analysis and applications in environmental engineering</u>, Danish Technical Press.

Good, J., A. Frisque, et al. (2008). The Role of Wind in Natural Ventilation Simulations Using Airflow Network Models. <u>The National Conference of IBPSA-USA</u>. Berkeley, CA.

Haldi, F. and D. Robinson (2008). A comparison of alternative approaches for the modelling of window opening and closing behaviour. Air Conditioning and the Low Carbon Cooling Challenge. Windsor, UK, Network for Comfort and Energy Use in Buildings.

Heijmans, N. and P. Wouters (2002). Impact of the uncertainties on wind pressures on the prediction of thermal comfort performances. Brussels, IEA ECB&CS Annex 35 Hybvent project.

Heiselberg, P. K. (2002). Principles of Hybrid Ventilation, Hybrid Ventilation Centre, Aalborg University.

Hellwig, R. T., F. Antretter, et al. (2008). The use of windows as controls for indoor environmental conditions in schools. Air Conditioning and the Low Carbon Cooling Challenge. Windsor, UK, Network for Comfort and Energy Use in Buildings.

Henze, G., C. Felsmann, et al. (2008). "Primary energy and comfort performance of ventilation assisted thermo-active building systems in continental climates." Energy & Buildings **40**(2): 99-111.

Herkel, S., U. Knapp, et al. (2008). "Towards a model of user behaviour regarding the manual control of windows in office buildings." Building and Environment **43**(4): 588-600.

Humphreys, M. A., J. F. Nicol, et al. (2008). Modelling window-opening and the use of other building controls. AIVC Conference. Tokyo, Japan.

Itron (2006). California Commercial End-Use Survey. Consultant Report, CEC.

Jaunzens, D., et al. (2000). Mixed Mode Ventilation - CIBSE Applications Manual AM13: 2000, The Chartered Institution of Building Services Engineers London.

Kiel, D. and D. Wilson (1986). Gravity driven flows through open doors. 7th AIC Conference, Stratford-upon-Avon, UK.

Knoll, B., J. Phaff, et al. (1996). "Pressure coefficient simulation program." Air Infiltration Review **17**(3): 1-5.

Luo, Z., J. Zhao, et al. (2007). "Estimating natural-ventilation potential considering both thermal comfort and IAQ issues." Building and Environment **42**(6): 2289-2298.

McConahey, E. (2008). Finding the Right Mix. ASHRAE Journal. **September**.

Moujalled, B., R. Cantin, et al. (2008). "Comparison of thermal comfort algorithms in naturally ventilated office buildings." Energy & Buildings **40**(12): 2215-2223.

Nicol, F. and M. Humphreys (2010). "Derivation of the adaptive equations for thermal comfort in free-running buildings in European standard EN15251." Building and Environment **45**(1): 11-17.

Nicol, F. J. (2001). Characterizing occupant behaviour in buildings: towards a stochastic model occupant use of windows, lights, blinds, heaters and fans. Seventh International IBPSA Conference. Rio de Janeiro, Brazil.

Nicol, J. and M. Humphreys (2004). "A stochastic approach to thermal comfort-Occupant behavior and energy use in buildings." ASHRAE Transactions **110**(2): 554-568.

Olesen, B. (2007). "The philosophy behind EN15251: Indoor environmental criteria for design and calculation of energy performance of buildings." Energy & Buildings **39**(7): 740-749.

Olesen, B., O. Seppanen, et al. (2006). "Criteria for the indoor environment for energy performance of buildings." Facilities **24**(11/12): 445-457.

Pendse, R., Ashok Kumar, Abhilash Vijayan (2005). "Development of a spreadsheet to determine natural ventilation cooling hours for a commercial hybrid HVAC system." Environmental Progress **24**(1): 16-23.

Pendse, R. S. (2004). Incorporation of Natural Ventilation in a Commercial HVAC System Using Temperature as a Comfort Parameter. Civil Engineering, University of Toledo. **Master of Science:** 170.

Pfafferott, J. and S. Herkel (2007). "Statistical simulation of user behaviour in low-energy office buildings." Solar Energy **81**(5): 676-682.

Pfafferott, J., S. Herkel, et al. (2007). "Comparison of low-energy office buildings in summer using different thermal comfort criteria." Energy & Buildings **39**(7): 750-757.

Raja, I., J. Nicol, et al. (2001). "Thermal comfort: use of controls in naturally ventilated buildings." Energy & Buildings **33**(3): 235-244.

