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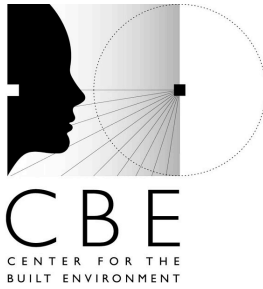
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SUMMARY REPORT APRIL 2011

WINDOW USE IN MIXED-MODE BUILDINGS: A LITERATURE REVIEW

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INTRODUCTION

Designs for low-energy office buildings increasingly incorporate operable windows for the benefits of personal control, environmental quality, and architectural value. However, integrating operable windows with mechanical systems to achieve their full benefits is an unresolved energy challenge. If operable windows are left up to the control of the occupants, designers run the risk of putting unpredictable or unnecessary loads on the HVAC system, causing air pressure balancing issues, or causing unreliable or unwanted air change rates. However, if windows are automated for natural ventilation, the building design loses the comfort benefits, amenity, appeal and robustness of manually-controlled windows.

New buildings with operable windows situate themselves in an ongoing debate about the efficiency benefits of manual versus automatic building control. The decision to use manually-operated windows rests on assumptions about their value and a faith in the idea that occupants will actively participate in maintaining indoor environmental quality (compared to a conventional, sealed office environment). Concurrent with this debate, there has been growing interest in occupant behavior as the new low-hanging fruit for improving a building's energy performance and closing the gap between predicted and actual performance. Emerging research that is relevant to these topics includes studies that better characterize and model behavior, as well as those that look at the impact of information systems and feedback on energy-using behaviors. However, these research questions are seldom considered together. This literature review draws together a number of topics that contribute to our understanding of building-occupant control interactions in mixed-mode buildings, beginning with the known (and as-yet unresolved) benefits and limits of operable windows when combined with mechanical cooling.

CONTENTS

1. The rationale for operable windows	3
Health and productivity	
Indoor air quality	
Personal control and thermal adaptation	
2. Integrating operable windows with mechanical cooling	5
Classifying mixed-mode operating strategies	
Performance of mixed-mode buildings	
3. Factors that drive window use	8
Environmental factors	
Psychological and social factors	
Summary of window control models	
4. Feedback, knowledge, and informed behavior	11
System legibility	
Knowledge	
Feedback	
5. Summary	15
References	16

1.0 THE RATIONALE FOR OPERABLE WINDOWS

The operable window is a mediator between indoor and outdoor environments, providing choice between a connection with or a barrier from a range of environmental factors (gaseous pollutants, particulates, sounds (noise), temperature, humidity, air movement, light transmission, view, and precipitation). Whereas fixed windows assume the creation of a homogenous, “ideal” indoor environment that is *protected* from the variability of the outdoors, operable windows inherently welcome the benefits and delights of this variability.

In the era before air conditioning, fluorescent lighting, and high-density urban construction, typical office designs depended on operable windows for environmental quality. Buildings had narrow floor-plates, private operable windows, and transom windows in the corridors for cross-ventilation. The ability to control temperature and humidity and mechanically filter air behind a fixed glass facade became a reality in the 1930s, beginning with the Philadelphia Savings Fund Society Building. By the 1950s, this practice was the norm. By 2000, Americans’ expectation of narrow-band climate control became embedded in our culture as well as building design practice (Ackermann 2002).

In recent decades, the building industry has started to re-examine operable windows in commercial buildings. Most people attribute this trend to the “green” building movement, but this is probably too generic an explanation; rather, the choice between operable and fixed windows has firm roots in the attitudes people have about what makes a “good work environment,” which have changed through the 20th century. While this change goes hand-in-hand with unprecedented market transformation for “green” buildings, it is important to discern that the decision to include operable windows in a contemporary commercial building is based first on an *idea* about their benefits that is then subject to reconciliation with how energy efficiency is handled in conventional practice (Lin, 2005). Across the board, operable windows are ultimately chosen not based on a consensus of their environmental benefits but based on someone’s *advocacy* for them (ibid). In advocating for operable windows, developers, owners, and building designers elevate their building over the conventional office model by evoking the familiar, domestic-scale, touchable, livable environment.

The following sections outline what is known and what is still under debate about the environmental and energy benefits of operable windows.

