MIXED-MODE SIMULATIONS FOR CLIMATE FEASIBILITY

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October 22, 2009

1. 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 and 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 superior energy performance and occupant satisfaction is hydronic radiant cooling via chilled slabs, walls, or strategically placed panels. This work set out to test the efficacy of mixed-mode strategies that utilize radiant cooling in California climates. Metrics of energy consumption and comfort provide quantitative values for assessing performance, and case studies of existing buildings provide valuable information on real world performance, occupant satisfaction, and control strategies.

2. OBJECTIVES

The goal of this project was to use both building simulation and the evaluation of existing buildings to better characterize the energy and comfort implications of mixed-mode building operation with radiant cooling in California climates. The work was intended to inform building industry professionals, interested lay people, and decision makers at energy utilities and regulatory agencies. 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.
- Identify, document, and assess the performance of real-world mixed-mode system configurations.
- Use lessons learned from successful mixed-mode buildings to inform the design and operation of the simulation models.
- Document measured occupant satisfaction and indoor environmental quality of existing mixed-mode buildings.

- Use simulation outcomes to quantify energy consumption and thermal comfort under varying building systems and control strategies across all 16 California climate zones.
- Quantify the larger scale energy benefits to widespread adoption of mixed-mode building operating strategies.
- Provide design guidance via graphical summaries designed to be accessible to non-technical stakeholders.

Detailed results from the occupant satisfaction surveys were presented in a previous publication. This Executive Summary highlights selected findings from the simulations. The full findings are described in Borgeson 2010.

3. METHODS: SIMULATION PLAN

The main simulation model used in this project was based on the Kirsch Center at DeAnza College in Cupertino, which was purposely built as a mixed-mode building and has many features, including orientation, massing, shading, window placement, and floor plate dimensions that enhance natural ventilation and minimize heat gains. The Kirsch EnergyPlus model can be operated using natural ventilation only, mechanical only, or mixed-mode conditioning strategies, and features best practice designs for mechanical systems, lighting, windows, insulation, and internal gains (except when variations of the above were being studied).

The Kirsch model was altered to support parametric studies of internal gains, shell performance, ventilation performance, operating control strategies, mechanical systems, and thermal mass with respect to occupant comfort and energy consumption. A version of the model with conventional shell characteristics, no external shading, and relatively little thermal mass was used to simulate retrofit scenarios. By utilizing active cooling all day long and a lower surface temperature set point, this version of the model emulated the performance of a radiant panel system.

As the modeling efforts progressed, it became increasingly clear that manual controls, particularly occupant decisions to open and close windows, are critical to the performance of mixed-mode buildings, and are thus quite relevant to their simulation. A literature review of occupant behavior with respect to operable windows identified many recent journal articles and several pieces of grey literature that directly addressed the question of modeling occupant control of 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. While it was not feasible to integrate such models into EnergyPlus within the scope of this project, they influenced the implementation and interpretation of natural ventilation in the EnergyPlus model.

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

An outline of the complete simulation plan for this project is included below.

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 (18C)
Cumulative hours with outdoor temperatures at or above 80F (27C)
Total number of nights with less than 8 hours below 65F (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 (27C) and > 32F (0C)
Fraction of temperate hours between 60-80F (15.5-27C) with rh < 70%
Total number of hours annually at or above 80F (27C)
Total number of nights annually that have less than 8 hours below 65F (18C)
Total number of hours annually with a dew point at or above 65F (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 climate 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

4. SELECTED RESULTS

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. The work assessing existing mixed-mode building performance documented generally high levels of occupant satisfaction with substantial energy savings. The simulation work confirmed that energy savings via mixed-mode strategies should be possible while preserving thermal comfort in the coastal climate zones. However, outcomes in warmer climates, which tend to be inland in California, range from probably acceptable to most likely unacceptable. Parametric sensitivity studies revealed that comfort in buildings in marginal climates is sensitive to internal and external heat gains, envelope performance, proper window operation, and other site-specific details. In addition, the choice of comfort model (between the adaptive comfort model, which is applicable to naturally ventilated spaces, and the Fanger Predicted Mean Vote model) had a large effect on predicted comfort outcomes.

Figures illustrating simulation results are included below. Figure 1 shows California's 16 climate zones.