Rijal, H., J. Nicol, et al. (2007). Use of windows, fans and doors to control the indoor environment in Pakistan: developing a behavioural model for use in thermal simulations. 2nd International Conference on Environmentally Sustainable Development, Pakistan.

Rijal, H., P. Tuohy, et al. (2007). "Using results from field surveys to predict the effect of open windows on thermal comfort and energy use in buildings." Energy & Buildings **39**(7): 823-836.

Rijal, H., P. Tuohy, et al. (2008a). "Development of an adaptive window-opening algorithm to predict the thermal comfort, energy use and overheating in buildings." Journal of Building Performance Simulation **1**(1): 17-30.

Seppanen, O. and W. Fisk (2002). "Association of ventilation system type with SBS symptoms in office workers." <u>Indoor Air</u> **12**(2): 98-112.

Shove, E., H. Chappells, et al. (2008). "Comfort in a lower carbon society." <u>Building Research and Information</u> **36**(4): 307-311.

Spindler, H. and L. Norford (2009). "Naturally ventilated and mixed-mode buildings—Part I: Thermal modeling." <u>Building and Environment</u> **44**(4): 736-749.

Spindler, H. and L. Norford (2009). "Naturally ventilated and mixed-mode buildings—Part II: Optimal control." <u>Building and Environment</u> **44**(4): 750-761.

Yun, G. and K. Steemers (2008). "Time-dependent occupant behaviour models of window control in summer." <u>Building and Environment</u> **43**(9): 1471-1482.

Appendix A: Glossary

Adaptive Comfort: The comfort standard that is based on empirical results of thermal comfort surveys from building around the world. It describes the range of indoor operative temperatures within which occupants are expected to be comfortable as a function of the recent average of outdoor temperatures.

ASHRAE: The American Society of Heating, Refrigeration, and Air-conditioning Engineers. ASHRAE researches and publishes many detailed references on building design, engineering, and simulation, including the Handbook of Fundamentals. It also develops and maintains several model building codes, including the industry standards for commercial and residential energy use, indoor air quality and ventilation, and others.

Center for the Built Environment: A research center at UC Berkeley dedicated to building research focused on energy and environmental quality and funded by members that include many leading architecture, engineering, and real estate firms.

Computational Fluid Dynamics (CFD): The simulation of fluid flows (specifically air flows in the context of ventilation analysis) using numerical integration of the coupled equations describing the physics of such flows. While the results of such simulations can be quite rich in detail, CFD is computationally intensive and sensitive to initial conditions.

Diurnal Swing: The difference between daily high and low temperatures.

Dry Bulb Temperature: The temperature read by a standard thermometer in a given location.

Energy Intensity: The amount of energy consumed per unit of floor area. This is often calculated in terms of annual consumption, as in kBtu/sqft/year.

EnergyPlus: Advanced building simulation software developed by the DoE to model complex building geometries, materials, equipment, and controls.

EPW file: The EnergyPlus format for weather data. On this project, the team used EPW files for California climate zones developed by the CEC.

Exceedence: The amount of time building conditions exceed acceptable comfort limits. For this project, this meant the fraction of occupant hours with conditions worse than the 80% satisfied line of the adaptive comfort model (where adaptive comfort applied) OR greater than 20% PPD according to Fanger's Predicted Mean Vote model (where Predicted Mean Vote applied).

(ASHRAE) Handbook of Fundamentals: The basic physics and engineering details of buildings and building systems are summarized in

HVAC: Heating Ventilation and Air-Conditioning. As in "building HVAC systems".

IAQ: Indoor Air Quality

IDF or IMF file: EnergyPlus input files. The only difference between an Input Data File (IDF) and an Input Macro File (IMF) is that the IMF can contain EnergyPlus macro language directives, including variable definitions and include files.

Mass Coupled: Conditioning strategies that strategically store thermal energy in the mass of dense materials like concrete, stone, or water.

Mean Radiant Temperature (MRT): The spatial average of the radiant surface temperatures experienced by a person (radiant cooling lowers the MRT).

Operative Temperature (OT): The dry bulb equivalent of the combined experience of dry bulb temperature and MRT (radiant cooling lowers the OT).

Percent of People Dissatisfied (PPD): The percentage of people expected to be dissatisfied with a given set of indoor conditions according to Fanger's comfort model. Using Fanger's work, PPD can be derived from PMV.