1.1 HEALTH AND PRODUCTIVITY

The health and productivity benefits of operable windows are minimally debated in the literature. The most extensive and heavily cited study drawing a connection between natural ventilation and health was a cross-sectional analysis of 12 field studies from six countries in Europe and the USA, totaling 467 buildings with approximately 24,000 subjects (Seppänen and Fisk, 2001). The air-conditioned buildings showed 30-200% higher incidences of sick building syndrome symptoms compared to naturally-ventilated buildings. Although smaller in scope, results from Hedge (1989) and Rowe (2003) conclude that these results extend to mixed-mode buildings. Carnegie Mellon’s Building Investment Decision Support tool (BIDS), has claimed that buildings with operable windows (naturally ventilated or mixed-mode) can lower health costs by around 1% and result in a 3-18% productivity gain. These results are modeled based on a large database of data from building owners and researchers from across the globe, but are not demonstrated in the field.

I.2 INDOOR AIR QUALITY

Under the right conditions, open windows can increase air change rates and improve indoor air quality, but how much and at what time is inherently unpredictable. The Chartered Institute of Building Service Engineers (CIBSE) in the UK indicates that, in naturally-ventilated buildings in cities (in the U.S., usually pre-World War II buildings with operable windows), 2-5% of windows can be expected to be open for most of the year, providing ventilation rates of 0.5 to 1.0 air changes per hour (ACH) (CIBSE 2000). They go on to speculate, based on a limited number of case studies in the UK, that these numbers are even lower in mixed-mode buildings, suggesting that manually operated windows can not be relied upon for maintaining adequate background ventilation. Hellwig (2008) similarly found operable windows not to maintain adequate temperature or air quality conditions in some European Schools. The implication is that people are not sensitive enough to the build-up of CO² to rely on them to provide themselves with adequate ventilation while they are doing other things.

I.3 PERSONAL CONTROL AND THERMAL ADAPTATION

One central argument in favor of operable windows is the idea that providing this type of thermal control to occupants enhances their overall workplace satisfaction and relaxes their thermal comfort expectations. The basic theory of thermal comfort used in international standards (Fanger, 1970; ISO, 1994) defines ideal operative temperatures for the human body according to the predicted percentage of people who are dissatisfied (PPD) at those temperatures, based on extensive controlled laboratory experiments. While this model is widely accepted as a way to describe heat balance in the human body under static conditions, many researchers and engineers contend that this model ignores the role of various contextual factors that influence thermal perception and has reinforced an over-dependence on tight and energy-intensive mechanical temperature control in buildings.

Drawing from a world-wide database of field studies, de Dear and Brager (1998a) proved a positive correlation between acceptable indoor temperatures (minimum and maximum “adaptive temperatures”) and monthly average outdoor temperatures. This “adaptive” model of thermal comfort has been incorporated into standards ASHRAE 55 (2010) and EN 15251 (2007) in the U.S. and Europe as a basis for allowing broader thermal variations in naturally-ventilated buildings. The phenomenon of thermal adaptation can be attributed both to relaxed thermal expectations from past thermal history in the building, as well as personal access to thermal controls (Brager and de Dear 1998b).

Numerous field studies in naturally-ventilated buildings have found a strong link between the perception of personal control and thermal comfort (Paciuk, 1989; Oseland, 1997; Baker and Standeven, 1996; Humphreys and Nicol, 1998; Leaman and Bordass, 1999; Roulet et al 2006; Yun, Steemers, Baker 2008; Haldi and Robinson 2008; Andersen, Toftum and Olesen, 2009). Brager, Paliaga, and de Dear (2004) measured the behavior and subjective thermal response of occupants in a single office building and found a 2.7°F difference in the reported “neutral” temperatures of occupants with “high” and “low” degrees of control.

The inclusion of the adaptive comfort model in international standards caused a shift in the standard of care for comfort in buildings based on the provision of personal control, and launched a wave of current research towards developing environmental control algorithms that better account for how building occupants interact with features such as windows. Brager and de Dear (1998b) summarize the advantages of developing control algorithms that incorporate adaptive actions, as follows:

- Energy savings from setpoint temperatures that track outdoor weather
- Comfort improvements by relating mechanical control to the “context-dependent and variable preferences of the occupants”
- Enabling an integrated approach to designing buildings involving both “passive” and “active” modes of operation.
- Enabling the use of adaptive control features as a low-cost retrofit strategy in lieu of air conditioning installation or replacement

Each of these opportunities implies a theoretical potential for mixed-mode solutions whereby the combination of thermal control features – specifically, operable windows – with active cooling systems allows for a reduction in mechanical system operation and improvements in comfort. However, it has been difficult to verify whether adaptive comfort and other benefits of operable windows apply to mixed-mode buildings (section 2.0), and it has been equally challenging to generate reliable behavior models and optimization tools that are needed to reap the potential benefits (Section 3.0).

