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OCCUPANT CONTROL OF WINDOWS: ACCOUNTING FOR HUMAN BEHAVIOR IN BUILDING SIMULATION

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INTRODUCTION

Within the Center for the Built Environment (CBE) and in the greater building research and engineering community, there is growing interest in low energy cooling strategies that take advantage of natural ventilation. To support this rising interest, there is an associated need for more sophisticated models of occupant control of windows. All too often, existing models rely on simplifications that fit occupant behavior into standard control schedules that lack the responsiveness to environmental conditions demonstrated by real people in real buildings. This report is intended to bring these issues to the attention of the CBE audience, and to provide a summary of the origin, implementation, and applicability of the surprising variety of models predicting occupant window control now emerging in the academic literature.

BACKGROUND

People generally like to have control over their environment and they like having access to fresh air, breezes, and the outdoor environment. These facts are not just casual observations. They have been carefully demonstrated using empirical data to support (among other things) adaptive comfort standards in the US and EU. Now that those standards are operational, building designers and engineers are developing new design and control strategies and re-visiting some old ones to take advantage of the greater code-compliant potential for natural ventilation. At the same time, researchers are accelerating their efforts to develop and utilize analysis tools to better understand the performance of buildings with operable windows, and help the building industry make more informed decisions. A better understanding of the role and impact of the occupant has become a critical part of this work.

It has been demonstrated that naturally ventilated buildings in some climates can operate for the entire cooling season within adaptive comfort constraints without mechanical cooling. However, many buildings taking advantage of natural ventilation also use mechanical cooling systems either for specific zones, or only during times of the day or year when it is most needed. The term “mixed-mode” was coined by Bill Bordass to describe the whole class of buildings where natural ventilation and mechanical cooling coexist. A PIER-funded research project is currently underway at the CBE to use EnergyPlus to better characterize control strategies, modeling techniques, and thermal comfort criteria for mixed-mode buildings, specifically those taking advantage of radiant cooling and natural ventilation.

The synthesis of this work will be a set of climate zone specific recommendations on the mixed-mode strategies best able to ensure comfort while saving energy. As one might expect in reality and simulation, user control of operable windows is a major driver of both comfort and energy consumption. Thus, our task of evaluating the controls and predicted performance of mixed-mode buildings requires us to understand and model (as well as we can) the occupant control of windows. We are by no means alone in recognizing the importance of occupant behavior to the performance of many low energy buildings. There is a rich body of literature emerging on integrating models of occupant behavior into building simulation. Just in the past few years, there has been a dramatic increase in the number of academic papers on the subject. After introducing the central issues in more detail, this report summarizes the approaches taken in the literature and discusses their potential impact on our PIER project and mixed-mode building simulation in general.

ON THE ADAPTIVE PRINCIPLE

It is common in adaptive comfort literature to see variants on the adaptive principle that "If a change occurs such as to produce discomfort, people react in ways which tend to restore their comfort" (Humphreys and Nicol 1998). Many of the window control algorithms examined for this study either implicitly or explicitly rely on this assumption about occupant behavior. However, this is likely to be an incomplete explanation for observed behavior. A major element of the studies underlying the adaptive comfort model is the observation that people are more satisfied with their environment when they can exert personal control, feel connected to the outside environment, and have access to fresh air. This implies that rather than merely operating windows *reactively* to restore comfort, building occupants will tend to *proactively* operate windows simply because they prefer to have them open. Air temperature has been shown to play a significant role (especially in explaining window-closing behavior), but our ability to accurately predict window control behavior is likely to require us to model more than one dominant factor. At the very least, we should expect to find circumstances where thermal comfort criteria alone inadequately predict observed behavior.

Furthermore, the operation of shared windows in work environments requires explicit or implicit consensus. Given the range of comfort experienced by different people in different parts of a space, we cannot expect the window operation to be independent of interpersonal dynamics or consistently driven by the average vote. Given the prevalence of shared windows in office environments, the social factors mitigating their control are sure to require more study over time.