Predicted Mean Vote (PMV): The expected average vote of building occupants on a scale of -3 (very cold) to +3 (very hot) describing thermal comfort. The Fanger Model, based on an empirical fit of controlled thermal test chamber experiments, is an equation based on several environmental parameters that can be used to predict the mean vote.

Post Occupancy Evaluation (POE): The evaluation of a how a building is performing when it is occupied by people as intended and is running under normal day to day operations.

SketchUp: An easy to use 3D design tool now owned by Google. SketchUp supports design plug-ins and there is one called OpenStudio that supports the creation of EnergyPlus model geometries[16].

(ASHRAE) Standard 55: ASHRAE's standard on thermal comfort. It recognizes the difference between occupant expectations in sealed buildings and naturally ventilated buildings and endorses the use of the adaptive comfort standard for naturally ventilated spaces.

VAV: Variable air volume air systems can scale their air flow and heating and cooling energy use to the actual (fraction of full capacity) demand. Compared to constant air volume systems, they provide more flexibility of control and offer potential energy savings.

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[16] See http://sketchup.google.com/ and http://apps1.eere.energy.gov/buildings/energyplus/openstudio.cfm.

Appendix B: Modeling Ventilation Potential in Early Design

Every person has direct, personal experience with natural ventilation. We roll down the windows in our cars, open windows at home for a breath of fresh air, and have experience the pleasures of a cross breeze on a warm sunny day. For this reason, we might expect that we all have some intuition about how a building will respond to wind and stack driven ventilation with a specific understanding of how to design for thermal comfort. However, for most people, past experience provides qualitative rather than quantitative guidance. As building occupants, we tend to respond reactively to uncomfortable conditions without a detailed knowledge of exact outdoor conditions or the flow rates that will be created by various strategies.

As a result, it is common for building designers to look to rules of thumb and tools of varying levels of technical sophistication to support decisions related to designs that incorporate natural ventilation. Given the range of options, it is natural to look at the comparative strengths and weaknesses and proper role of each in the design of naturally ventilated spaces.

Rules of thumb are clearly intended to provide fast approximation methods for roughly ensuring that ventilation is adequate. Good examples of rules of thumb for natural ventilation include the requirements for naturally ventilated spaces defined by ASHRAE standard 62 (and the extremely similar requirements defined by Title 24):

- Naturally ventilated spaces shall be permanently open to and within 8m (6m for Title 24) of operable wall or roof openings to the outdoors.
- The openable area of these openings shall be a minimum of 4% (5% for Title 24) of the net occupiable floor area.

- The means to open required operable openings shall be readily accessible to building occupants whenever the space is occupied.

Emmerich critiques the code requirements this way:

> "There is little doubt that under mild outdoor air temperatures and low wind speeds, the specified opening sizes are unlikely to result in adequate ventilation rates relative to the specific numerical requirements for mechanical ventilation systems. While these floor-area based requirements have a long history in building codes, that does not mean they are technically correct, and many view them as a 'loophole' in the standard." (Emmerich 2003)

While the paper suggests changes intended to address these specific limitations, this is a critique based on the inevitable limitations of rules of thumb. There are always special cases that they are ill equipped to address.

To really get a handle on the exact performance of naturally ventilated spaces, we would ideally be able to model airflow around and through the spaces with great accuracy. Our options for doing this include building physical models that can be subjected to wind tunnel and salt tank testing and/or utilizing Computational Fluid Dynamics (CFD) software.

Physical modeling is not always feasible within the constraints of a typical design process. It requires access to testing facilities and time consuming and potentially expensive construction of test models with careful attention to detail. If part of the exercise is to help shape unresolved features of a building, physically testing all the variations of the design can become quite tedious and time consuming indeed.

A CFD simulation is based on the application of the laws of physics that govern the fluid flow of air to a computer model of the space to be ventilated. The precision of the CFD simulation is limited only by the speed of the simulating computer and the time you have available to wait for a result. On the surface, the potential precision might make CFD sound like an ideal tool, but setting up a CFD simulation is extremely time

consuming and CFD software tends to be written for highly specialized users. The learning curve is steep, and CFD simulations are sensitively dependent on boundary and initial conditions. For ventilation simulations, the required inputs will include detailed information about the wind driven flow through building openings and may even include the textures and furnishings of the space you are modeling. Much of this information is best derived using a physical model in a wind tunnel, so in this sense accurate CFD modeling cannot entirely replace wind tunnel work. As a practical matter, you are expected to be able to input a lot of very specific information about the space even as you are trying to work out the details. Even when this information is know well enough to produce meaningful modeled results, building the model can become extremely time consuming and thus expensive. For these reasons, CFD can be too precise and sensitive to be of practical value in assessing general ventilation potential. It tends to be used more to look at specific issues that may arise in building that are already well specified.