2.0 INTEGRATING OPERABLE WINDOWS WITH A MECHANICAL COOLING SYSTEM

2.1 CLASSIFYING DESIGN STRATEGIES

The concept of mixed-mode cooling was originally proposed by Max Fordham and Partners, revised by William Bordass and Adrian Leaman of the Usable Buildings Trust, and described at length in CIBSE (2000) and Ring (2000). The definition and objectives of mixed-mode as a design strategy is continually under revision, as there are no prescriptive design guidelines. Existing mixed-mode buildings are furthermore so case-specific that it is difficult to establish a satisfying classification scheme or performance metric to evaluate performance and establish best practices.

The most widely used mixed-mode taxonomy differentiates three main operational strategies: concurrent (where natural ventilation and cooling can occur in the same place at the same time); change-over (where they occur in the same place at different times); and zoned (occurring in different places). A fourth class, “contingency,” describes buildings that are “natural-ventilation-ready;” they may normally operate like a conventional building, but in the event of a power outage or other disruption, built-in measures keep the building livable. Given the diversity of existing mixed-mode buildings, this taxonomy is useful to describe what is happening within a given space, but it has insufficient resolution to fully describe whole-building operations with all of the complex factors that are involved in making design decisions (Brager, Borgeson and Lee 2008).

Bordass suggested that mixed-mode buildings may be classified according to the level of innovation or aggressiveness the design team is aiming for. He distinguishes “traditional,” “integrated,” and “opportunistic” types, according to the technological solutions that have been typically achieved in real, completed buildings. “Traditional” refers to a fairly conventional air conditioning system combined with simple operable windows, where the windows are primarily a value-added amenity for occupants. This type is most commonly concurrent, and energy savings, if any, is not dramatic. The “integrated” design approach is typified by a building that relies little on mechanical refrigeration and may incorporate night ventilation or thermal mass effects to reduce loads and allow for alternative forms of cooling such as radiant slab. “Opportunistic” is a catch-all term for more advanced approaches that achieve an almost entirely naturally-ventilated building. Ring (2000) proposed that mixed-mode buildings are best classified based on how natural ventilation and

mechanical cooling strategies, at varying levels of complexity and automation, are combined; the options are summarized in Table 2.1.

Table 0.1 Window and Mechanical System Options for Mixed-Mode Buildings

	Window Systems	Mechanical Systems
Increasing cost and/or complexity ↘	<p>Simple Manual Operable Window The most basic and common way to allow natural ventilation. Usually refers to view-level windows.</p> <p>Multi-element operable window More expensive but sometimes more preferred to allow more precise control over ventilation, air movement and heat exhaust functions of windows</p> <p>Automated operable window Actuators control some or all elements, may be used exclusively for night ventilation, may or may not have manual over-ride.</p> <p>Advanced Natural Ventilation (ANV) Used by Bordass et al (1998) to describe large, complex buildings with sophisticated automated natural ventilation systems.</p>	<p>Minimal “Background” Ventilation Trickle ventilators, stack assist fans and other low-energy devices that induce a minimal amount of ventilation.</p> <p>Mechanical (economizer) Ventilation Outside air (no refrigeration) centrally delivered to larger, more complex buildings</p> <p>Static Cooling Radiant cooling panels, chilled beams</p> <p>Single zone air conditioning Window or wall AC units, PTACs, RTUs with one system serving one zone.</p> <p>Distributed Air Conditioning Fan coil units, variable refrigerant volume heat pumps and water-source heat pumps. Units may include dedicated ventilation intake or paired with a separate ducted ventilation system.</p> <p>Central Air Conditioning One or more central air handling units (AHUs), each providing both ventilation and cooling. Individual zone controllers control, mix, and/or reheat supply air at the zone.</p>

(simplified from Ring 2000)

Because mixed-mode design is ultimately based on project-specific considerations, Brager, Borgeson and Lee (2008) propose a new framework that places concurrent, changeover and zoned classifications in the context of how “spatial,” “temporal,” and “practical” factors that drive a mixed-mode project. Based on a series of case studies of mixed-mode controls in existing buildings, they underscore the lack of consensus in the industry regarding an ideal balance of manual control versus automation. They find that a wide variety of input values, modifying criteria, and control functions (ventilation, thermal comfort, space cooling and structural cooling) are used, even among projects with similar goals and approaches.