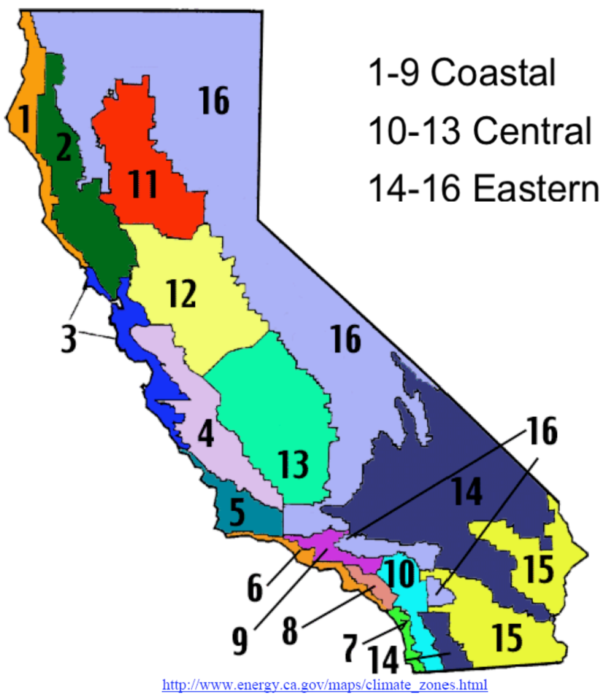

Figure 1: California's 16 climate zones

The graphic in Figure 2 uses the comfort exceedance and cooling energy intensity metrics developed for this project as two axes extending in opposite directions. Here, exceedance is defined as the number (or percentage) of occupant hours when less than 80% of people are predicted to be satisfied with the thermal environment. Both the adaptive comfort model (de Dear and Brager 1998) and Fanger's Predicted Mean Vote (PMV) model can identify this condition, but using different predictive methods of satisfaction, so the exceedance approach allows for cross comparison. Each of the 16 climate zones has the modeled results of five configuration variations plotted on these two axes. 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. Proceeding from top to bottom in the legend, the data for each climate zone starts with the pure natural ventilation scenario (labeled "NV"). Natural ventilation uses no cooling energy, so there is no bar on the right hand side. The left hand side displays the percentage of occupant hours in exceedance of the adaptive comfort standard (which was developed with field data from naturally ventilated buildings).