The pragmatic optimum for tools supporting the design phase of naturally ventilated spaces under ordinary circumstances is somewhere between the speed and inaccuracy of rules of thumb and the more precise but resource consuming full physical simulation. The basic physics equations that describe air flow in terms of conserved energy and mass can be simplified from the form used in CFD software to bulk air flow equations with closed form solutions that capture the approximate behavior of spaces under various wind, stack, and temperature conditions. Bulk air flow models, like AIRNET (from EnergyPlus), CONTAM, and COMIS apply these approximate equations governing bulk flows to "networks" of interconnected "nodes" within spaces and are capable of modeling ventilation performance of fairly complex multi-zoned spaces.

However, even these bulk flow tools can take a great deal of time to configure and may not be worth the effort for designers looking for a general or intuitive picture of the air flow though a relatively simple space. The air flow equations found in the ASHRAE Handbook of Fundamentals (and similar sources) that are the basis for bulk airflow models can also be used to support simplified direct calculations (ASHRAE 2005). Spread sheets that tackle these tasks with varying degrees of precision and sophistication are alluded to and occasionally even described in the literature on tools for designing naturally ventilated spaces.

The air flow equations in the Handbook of Fundamentals (HOF) cover ventilation through building openings driven by wind as well as ventilation driven by the stack effect. The remainder of this appendix is an exploration of the HOF equations and their potential application in determining likely Indoor Air Quality and thermal comfort in spaces as they are designed.

The Kreuger HVAC Ventilation Calculator for ASHRAE Standard 62[17] is a fairly typical example of a simple ventilation model built into a spreadsheet (and locked against inspection or changes in this case). In 2004, Pendse provided a more sophisticated exploration of the potential of spread sheet modeling of ventilation that was submitted as a Master's Thesis in Civil Engineering (Pendse 2004). The Pendse model (Pendse 2005) uses inputs of pressure coefficients, weather data, comfort criteria, room dimensions, etc. to derive the hours of the day for design months at a range of climate locations for which night cooling is expected to be a viable conditioning strategy. It is this question of viability that designers will typically encounter early in their process.

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[17] Located at http://www.krueger-hvac.com/lit/whitepaper.asp at the time of this writing

Qualitative Description of Wind Flow Around Buildings

The first thing to understand about wind flow around buildings is that it is complicated and can easily produce non-intuitive conditions. A corollary to this fact is that many of the non-intuitive conditions can also be very difficult to model accurately. Below are two figures from the HOF that give a visual and qualitative view of wind flows.
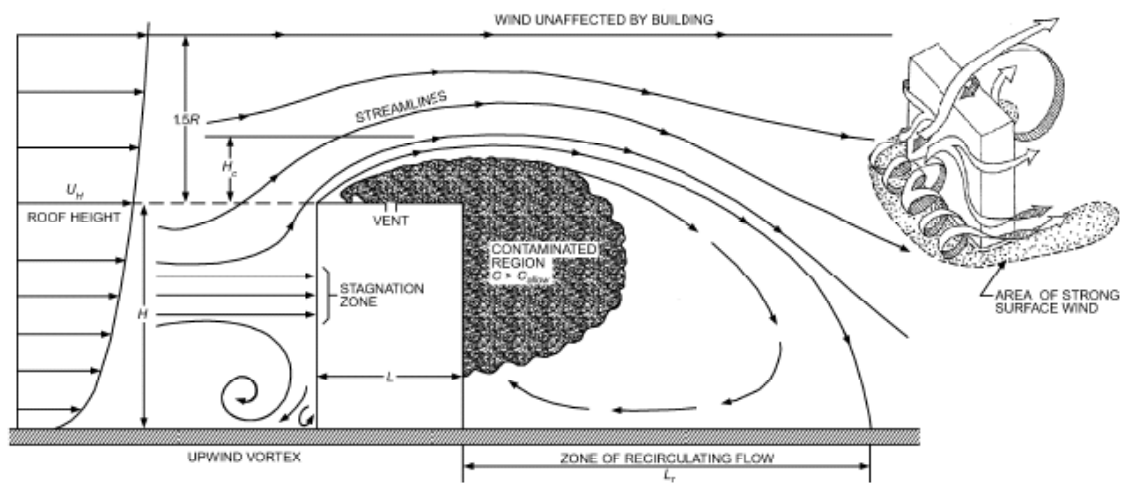