2.2 PERFORMANCE OF MIXED-MODE BUILDINGS

Assessing the performance of mixed-mode buildings is particularly challenging; energy simulations are limited by oversimplified or unrealistic models of human behavior and HVAC control (Arnold 1996, Daly 2002, Rowe 2003, Cron et al 2003, Ogden et al 2004, Emmerich and Crum 2005). Meanwhile, measuring energy savings and comfort satisfaction in real buildings suffers from the

common difficulty of isolating the performance benefits of natural ventilation alone. (e.g. case studies generated in Torcellini 2006). Furthermore, the advantages of mixed-mode dictate that designs are selected according to the unique circumstances of the project, making quantitative results difficult to generalize.

Performance assessment depends in part on whether the adaptive comfort model is applicable to mixed-mode buildings. Simulation results suggest that the comfort model that is used to evaluate a mixed-mode design makes a difference of about 10 percentage points in the number of hours that can be claimed to exceed acceptable limits (Brager and Borgeson, 2011). The comfort standard used in North America (ASHRAE 55) restricts the use of the adaptive model to buildings that are purely naturally ventilated, while standards in Europe expand its application to mixed-mode buildings only during those times when the building is operating in a ‘free-running’ (natural ventilation only) mode (ASHRAE 2010; EN 15251, 2007).

Very little is known about how occupants take adaptive measures (use the windows for comfort) in buildings with a mechanical cooling system. Preliminary findings suggest that people in mixed-mode buildings generally use windows similarly to those in naturally-ventilated buildings (Rijal, Humphreys, and Nicol 2009). However, the type of control system or the appearance of the building might have a real effect on expectations.

In terms of comfort, mixed-mode buildings tend to receive high occupant satisfaction scores (Bordass et al. 2001, Rowe 2003, Brohus et al. 2003, Principi et al. 2003, Brager and Baker 2008). Bordass and Jaunzens (1996) found that occupants of mixed-mode buildings report their perceived air movement and peak temperatures to be better than occupants in naturally-ventilated or air-conditioned buildings.

Post-occupancy studies in real buildings, although they don’t attempt to quantify energy or comfort achievements, are perhaps more useful to understand the success of particular design strategies. For example, Lomas, Cook and Short (2008) find, during the commissioning of a deep-plan mixed-mode library in Chicago, that easily accessible and visible control points for air flow was the chief benefit of the mixed-mode approach, while several operational issues – including poor louver performance, incorrect control logic and construction detailing – could be attributed primarily to coordination failures and miscommunication among members of the design team. This type of detailed, qualitative post-occupancy study targeting specific success factors in design and operation of mixed-mode building controls is generally lacking.

The PROBE project in the UK represents perhaps the most comprehensive attempt to characterize how well mixed-mode design ideas materialize in operation, focusing on the successes and failures of combining automatic and manual control solutions. The principal finding from this work is that buildings that have more automated and complex naturally-ventilated control solutions require tighter management to ensure performance. They cite the following common shortcomings of automated window controls (Cohen, et al 1998):

- Draughts from windows opened to remove heat on sunny but cool days
- The inability to close windows which were letting in fumes, noise or insects
- The denial to occupants of the opportunity to trade off different types of discomfort (noise, versus overheating)

The project establishes important principles of automation, including the claim that automatic controls must be “imperceptible to the user;” if not, user overrides must be provided. Manual window operation is also limited. The CIBSE Applications Manual 13 (CIBSE 2000) for mixed-mode buildings advises avoiding manual window control by occupants in light-weight buildings

subject to high internal loads, since occupants are “unlikely to respond early or frequently enough.” Operable windows are most appropriate where the mass of the building does most of the work to attenuate temperature extremes.

Experimental studies that investigate the dynamics of manual and automatic thermal control are also informative. Evans (2008) took a closer look at the cycles by which manual and automatic control of air conditioning takes place and points out a tradeoff with thermal storage benefits. While an air conditioner will automatically cycle on every hour to maintain temperatures within a three-degree band (72-75 F), people will exercise control on a 3-4-hour cycle, allowing temperatures to oscillate between 70 and 81 F. If control is left up to the occupants, the space is likely to reach more extreme, uncomfortable conditions, but there is also a higher potential for thermal storage to play a role in regulating loads. The author proposes modified automated strategy, an “intelligent” temperature control, that allows the average indoor temperature to ramp up and down slowly throughout the day to allow thermal mass of materials in the building to take some of the load.