NATURAL VENTILATION VS. MIXED MODE

There have not been exhaustive studies dedicated to occupant behavior in buildings with operable windows, although they have begun to increase in recent years. For the most part, the studies examined by this report have been concerned with window operation in naturally ventilated (NV) buildings. Given the presence of operable windows in both cases, and the common aspiration for mixed-mode buildings to take advantage of free cooling whenever possible, we can expect some correlation. However, mixed-mode buildings span a range of strategies between (but not including) the extremes of free running NV and completely sealed. The adaptive comfort models used in the US and Europe clearly demonstrate that people apply different subjective comfort criteria in buildings that are naturally ventilated vs. sealed with air-conditioning (AC). Although there has not yet been a study detailed enough to definitively substantiate the relative impacts of the various causal effects, the different adaptive mechanisms have been described as altered met and clo levels as people adapt to the conditions of their buildings, shifted occupant expectations in free running buildings, and potential physiological changes from consistent exposure to warmer temperatures. Depending on the actual design and operational strategies employed in mixed-mode buildings, each of these effects can potentially differ from what might occur in a purely naturally ventilated building.

Logic dictates that comfort criteria in mixed-mode buildings should be somewhere between the adaptive criteria applicable to NV and the more conservative criteria traditionally applied to fully sealed buildings, but how close a given building is to one or the other will depend on its specific circumstances. We imagine that the degree to which occupants prefer or accept a wider temperature range would depend largely on factors such as how much direct access occupants have to the windows, dress code flexibility, and the percentage of the year that building is in free-running mode vs. having the mechanical cooling operating.

Since most of the studies about occupant control of windows are for naturally ventilated buildings, we will have to take some liberties in deciding how to apply them to mixed-mode buildings. Mixed-mode strategies that obviously impact either occupant control of windows or the subsequent building conditions, and will have to thus be taken into account, include:

- **Informational control systems** (such as red/green light systems): These are designed to inform occupants when the building control system senses that windows would be optimally closed or opened; these would ideally bring occupant behavior into better alignment with model expectations and "optimal" operation.
- **Automated window controls**: These manage air flow to control indoor conditions automatically according to specific control algorithms; they could potentially offset, enhance, or moderate the effects of manually controlled windows in the building.
- **HVAC override controls**: These typically employ window switches to disable or scale back HVAC system operation when windows are opened; they could potentially move indoor conditions more closely in line with a purely NV building.

SIMULATION OF WINDOW OPERATION

One of the challenges of incorporating models of human behavior into building simulation programs, is that they are based on different modeling approaches. This is also complicated by the differences in what one is able to program into a simulation, vs. the actual control strategies in a building.

Like other representations of aggregated human behavior, the emerging empirical models of window operation tend to be based on statistical algorithms that predict the probability of an event, say opening a window, given certain environmental conditions. They are based on observations of real windows in real buildings that allow statistical correlation between window state and temperature, time of day, season, indoor conditions, etc. In other words, they treat window operation as a *stochastic* (i.e. probabilistic) process where the odds of control events are based on environmental factors.

Building simulation packages, on the other hand, often model building dynamics using closed form solutions or numerical approximations of equations drawn from thermodynamics, fluid mechanics, classical mechanics, etc. Thus, they generally assume, are good at modeling, and are optimized for *deterministic* (i.e. fully predictable and repeatable) behaviors.

In most modeling tools, stochastic processes determined by human behavior like lighting control, occupancy, and window operation are forced to operate on a fixed schedule, or according to control rules similar to the sequences that run the mechanical systems. This is a compromise that plays to the strengths of software tools designed to simulate buildings with predictable mechanical controls. In actual buildings, we know that manual control decisions can deviate substantially from what these simplified models dictate and that mixed-mode buildings in particular must respond to occupant behaviors to be successful. By extension, the tools that are best able to support the design of mixed-mode buildings must also tackle occupant control and behavior head on. Referring to both the need for more empirical data and improved stochastic modeling facility, Voss (2007) wrote (British spelling and all):

> Due to the complex interactions between the outdoor climate, the building, the technical services and user behaviour, the success of a passive cooling concept is jeopardised at many points of the planning, building and commissioning process…More knowledge must be gained on typical user behaviour patterns concerning ventilation through windows, operation of blinds and manually activated components of passive cooling (ventilation flaps, etc.)…Simulation models can then be improved with statistically reliable user models.