Fig. 1   Flow Patterns Around Rectangular Building

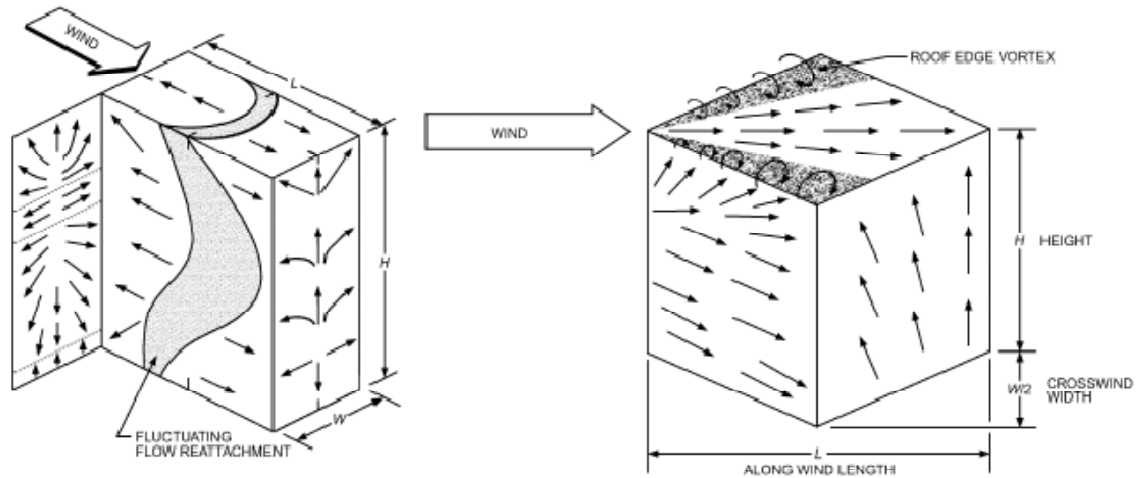Figure 1. From ASHRAE Handbook of Fundamentals 16.1

Fig. 2 Surface Flow Patterns and Building Dimensions
(Wilson 1979)

Figure 2. From ASHRAE Handbook of Fundamentals 16.2

The main things to take away from these figures are that pressure builds up on the

windward surface of a building and tends to be lowered on the leeward side. However,

the vortices that form as air flows around a building can create either high or low pressure

conditions and can also be unstable over time. Thus the nature of the wind pressures on a

building depend sensitively on the wind's angle of approach and the building geometry.

Pressure Coefficients

When modeling airflow in and around buildings, pressure coefficients C_p whose

values are functions of wind direction, building geometry, and location on the surface of

the building are used to relate the free flowing wind speed to the pressure the wind exerts

at the location for which C_p is defined. This relationship is given by the Bernoulli

equation, assuming no height change or pressure losses:

$$p_w = C_p \rho \frac{U^2}{2}$$

Where

p_w = wind surface pressure relative to outdoor static pressure, P_a

ρ = outside air density in kg/m^3 (about 1.2 under normal conditions)

U = wind speed in m/s

C_p = wind surface pressure coefficient, which is a dimensionless ratio

Apart from C_p, which is itself a function of wind direction, the wind speed is the only other variable required to determine the pressure. Note that the pressure is a function of wind speed squared, which means that errors and over simplifications in wind speed numbers could lead to inaccurate results.

As for determining C_p's themselves, HOF 2005 16.3 says: "Accurate determination of C_p can be obtained only from wind tunnel model tests of the specific site and building. Ventilation rate calculations for a single, unshielded rectangular building can be reasonably estimated using existing wind tunnel data." Thus the question of wind driven flows through building openings given known wind speeds comes down to determining the pressure coefficients, which are only widely available for simple building geometries.