In sum, although there is research to support energy and comfort benefits of mixed-mode buildings, standards and design guidelines do not provide a good way for designers to account for these benefits, because they are difficult to reliably quantify. As demonstrated in the PROBE studies, Much of the performance of mixed-mode buildings may ultimately be tied up in the psychological, social and logistical factors relating to how building users understand and operate windows and other controls.

3.0 WINDOW CONTROL FACTORS AND BEHAVIOR MODELS

The next two sections outline relevant research in human-building interaction. The broader fields of research within which these studies are diverse, including those that attempt to predict behavior (this section) as well as those that attempt to quantify the energy impact of behavioral diversity and analyze the factors driving this diversity. This includes how behavior is influenced, and how control interfaces contribute to break-downs in building legibility and efficient operation (section 4.0).

Historically, window behavior has been modeled with very limited evidence from the field. Assumptions about behavior are made based on generic occupancy patterns or outdoor conditions, usually outdoor temperature. Models also commonly assume occupants will behave in accordance with ideal (design) thermal conditions and ventilation rates. This is particularly problematic when analyzing air flow rates from window operation, as human perception of and adaptation to elevated CO₂ levels is not reliable for maintaining indoor air quality.

For the most part, attempts to characterize human interactions with windows and other controls are grounded in the principle of adaptation, which states: “If a change occurs such as to produce discomfort, people react in ways which tend to restore their comfort.” (Humphreys and Nicol, 1998). Adaptive actions either fall into the category of modifying the environment – such as adjusting the thermostat, ceiling fan or window – or modifying one’s clothing or activities to adapt to changing conditions.

3.1 ENVIRONMENTAL FACTORS

Field studies about window operation and its impact on energy consumption (heating, primarily) date back to the 1950s. Studies in homes found that outdoor weather (temperature, humidity, wind) could explain a majority (~65-70%) of window interactions (Dick and Thomas 1951; Brudrett 1977). Extending this investigation to office buildings, Warren and Parkins (1984) applied similar

methods to five naturally-ventilated office buildings in the UK and found outdoor air temperature to explain 76% of variance in window state, and that solar gain and wind speed also played a role (8% and 4% respectively). In addition to field monitoring, the study asked occupants why they used windows, and found fresh air to be the most common reason for opening windows in both winter (51%) and summer (74%) and of equal importance to “keeping cool” during the summer. It should be noted that “air movement” was not provided as a selection. Although air quality wasn’t used as an independent variable for analyzing behavior, an analysis of small/slightly open windows compared to large open windows led to the conclusion that there are two control modes for windows, one related to air quality and the other to temperature.

Until recently, subsequent attempts to characterize and predict window operation have been based exclusively on outdoor and/or indoor temperatures (Fritsch et al 1990; Nicol 2001; Raja et al 2001; Nicol and Humphreys 2004; Inkarojrit and Paliaga, 2004). The models are based on empirical data of control actions collected predominantly from buildings without cooling systems in Europe and the UK. The focus on temperature makes intuitive sense given that windows aren’t likely to be opened if it is too hot or cold outside, and given the important role of indoor temperature in maintaining occupant comfort. However, consensus has not been reached about whether to use indoor temperature, outdoor temperature or both as the independent variable when simulating window use, because of the inherent interactions between indoor and outdoor temperature in naturally-ventilated buildings. For instance, rising indoor temperatures might drive the opening of windows, but how long the window stays open might depend more on outdoor temperature. As Robinson (2006) points out, the use of indoor temperature is more appropriate given that models based on outdoor temperature alone are entirely independent of building design and context.

Fritsch (1990) was the first to propose a mathematical model to predict window state based on a strong correlation observed between window angle and outdoor temperature. A discrete Markov chain was used to predict the transitions among six window states. Wind speed and solar radiation were ruled out as significant parameters. Nicol (2001) and Nicol and Humphreys (2004) proposed the use of probability distribution for window state based on outdoor temperature and then ultimately indoor and outdoor temperature. The correlations were based on empirical data including “binary” (open/close) states of windows and other controls, collected in the 1990s from naturally ventilated buildings in the UK, Pakistan and 5 European countries. Their method later evolved into the “Humphreys window opening algorithm,” which used multiple logistic regression based on outdoor and indoor temperature combined with a “deadband” to distinguish temperature triggers for opening and closing actions (Rijal et al, 2007).