Building simulation expert Joe A. Clarke, in his 2006 paper with Macdonald and Nicol on predicting adaptive responses, provides a fairly concise summary of the issue and his recommended approach:

> For example for a given condition one person may feel comfortable and another uncomfortable, the uncomfortable person may then have several options for controlling their environment, say opening a window; but then how far do they open the window and would they do exactly the same given the same stimulus on another occasion? Given these natural uncertainties it is not possible to develop a single deterministic description of occupant behaviour, a probabilistic model is required.

In generic terms, he observes that the probability P_d that a building occupant is experiencing discomfort is a function of environmental conditions:

P_d(discomfort) = f(thermal, indoor air, visual, and acoustical environment)

This then leads to a probability P_a of some action taken to mitigate the discomfort that is a function of an individual's discomfort, but also personality, social influences, etc.:

Pa(action) = f(discomfort, personality, social influences)

Clarke asserts that given a probabilistic model of discomfort, and a second probabilistic model of actions taken in response to that discomfort (along with other influences), it should be possible to model stochastic occupant behavior in buildings. He also points out that ESP-r (an open source building simulation package developed in Europe) is in a position to support such stochastic models. "When implementing a stochastic algorithm in a deterministic solver there is an inherent uncertainty defined in the results. This is due to the randomness of the process which requires testing. The framework for assessing the effects of uncertainty in ESP-r is well suited for this purpose." (Clarke 2006) In fact, ESP-r is the most common platform used to implement the models of occupant control developed in the papers summarized below.

THE INPUTS

Models of window control rely on a range of environmental inputs to predict occupant behavior. As early as 1951, Dick had quantified the relationship between outside air temperature (T_{out}), wind speed, and window operation in homes (Dick and Thomas, 1951). Warren's 1984 classic on "Window-Opening Behavior in Office Buildings" extended the list of influences on window operation to include virtually all of the elements that we see today (Warren and Parkins, 1984). Below is a list of potential inputs into a window control model (all have been used in the various models studied) and a brief discussion of each:

- **T_{out}**: Naturally, the outdoor temperature is an influence over window operation. If it is either too hot or too cold outside, we can bet most or all windows will be closed. In many cases outdoor temperature is such a strong driver of window control that many models use it as their only input. Robinson (2006) pointed out that such models are entirely independent of the design of the building and building conditions, but the statistical correlation is nonetheless significant.

- **T_{in}**: It is easy to imagine that indoor temperature, with its impact on occupant comfort, is a primary driver of window operation. However, the relationship is not cut and dry. Indoor temperature and outdoor temperature tend to co-vary, so one is often a crude stand in for the other. We also might imagine that no matter the indoor conditions, windows will not stay open for long if the outdoor conditions are worse. Thus window control initiated due to indoor temperature can be quickly reversed by outdoor temperature. Furthermore, opening a window under more favorable outdoor temperature conditions will tend to change the indoor temperature, so models involving indoor temperature often apply some sort of dead band or distinguish criteria between open and closed window states. One version of the Humphreys model is based on a regression of T_{out} and T_{in} together (Humphreys et al., 2008).
- **Wind**: The wind affects the volume and velocity of air coming through the window. Naturally, high winds should be expected to cause users to partially or fully close their windows. However, much of the data gathered on window operation is binary: they are recorded as either open or closed. "Less open" is still open in those data sets. Still, contributions from 4-10% of behavior are attributed to wind.
- **Insolation**: The direct effect of radiative heating from the sun shows up as an explanatory variable in several models of window operation. For example, in a few studies, window control behavior is demonstrated to be different between cloudy and sunny days.
- **Façade orientation**: Most likely due to radiative heating from the sun, different façade orientations of the same building will often produce different control responses.
- **Air quality**: Although it is difficult to quantify, "fresh air" and related terms often top the list of self reported reasons for window operation. Obviously a common reaction to odors or other acute indoor air quality concerns is to open a window. However, these survey responses also suggest that a general desire for fresh air may drive window operation under thermally acceptable conditions. These cases are difficult to meaningfully include in a general purpose model of behavior, but, starting with Warren's 1984 paper, differentiating between window operation for ventilation vs. temperature control is an important theme in the literature.
- **Noise levels**: Outdoor noise can easily cause an occupant to close a window that would otherwise be open. This effect is very site specific and not expected to dominate in general. However, there are some sites where this concern will be a major influence on behavior. This can be seen in site-specific differences in window behavior across façade orientation or elevation. Although it has been included in regression analysis (Warren 1984), noise is often ephemeral and has not been included in proposed generalized models of behavior.
- **Occupancy patterns**: As one might expect with an occupant determined phenomena, occupancy patterns directly affect patterns of window control. This seems obvious, but some window control models actually model occupancy before using occupancy to predict window control. It has also been observed in several data sets that occupants are overwhelmingly more likely to adjust windows right after arriving (open) at or just before leaving their building (closed). This "frame of mind" driven control results in some models using different criteria for transition periods.
- **Season**: Occupant expectations of comfort, and clothing levels change with the seasons. Several studies have found markedly different behavior across seasons.