The HOF provides coefficients for one short and one tall rectangular building. The tall building information shown in Figure 3 below reveals the spatial complexity and angular sensitivity of the coefficients. It is useful to note that they range from above 0.9 to below -1.20, or roughly +1 to -1 and that the largest negative pressures come on surface 90 degrees off the wind direction. This implies that "cross ventilation" could be strongest along a diagonal path through the building.
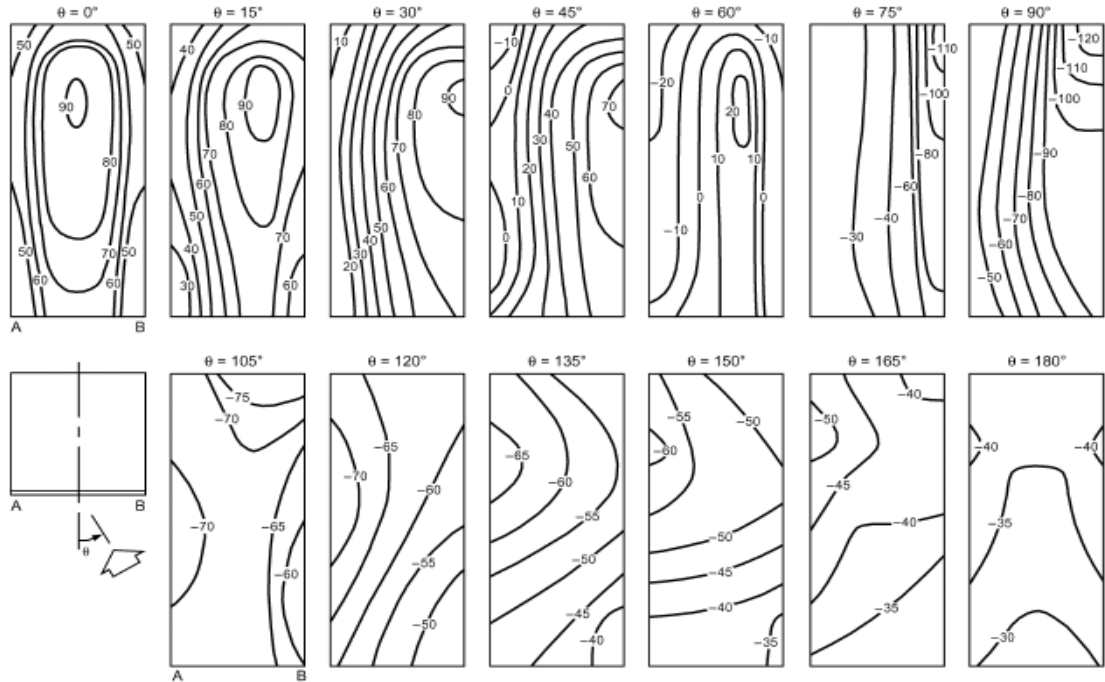
Fig. 4 Local Pressure Coefficients ($C_p \times 100$) for Tall Building with Varying Wind Direction
(Davenport and Hui 1982)

Figure 3. Pressure coefficients for a High rise (height/width > 3) building from HOF 16.4

For many applications, the surface averaged wind pressure can be used to calculate

ventilation rates, and that average is much simple to work with. Figure 4 below gives
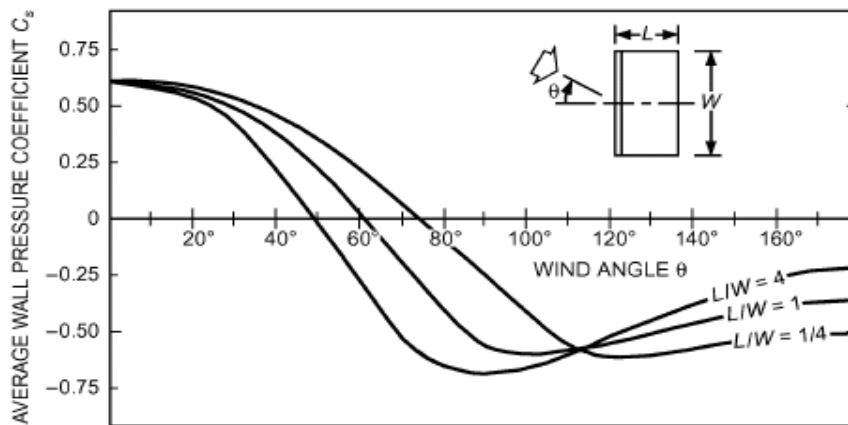
such values for a high rise building.

Figure 4. Surface average wall pressure coefficients for tall buildings as a function of

angle adapted from Akins et al. (1979) as HOF 16.5.