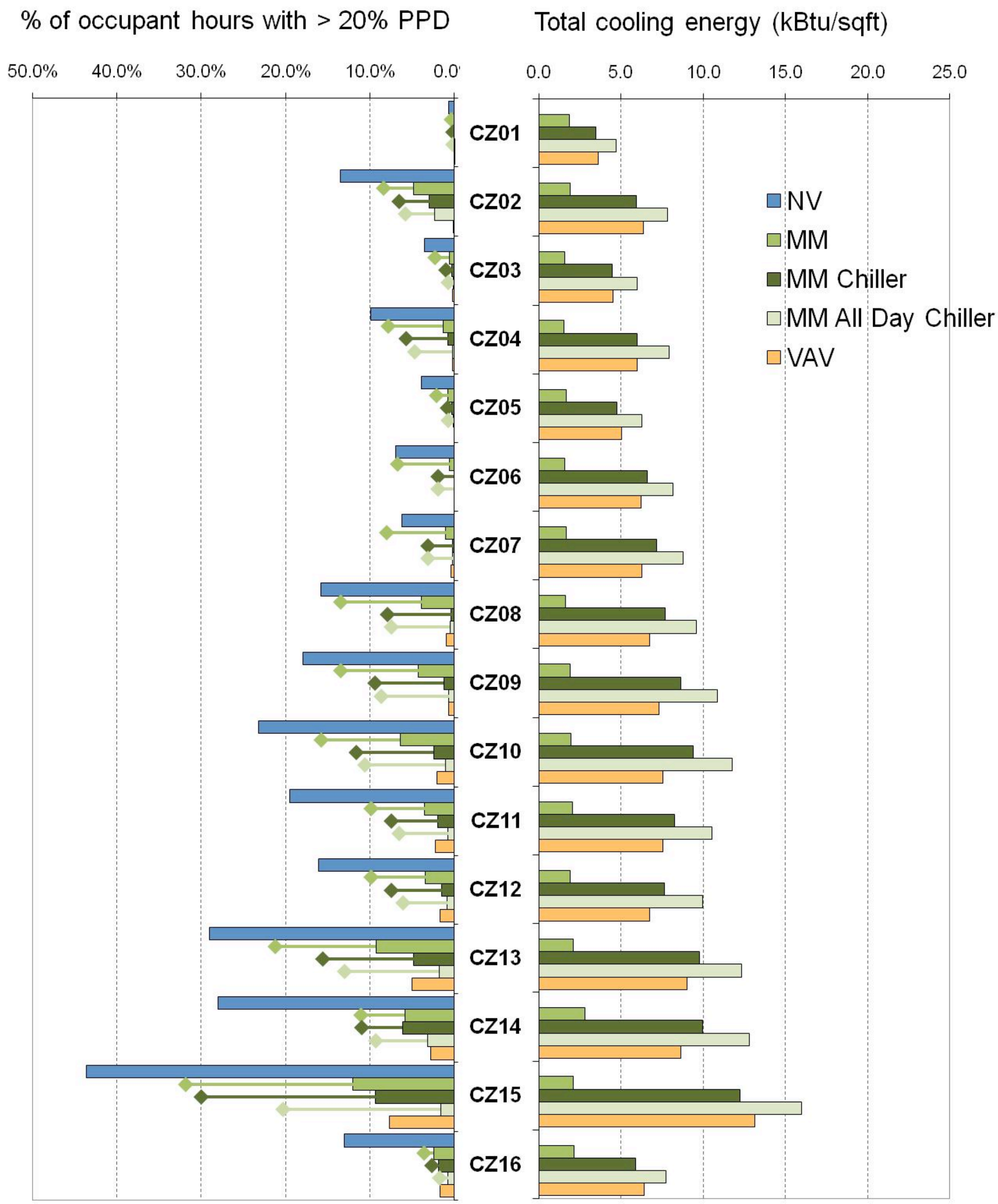

Figure 2: Simulation results for natural ventilation, variable-air-volume, and the 3 main permutations of mixed-mode (tower only, tower with chiller overnight, tower with chiller active all day). Left facing bars represent adaptive comfort exceedance (as a percentage of occupant hours), extenders represent Predicted Mean Vote comfort exceedance. Right facing bars represent cooling energy use.

A set of three variants of mixed-mode strategies follows the natural ventilation case in Figure 2. The *first* of these (labeled simply "MM") is mixed-mode operation with a radiant slab that is cooled using a cooling tower that only operates overnight. The left hand side features a bar that corresponds to the percentage of exceedance for the adaptive comfort model. However, there is not yet consensus in either the research or professional community whether people in mixed-mode buildings are likely experience comfort as predicted by the adaptive comfort zone or by the PMV-based comfort zone. To account for this uncertainly, the bar is extended out with a line to a point that corresponds to the percentage of exceedance for the Fanger Predicted Mean Vote model.

The *second* mixed-mode variant (labeled "MM Chiller") also features a cooling tower that only operates at night, but it is supplemented with a chiller that ensures that the slab temperature set point is reached every night. The *third* mixed-mode variant (labeled "MM All Day Chiller") employs a cooling tower and chiller that actively maintain the slab temperature set point all day. Note that for both variants with chillers, controls are coarse compared to the VAV controls and window use is unconstrained. Therefore somewhat lower energy consumption should be possible.

Finally, the last model variant for each climate zone (labeled "VAV") is the performance of a variable-air-volume forced air system without operable windows. For the VAV case, the left hand side shows the percentage of exceedance only using Fanger's Predicted Mean Vote model, since the adaptive comfort model does not apply to buildings without operable windows. When examining the chart, note how sensitive the comfort results are to the comfort model being applied.

Low energy cooling systems tend to have firm limits on their rate of heat extraction from a space. It is thus wise to take steps to minimize heat gains. Figure 3 displays the results of a simulated experiment attempting to understand the impact of heat gains on the modeled performance. For each of six representative climate zones, a baseline, and high and low gains scenario were run. All scenarios charge the slab overnight with a cooling tower (note the similar energy consumption), and the baseline is identical to the "cooling tower only" scenario from the 16 zone summary above. Based on the data, it is clear that internal gains can dramatically impact comfort and thus well managed gains are imperative for successful deployment in warmer climates.

Figure 4 shows the modeled results using the same gain scenarios with pure natural ventilation.