The research team validated their model by comparing observed and simulated open windows, and tested their model using the open-source ESP-r simulation tool to demonstrate the comfort impact of various design features, such as external solar control and thermal mass, and the resulting window use behavior and impact on heating demand (ibid).

The Humphreys algorithm is useful for analyzing naturally ventilated buildings in order to avoid the addition of air conditioning. Although the correlations with temperature are significant, such models are not agile enough to address interacting factors that inevitably influence behavior, such as non-thermal comfort needs or environmental constraints. In part, this is because these parameters simply aren’t present in the datasets with enough resolution. There is also a limitation in the method of logistic regression, in which the probability of an outcome (open window) is determined, rather than determining the probability that a variable will change from one state to another.

3.2 PSYCHOLOGICAL AND SOCIAL FACTORS

In addition to interacting factors, focusing on the adaptive principle necessarily ignores psychological, social, temporal and other reasons for using windows that might be *pro-active*, rather than adaptive. For instance, researchers have found a strong correlation between window adjustment and time of arrival and departure (Yun and Steemers 2007; Haldi and Robinson 2008; Pfafferott and Herkel 2008). Although these studies use this analysis to modify algorithms for predicting behaviors, one implication of their observations that is not further studied is that many window control actions could be a function of routine, habit or state of mind rather than simple environmental response. In fact, related research on thermostat control has found that major differences in control patterns were largely related to the habits and routines of households (Xu et al. 2009). Wallace et al. (2002) and Pfafferott and Herkel (2008) found a strong link between time of year (season) and the amount of time a window stayed open, suggesting that adaptive behaviors are not necessarily in reaction to a thermal stimulus directly, but may be influenced by long-term experience. In naturally ventilated buildings, this behavior could be interpreted as an avoidance of discomfort that has evolved to become a daily routine.

The current state of the window also plays a role in how likely it is to be adjusted. Several studies find that windows that are opened tend to stay that way (Fritsch 1990; Yun and Steemers 2007; Rijal et al 2008). These findings led to alternative regression equations similar to the Humphreys algorithm that add occupancy status and previous window state to the inputs. This “inertia” phenomenon has been found to be true of other control features as well. Occupants tend only to take action once they reach a “crisis of discomfort,” which may occur some time after the undesirable conditions have set in (Haigh 1981). Furthermore, once the occupant has taken action, they usually will not revert back to the original state once comfort has been restored, but are more likely to wait until another crisis of discomfort is reached (Leaman and Bordass, 1999).

Building on the work of Yun and Steemers (2007) and Herkel (2008), Haldi and Robinson (2008) studied eight office buildings in Lausanne, Switzerland over the summer of 2006, comparing logistic regression of numerous adaptive behaviors based on indoor and outdoor temperature. They concluded that, although window operation is better correlated with indoor versus outdoor temperature, “indoor temperature alone is not sufficient” to model behavior. They observe that other actions, such as clothing adjustments, many of which are preventative actions rather than reactive actions, show similar relationships to indoor temperature.

In a separate study spanning five years of continuous monitoring of the Solar Energy and Building Physics Laboratory in Lausanne, Haldi and Robinson (2010) present an alternative technique to logistic regression, using Markov chains and survival analysis to produce a stochastic model that predicts the probability of transition from one state to another. Their algorithm uses indoor temperature as well as occupancy status, the prior window state, the presence of rain, and a Weibull distribution to determine the length of time the window is to stay open or closed. Based on additional data on clothing and other environmental adjustments, the latest iteration attempts to account for the feedback among adaptive actions, allowing the reference neutral comfort temperatures to be derived from available adaptive actions in a particular context rather than the running mean outdoor air temperature, as was the case in all previous models. (ibid)

The social dynamics of shared office space can also have a dramatic impact on window operating behavior. As observed by Cohen et al (1998), manual controls (windows, blinds, lights) in open-plan offices tend to “lapse into default states that minimize conflict and inconvenience but are not optimal, e.g. ‘blinds down, lights on.’” In part, this phenomenon points to differences in office inhabitants’ natural disposition towards or awareness of their environment while they are working.

Several researchers have looked into establishing user “types” with respect to lighting control (e.g. Reinhart 2004). Borgeois et al (2005) proposed modifying the Humphreys algorithm to distinguish “active,” “medium” and “passive” occupants based on the distribution of behavior he observed in a Quebec office building. Haldi and Robinson (2010) also proposed assigning “active,” “average” and “passive” modes to given proportions of an occupant group based on their own field data. Their probability distributions show that, for a minority of occupants, temperature has a weaker influence on their behavior as it does for the whole sample.