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Airflow Through Building Openings

The relationship describing the airflow through a large intentional opening is based on the Bernoulli equation with steady, incompressible flow. The general form that includes stack, wind, and mechanical ventilation pressures across the opening is:

$$Q = C_D A\sqrt{2\Delta p/\rho}$$

Where

Q = airflow rate in m^3/s
C$_D$= discharge coefficient for the opening, which is a dimensionless ratio based on opening geometry and the Reynolds number of the flow
A = cross sectional area of the opening in m^2
P = air density in kg/m^3
Δp = the pressure difference across the opening in Pascals

Flow Caused by Wind Only

"Factors due to wind forces that affect the ventilation rate include average speed, prevailing direction, seasonal and daily variation in speed and direction, and local obstructions such as nearby buildings, hills, trees, and shrubbery…Natural ventilation systems are often designed for wind speeds one-half the seasonal average." HOF 27.10

Given the complexity of deriving proper pressure coefficients, wind driven ventilation is often simplified to the following equation (from HOF 27.10):

$$Q = C_v A U$$

Where

Q = airflow rate in m^3/s

C_v = effectiveness of the opening, assumed to be 0.5 or 0.6 for perpendicular winds and 0.25 to 0.35 for diagonal winds

A = free area of the opening in m^2

U = wind speed in m/s

This equation assumes wind blowing directly perpendicular to the opening, no obstructions to the flow of the wind to the outlet, and no geometrical interactions that would cause the pressure coefficients to play a large role. Since it multiplies the cross sectional area of the opening with the flow speed through the opening to get the total volumetric flow, it makes intuitive geometric sense.

Now that we have a good sense of how to calculate wind driven flows, we can turn our attention to ventilation from the stack effect. If building internal resistance is not significant, the flow caused by stack effect can be expressed by the following equation (HOF 27.11):

$$Q = C_D A \sqrt{2g\Delta H_{NPL}(T_i - T_o)/T_i}$$

Where

Q = airflow rate in m^3/s

C_D = discharge coefficient for the opening, which accounts for all viscous effects such as surface drag and interfacial mixing

ΔH_{NPL} = height from the midpoint of the lower opening to the Neutral Pressure Level in m

T_i and T_o = Indoor temperature and outdoor temperature, respectively in ˚K

Estimation of ΔH_{NPL} is difficult for naturally ventilated buildings. If one window or door represents a large fraction (approximately 90%) of the total opening area in the envelope, then the NPL is at the mid-height of that aperture, and ΔH_{NPL} equals one-half the height of the aperture. According to HOF 27.7 "Internal partitions, stairwells, elevator shafts, utility ducts, chimneys, vents, operable windows, and mechanical supply and exhaust systems complicate the analysis of NPL location." For tall buildings NPL is usually 0.3-0.7 of the total building height; for houses, the NPL is typically around mid height. Professional judgment is required when determining what value to use for a specific design project.

For the case where window or door represents a large fraction (approximately 90%) of the total opening area in the envelope, flow through the opening is bidirectional and C_D can be calculated according to the following equation (Kiel and Wilson 1986):

$$C_D = 0.40 + 0.0045\,|T_i - T_o|$$

If enough other openings are available, the airflow through the opening will be unidirectional. An approximate discharge coefficient of $C_D = 0.65$ can then be used. Apart from NPL and the related decision on which C_D to use, the stack flow is also a function of the temperature difference indoors and out. Internal heat loads should be accounted for when determining the overall effectiveness of the stack.

Once we have estimates of flow from wind and stack, we can add them together to get the total flow. However they interact and do not just add linearly. Empirical observations have found that a sum of squares approach provides a good fit for determining the total air flow, Q, given the stack flow, Q_s, and the wind driven flow, Q_w:

$$Q = \sqrt{Q_s^2 + Q_w^2}$$

Determining IAQ and Comfort

Now that we have a basis for calculating total airflow from stack and wind ventilation, we can apply those flow rates to the task of assessing compliance with IAQ and thermal comfort standards. For IAQ, the requirement is usually dictated as a function of the number of people, N, and the area, A, of the space in question (Luo, Zhao et al. 2007):

$$Q = 0.0075 \times N + 0.0001 \times A$$

We can compare the preceding to the predicted natural ventilation flow. If the total Q for a given space, given conservative assumption about wind and stack flows, is greater than the IAQ flow requirement, then we can reasonably expect that the IAQ requirements of the space could be met through natural ventilation. In practice, this condition will often be easily satisfied, with the exception of high occupancy spaces and spaces with contaminants or other reasons for higher required ventilation rates.