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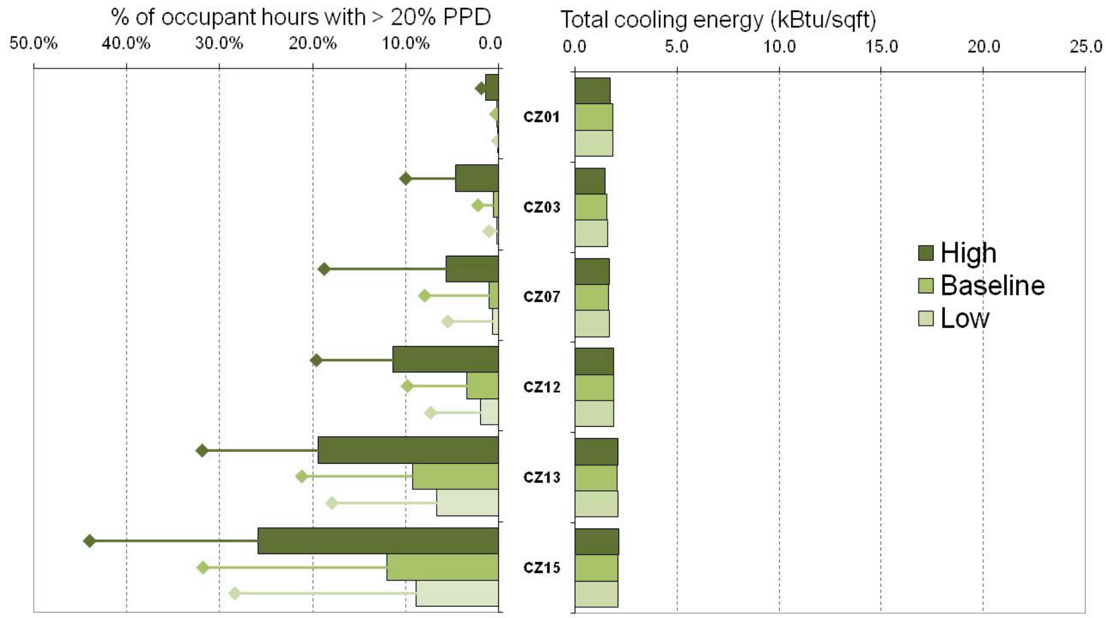

Lighting power density in W/m2: low=7.53, baseline=9.68, ASHRAE "high"=11.83

Equipment power density in W/m2: low-5.4, baseline=10.75, high=28.0

Figure 3: Comparison between high, medium and low internal gains scenarios with radiant cooling. Left facing bars represent adaptive comfort exceedance, extenders represent Predicted Mean Vote comfort exceedance. Right facing bars represent cooling energy use.

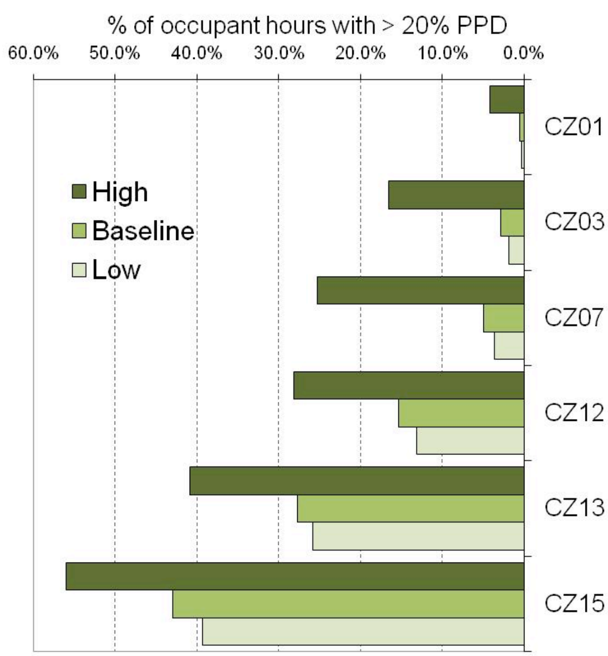

Figure 4: Comparison between high, medium and low internal gains scenarios for natural ventilation only. Bars represent adaptive comfort exceedance. Note the dramatic difference in the "middle" climate zones 3, 7 and 12.

5. CONCLUSIONS

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

The sensitivity of modeled outcomes to bracketed climate and operational parameters underscores that higher performing buildings are more strongly influenced by environmental conditions.

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.

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

6. 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 should be gathered over time to further characterize which strategies are working in the highly diverse building stock.

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

Metrics of exceedance and energy use intensity similar to those used in this report should be used to evaluate future Mixed-Mode simulation efforts and real-world case studies to facilitate cross-comparison and converge on an improved understanding of comfort and energy use in the wide variety of Mixed-Mode building configurations. This study provides only one set of data points, after all.

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

7. ACKNOWLEDGEMENTS

The authors wish to thank the following for their assistance with the work reported here: Katie Ackerly (CBE), Lindsay Baker (CBE), Fred Buhl (Lawrence Berkeley National Laboratory), Pat Cornely (De Anza College), Taylor Keep (Lawrence Berkeley National Laboratory), Cole Roberts (Arup)

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