3.3 SUMMARY OF WINDOW CONTROL MODELS

Taken together, existing literature agrees that window use is not deterministic (that is, predictable and repeatable), and models intended for use in building simulation become increasingly complex as they develop. Secondly, although there is ample evidence to suggest that occupants generally use windows when given access to them, field observations agree that people do not manage windows very actively throughout the day, and therefore can’t be relied upon to provide optimum control. In fact, aggregate patterns of control throughout the year may have more to do with ideas and expectations about seasonal conditions rather than real-time variations in temperature. In addition, it is still unknown whether any of the observed patterns apply to mixed-mode buildings, particularly within a U.S. context, where operable windows are much less common or accepted.

Another lesson learned from existing field studies is the inherent limitation of emerging models given the wide spread in individual behaviors observed even under similar circumstances. The latest advances in window control modeling struggle to account for multiple interacting variables. The more control options are available, as is often the case in mixed-mode buildings, the less agile models are at predicting the consequences of human diversity. Numerous studies have pointed out a +/- 50% spread in the energy consumption attributed to differences in building use and behavior patterns (e.g. Socolow 1977; Sonderegger, 1977; Marchio & Rabi, 1991; Gram-Hanssen 2010; Masoso and Grobler 2010). Most of these studies focus on personal differences and habits to explain the variation (heating and cooling setpoints, systems left running, etc).

For the purposes of modeling, industry may be best served by estimation methods that allow designers to define upper and lower limits of possible control variations rather than a single algorithm that approximates a “most likely” pattern of aggregate behavior (Roetzel et al 2010). For the purposes of building design practice, the discipline would benefit from further examining the spread of individual behaviors, and the extent to which building legibility, ease of use, occupant education and other factors can bring behaviors into alignment with designers’ expectations (and vice versa).

4.0 SYSTEM LEGIBILITY, KNOWLEDGE, AND INFORMED BEHAVIOR

Within the discipline of building science, remarkably little research has been devoted to understanding the mechanics of human disposition and decision-making as they pertain to adaptive behaviors. Research tends to focus on either a) behavior prediction (for building simulation), or b) behavior modification (usually for the purposes of conserving energy). When it comes to anticipating the use of a building by its users, however, between these two book-ends is a wealth of knowledge to be gained about the user experience, that is, how the user-building relationship is defined in more symbiotic terms (“user-centered theory,” Vischer 2008). For instance, we have identified the existence of “passive” and “active” users but have few clues into *what factors determine* whether a person is an “active” or a “passive” window user, and how fixed these distinctions are for individuals.

First, it is worth taking a closer look at the theory of adaptation as stated by Humphreys and Nicol (1998) (see the beginning of section 3.0). Typically, evoking this theory assumes that all adaptive responses achieve the same end result. But as building design research becomes more interested in the human-environment relationship, it is valuable to see how psychologists understand this dynamic. Coelho, Hamburg and Adams (1974) define four different types of adaptation: adaptation, mastery, coping, and defense, where basic “adaptation” is essentially a neutral compromise between a person and the environment. Mastery is when the compromise has a favorable outcome, coping is the surrender to sub-optimal outcome, and defense is the rejection or escape from the environmental circumstance altogether. In other words, identifying an “active” window user does not describe the interaction in terms that become useful feedback for building designers.

4.1 ENERGY CONSERVATION

Research into how individual differences plays out in building operations focuses primarily on energy-saving behavior, for example, understanding the behavior and influence of energy “champions” (Hitchings, 2009) or motivations for energy-saving behavior (e.g. turning off lights), which are best predicted by personal values (or “environmental personal norms”) (Scherbaum, Popovich and Finlinson 2008). This is relevant to mixed-mode control design only inasmuch as ideal control by building users is seen as being related to “energy consciousness.” However, numerous studies have found that energy-saving behavior is seldom motivated by generic values like “saving energy,” and that programs to influence behavior are most successful when designed from the perspective of the user, appealing to the social norms and/or tangible benefits familiar to them (Abrahamse 2005; Gardener and Stern 1996; McKenzie-Mohr and Smith 1999; Stern 2002; Campbell et al. 2000; Staats et al. 2004). For thermal control behaviors, which have clear personal motivations, this is particularly relevant.