- **Current window state**: Many studies find that an open window is likely to stay open and a closed window is likely to stay closed. This state (or path) dependence in the basis for models that predict the probability of window states "surviving" over time. One method of determining the future outcome of a process based on its current state is through "Markov chains" that use matrix algebra to apply different probabilities of control events based on the current state.
- **Social factors**: Anyone who has ever worked in a shared office space can tell you that social dynamics can also influence window control behavior. Unspoken assumptions of preference, varying personal criteria, and various forms of social etiquette can produce occupant behavior that is substantially different from modeled personal preference. These factors are hard to model explicitly. However, some of the studies (e.g. Haldi 2008 and Herkel 2005) gathered data from office spaces with double or triple occupancy. The observed behavior in these studies can be assumed to include the influence of social factors.

Naturally, window control decisions have a lot to do with thermal comfort and air flow, but studies have shown that all of the above inputs play important roles in explaining behavior. For better or worse, most modeled control strategies include just a handful of the inputs above. The specific, narrow applicability of many of these factors suggests that savvy modelers should work to develop an intuitive feel for which circumstances require accounting for which inputs.

COMPETING MODELS OF WINDOW CONTROL

Traditionally, window operation is modeled in simulation software according to a fixed schedule or by using indoor temperature (or the difference between indoor and outdoor temperature) to trigger a window opening at a threshold and proportional control above that threshold. Improved models are entering the mainstream. Rijal (2008) summarized the situation as follows:

> Various window opening models have been put forward in recent years, based on indoor or outdoor temperature (Warren and Parkins 1984, Fritsch et al. 1990, Nicol et al. 1999, Raja et al. 2001, Nicol and Humphreys 2004, Inkarojrit and Paliaga 2004, Yun and Steemers 2007, Herkel et al. 2008). Fritsch et al. (1990) proposed a model based on Markov chains (probabilities of window operation based on current state) for random window opening prediction. Pfafferott and Herkel (2007) used Monte-Carlo (multiple runs with randomly determined outcomes consistent with the observed probabilities used to explore all the outcomes that are within the range of expected behavior) simulations to predict user behavior. Herkel et al. (2008) develop a window opening model based on outdoor temperature and occupancy levels. The way in which these occupant behaviors work is not yet fully understood and yet realistic patterns of occupant behavior are needed in building simulations.

The table that follows offers an at-a-glance summary of the leading models, their inputs, and the data they are based on to help tease apart and summarize all this academic activity.

We had expected that others would be asking the same questions we have been about modeling occupant controlled windows, but were quite surprised by how much recent work has been published on the subject. As this report's summary of the modeling inputs and the above summary of relevant studies show, there is a fairly coherent picture shaping up of the various potential control strategies and their proper application. However, our specific focus with this current project is on mixed-mode buildings with radiant cooling and operable windows. Given their reliance on thermal mass, and tendency to feature concurrent operation of the slab and windows, such buildings present some unique modeling challenges. In the context of window operation, we can expect that users in a building with radiant cooling will feel cooler than the dry bulb temperature alone would imply, and may consequently *behave* as though the indoor or outdoor temperature is a few degrees cooler than measured. In the mornings when occupants arrive (and data suggests much of the daily window opening occurs during this time), the slab is typically pre-chilled and may actually discourage window operation. These are just a few examples of the challenges and research questions we face as we apply the existing algorithms, based primarily on research in naturally ventilated buildings, to the simulation of mixed-mode buildings with radiant cooling.

Table 1. Summary of existing models of occupant control of windows.