Assuming IAQ requirements are met, the feasibility of comfort cooling using natural ventilation becomes the operative question. Starting with the adaptive comfort model, which defines acceptable temperatures as within ±3.5 degs C of:

$$T_{comf} = 0.31T_{a,out} + 17.8$$

and with hard cut offs at the upper and lower temperature bounds, we can easily derive our upper and lower bounds for thermal comfort. Based on the calculated air flows from stack and wind driven ventilation, we can derive the cooling capacity of the volume of incoming outdoor air at temperature T_{out} mixing with indoor air at T_{in}. This calculation depends on the shell insulating characteristics (which determine the heat load from

outside the building and the heat losses to the environment) coupled with the total additional energy added to the space through internal loads.

As shown by Luo (2007), a heat balance equation can be derived that relates the incoming air flow to the expected indoor temperature:

$$T_{in} - T_{out} = \frac{E}{\rho C_p Q + \sum K_j A_j}$$

Where

$K_j A_j$ are the shell insulating characteristics for the jth building surface

E is the total internal heat loads

ρ is the air density

Q is the air flow rate from outside to inside

Given T_{out} less than T_{in} and a specific desired T_{in}, such a heat balance equation can be solved for the airflow Q necessary to achieve that temperature. Essentially, the ventilation must flow at a rate sufficient to remove as much heat from the space as is being introduced to it through loads. We can compare this required rate to NV rates of airflow to determine whether or not comfort can be achieved through NV alone given specific wind and temperature conditions.

Conclusion

This appendix has outlined the data and mathematical relationships that govern airflow for Natural Ventilation. It has gone a step further to look at the relationship between airflow, IAQ, and basic thermal comfort criteria to derive relationships that roughly give the conditions under which NV can meet those comfort criteria. In theory, these relationships could be programmed into a spread sheet and used with various sources of weather data to determine the hours for which natural ventilation would be effective during given design days. This data in turn could be aggregated into a metric of

the total expected percentage of time that a given building will be able to meet its comfort requirements using natural ventilation. It could also be used to size the mechanical systems required to pick up the left over demands by modeling worst case situations. As a simple design tool, it could provide valuable insights into the viable strategies for cooling early in the process without requiring a great deal of detailed building-specific information.

Further reading on Natural Ventilation

Bradley, D. E., Utzinger, D. M. (2006). Natural Ventilation Measurements and Simulation at Two Milwaukee Nature Centers. SimBuild 2006, Cambridge, MA.

Deru, M. P. and P. J. Burns (2003). "Infiltration and natural ventilation model for whole building energy simulation of residential buildings." ASHRAE Transactions 109(2): 801-811.

Eley, C., Associates (2003). Chapter 2: Natural Ventilation Guidelines. Hawaii Commercial Building Guidelines for Energy Efficiency. DBEDT, State of Hawaii 2-1 to 2-23.

Ernest, D. R. (1991). Predicting wind-induced indoor air motion, occupant comfort and cooling loads in naturally ventilated buildings. Center for the Built Environment. Berkeley, CA, UC Berkeley. PhD: 261.

Ernest, D. R., Bauman, F. S., Arens, E. A. (1991). "The Prediction of Indoor AIr Motion for Occupant Cooling in Naturally Ventilated Buildings." ASHRAE Transactions 97(1).

Zhao, Y. and J. R. Jones (2007). "Decision Support for Natural Ventilation of Nonresidential Buildings." Journal of Architectural Engineering 13: 95.

References for Appendix B

ASHRAE, E. (2005). "ASHRAE Handbook-Fundamentals." <u>American Society of Heating Refrigerating and Air-Conditioning Engineers, Atlanta</u>.

Emmerich, S. J. (2003). <u>Impact of Natural Ventilation Strategies and Design Issues for California Applications, Including Input to ASHRAE Standard 62 and California Title 24</u>, US Dept. of Commerce, Technology Administration, National Institute of Standards and Technology.

Kiel, D. and D. Wilson (1986). <u>Gravity driven flows through open doors</u>. 7th AIC Conference, Stratford-upon-Avon, UK.

Luo, Z., J. Zhao, et al. (2007). "Estimating natural-ventilation potential considering both thermal comfort and IAQ issues." <u>Building and Environment</u> **42**(6): 2289-2298.

Pendse, R., Ashok Kumar, Abhilash Vijayan (2005). "Development of a spreadsheet to determine natural ventilation cooling hours for a commercial hybrid HVAC system." <u>Environmental Progress</u> **24**(1): 16-23.

Pendse, R. S. (2004). Incorporation of Natural Ventilation in a Commercial HVAC System Using Temperature as a Comfort Parameter. <u>Civil Engineering</u>, University of Toledo. **Master of Science:** 170.

Appendix C: Details by Climate Zone