Author & Date	Inputs	Data	Description/Results
Warren (1984)	T_{out}, season, noise, insolation, wind	Photographic survey of 5 buildings 30 miles north of London. One photo at 11am and a second at 2pm every day for 13 weeks from February 26 to May 25. Tracked large and small windows separately.	Laid the groundwork for most or all subsequent studies. Found many environmental factors influence window control. Suggested both a ventilation role and temperature role for window operation. Speculated on seasonal variations in control behavior. Included an occupant survey where fresh air was the most frequently given reason for window operation.
Fritsch (1990)	T_{out}, current state	The model is based on measurements taken every half hour in four office rooms facing south in the LESO building.	Markov chains for modeling winter window operation. "The first approach was to analyse the autocorrelation functions of the data… the relationship between two successive measurements (0.5 h delay) is strong: this simply states the fact that a window is usually left in one position for long periods of time."
Inkarojrit & Paliaga (2004)	T_{in}	The photographic survey was carried out over a period of nine working days from September 24 to October 4, 2002. Three building façades on the north, east and south orientation were digitally photographed four times each day at 9:00, 13:00, 16:00, and 18:00.	Grounded in adaptive principle. Uses indoor temperature for regressions. "Results show that percentage of open windows varies between different façade orientations. Results show that there is a statistically significant positive correlation between the proportion of open windows and interior operative temperature for all façade orientations. The paper discusses the possibility of using indoor temperature as an indicator for predicting percentage window opening in addition to outdoor temperature and outdoor wind speed."
Humphreys & Rijal (2008)	T_{out}, T_{in}	Longitudinal and transverse surveys were conducted in 15 office buildings (seven NV and 2 AC buildings in Oxford, three NV and three AC buildings in Aberdeen) and year-round field investigation of the use of building controls (windows, doors and fans) in 33 Pakistani offices and commercial buildings.	Grounded in the adaptive principle that "If a change occurs such as to produce discomfort, people react in ways which tend to restore their comfort". Applied logistic regression to their binary open/closed data as a function of both T_{in} and T_{out}.

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Yun (2008)	T_{in}, current state, time of day	Field study from June to Sept', 2006 in offices with and without night ventilation, located in Cambridge, UK. T_{in} in each office were monitored by two stand-alone data loggers that recorded the temperature at 10 min intervals. State data loggers provided continuous monitoring of the window state.	"The Yun algorithm approach, of defining different user types and different probabilities as a function of time of day or on arrival, may offer advantages in identifying the critical roles of occupant behaviour in naturally ventilated buildings and of better reflecting occupant window-control behaviours discovered in the monitoring activities"
Haldi (2008)	T_{in} for opening, T_{out}, time of day (occupancy), current state, active/passive users	Measurements recorded between 2002 and 2008 in 14 offices of the Solar Energy and Building Physics Laboratory of EPFL.	Very quantitative comparative approach between logistic regression, Markov chains, and survival analysis. "Results from this work suggest that a model based on survival analysis is both more robust and more computationally efficient than the alternative Markov and logistic distribution models tested." Suggests a distinction between "active" and "passive" occupants. "Actions on windows most commonly occur when an occupant arrives or leaves his office." "Leaving windows open is influenced by indoor and outdoor conditions, while the duration for which windows are left closed depends mainly on indoor conditions."
Pfafferott & Herkel (2008)	T_{out} (T_{in} found to co-vary with T_{out}), time of day (occupancy), current state, season	"Field study of manual control of windows which has been carried out in 21 individual offices within the Fraunhofer Institute's building in Freiburg, Germany, from July 2002 to July 2003. Window status, occupancy, indoor and outdoor climatic conditions were measured every minute." Very high resolution data. Differentiation between window types, and degree of opening.	"The analysis of user behaviour reveals a strong correlation between the percentage of open windows and the time of year, outdoor temperature and building occupancy patterns. Most window opening is connected with the arrival of a person." "While the highest percentage of open windows was found in summer, the highest frequency of opening and closing windows occurs in autumn and spring, since weather conditions change most often during these seasons."

A FIRST CUT: SIMULATION OF WINDOW BEHAVIOR IN ENERGYPLUS

As mentioned earlier, our project is using the EnergyPlus simulation program, and a critical challenge for us is how to simulate occupants' use of windows. EnergyPlus models natural ventilation using outside air coupled to a bulk airflow model by surface pressure coefficients. Air flow rates are determined by wind speed and direction, those pressure coefficients, and the percentage of window surface area that is open. Window surface area, in turn can be hard coded or controlled using the same type of schedule object that is used to dictate occupancy schedules. There is currently work underway at another University to develop more sophisticated control inputs for windows, but because of the timing, our project is unlikely to benefit directly from that work. For the time being, we need to live with the fact that EnergyPlus was not designed with stochastic processes or sophisticated window control algorithms in mind. To help compensate for these limitations, we have devised a pre-processor that can generate an hour-by-hour operating schedule based on weather data, time of day, season, and other external factors.

Our pre-processor parses Energy Plus weather files, calculates average, max, min and other values for hourly, daily, and monthly time steps, and runs through these values with specific "Schedule Strategy" objects that write out Energy Plus schedule information based on the weather data. To the extent that the inputs to the window operation models found in the literature can be limited to weather file data (T_{out}, incident solar radiation, humidity, wind speed, etc.) or temporal factors (such as seasonal or time-of-day probabilities), we can readily use this "Schedule Strategy" framework to generate window operation schedules consistent with observed behavior.

SUMMARY

The advent of adaptive comfort standards and growing interest in low energy building designs are driving a trend toward buildings designed to take advantage of natural ventilation. The purpose of this paper is to examine rapidly evolving models of occupant window control with an eye toward supporting improved simulation, design and operation of buildings. To that end, we have used this research to improve simulations in our current project examining radiant cooling and natural ventilation in California climates.

The two dozen or so papers consulted while compiling this report were generally based on studies of naturally ventilated buildings (as opposed to mixed-mode buildings), and put forward a large variety of modeling strategies based on different data sets from a variety of buildings located around the world. It might be easy to conclude that window control modeling is a bit of a free for all at the moment, but much of the work cited explores related techniques and the big picture is quite consistent.

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

- Human behavior is not *deterministic*, but aggregate tendencies are recognizable in the data that has been collecgted. Models based on the *probability* of observed phenomena (like window opening and closing) 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 and survival analysis can use the current state of the window or other time varying factors to influence the outcome.
- People do not typically manage their windows very actively or regularly throughout the day. Thus, we see the most opening and closing behavior associated with arrival and departure from the office. We also see 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.

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 produce good results.
- 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 BOTTOM LINE: WHICH MODEL TO CHOOSE?

For the purposes of simulation, outdoor conditions are limited to the information available in the weather file and indoor conditions are limited by the strengths and level of detail of the simulation itself. A good starting guideline is to choose the model most compatible with the data that you have access to and that is no more complicated that you need. In cases of regimented usage or predictable weather conditions, even simple schedules, coupled with some intuition and common sense, will often approximate occupant behavior well enough to support believable aggregated airflow, comfort, and energy consumption results.

However, in the case of high performance buildings, particularly mixed-mode buildings, it is desirable for automated building systems to be responsive to, or encourage and enforce, specific patterns of window control. In buildings where natural ventilation coexists with other strategies, occupant comfort and building energy use can be significantly influenced by subtle changes in control strategies. In these cases, we want models that can account for greater window operation at occupant arrival and departure, the tendency for windows to stay in their current state, seasonal variations in control, and, of course thermal comfort and ventilation.

LOOKING FORWARD

Based on the number of publications, 2008 appears in the literature to be a golden age of research about occupant control of windows, but there are still many questions left unanswered. The new information emerging from these most recent studies leads to several promising avenues of further research. In our mind, most important among these include:

- 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.

- Further empirical study of mixed-mode and NV buildings is needed to better understand the energy and comfort consequences of building control strategies that interact with human behaviors. Specifically, we need to better characterize 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 completely sealed to free running NV. 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.

Simply put, people like having windows that they can open, for a variety of reasons. As building professionals, we are beginning to understand the tools and techniques we can use to provide operable windows in commercial buildings that deliver superior occupant satisfaction while dramatically decreasing energy consumption. Through the study of occupant behavior and mixed-mode control strategies compatible with adaptive comfort, we can learn new ways to keep people comfortable without warming the rest of the earth.

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