4.2 SYSTEM LEGIBILITY

The simplicity and legibility of a building design to users is a major factor that affects behavioral outcomes. Bordass and Leamann (2007) establish the following set of usability criteria for manual controls in buildings:

1. Clarity of purpose
2. Intuitive switching
3. Labeling/annotation
4. Ease of use
5. Indication of system response
6. Degree of fine control

Considerations of legibility and usability typically relate to navigation and interface design, but the legibility of how manual, mechanical and electrical systems work is also important in building usability. Bordass and Leaman (1993) discovered from surveys and field observations that, “when discomfort arises, what gets operated first is what comes easiest, not what is desirable technically.”

Lutzenhiser (1993) points out the importance of examining adaptive behaviors alongside the design of control interfaces themselves. In the case of a thermostat, he finds manual dial control to be superior to digital setpoint-driven control because it is predicated on the user acting on their preference rather than a pre-defined “ideal temperature,” even if it is the user defining the setpoint. Finding the right degree of adjustability is an added challenge; maximizing flexibility is not often optimum (Nielsen 2004).

As stated in the CIBSE Applications Manual for mixed-mode buildings (CIBSE 2000), the Usable Buildings Trust (www.usablebuildings.co.uk) and other UK researchers have concluded that people are less likely to operate controls in a space “for the common good.” Because ease of use is the primary factor determining whether occupants behave according to designers’ expectations, they find occupants seldom appreciate acting on “good practice” principles. These include messages such as ‘open the windows on mild days, but keep them shut when the outside temperature exceeds that indoors.’ The CIBSE manual also states that individuals are not good at making “anticipatory responses,” for example, opening vents for night-cooling. The text does not, unfortunately, cite research specifically related to these findings.

As stated in section 3.2, much of the literature operates under the assumption that adaptive behaviors are reactive, and that behavioral tendencies are generally fixed. It should be fairly obvious, however, that an individual’s personal logic and habits for operating thermal controls is tied, at least in part, to different levels of knowledge about how controls work, levels of interest in using the controls, and the design of the controls (Karjalainen, 2007; Kempton, Feuermann, & McGarity, 1992; Kempton & Montgomery, 1982; Lutzenhiser, 1992; Meier et al., 2010; Rathouse & Young, 2004). As an example, Rathouse and Young (2004) found a wide variance in thermostat adjustments tied to a lack of knowledge about how to use them.

4.3 KNOWLEDGE

Guidance on mixed-mode controls (Bordass and Leamann 2007, CIBSE 2000) specify that occupants “must be aware of the building control concepts” as a pre-requisite to successful operation. The CIBSE manual goes on to state that making control systems legible might mean adopting a “standard’ control solution unless there are over-riding benefits in adopting an innovative approach.”

More recently, Brown and Cole (2009) combined web-based surveys with expert interviews to investigate similar performance gaps in green buildings. A first study conducted surveys in six Canadian office buildings with varying degrees of energy efficiency, and a second study (Brown Dowlatabadi and Cole 2009) conducted surveys in two green buildings to relate knowledge levels about innovative features and the use of personal controls. The surveys were supplemented by interviews and walk-throughs to provide an “expert baseline” for evaluating the knowledge level of building users; the study also documented how building information was disseminated to occupants. The authors found that contemporary green buildings seldom communicate how building systems function and that occupants are only active participants if they receive effective feedback for their behavior that *supports their understanding of the building*; findings suggest that occupants become passive when they lack knowledge and positive feedback (ibid).

4.4 FEEDBACK

In the energy-efficiency community, the term “feedback” has many different definitions. Seligman, Becker and Darley (1981) summarize different ways that feedback is framed in literature:

- **Human Factors Approach**
The teaching of new skilled responses (McCormick 1976), as in the use of information that helps an airplane pilot make control decisions
- **Reinforcement Approach**
The use of feedback and reward interchangeably (Bilodeau and Bilodeau 1961), as in a Pavlovian sort of “feedback” that conditions users to behave a certain way
- **Motivational Approach**
The ability for feedback to aid goal-setting and benchmarking behaviors against others (Locke, Cartledge and Koeppel 1968)

Feedback mechanisms can include information dissemination techniques, indicator signals, real-time energy monitors and dashboards and other means of energy visualization (i.e. the “Energy orb” tested by California utilities as a way to indicate time-of-use electricity price changes). Feedback also includes institutionalized person-to-person communication, such as standardized utility bills and informal conversations with a building operator.

Becker and Seligman (1978) compared the electricity consumption of households given three different types of feedback: a) daily electricity usage (producing 10.5% savings over the test period), daily electricity usage accompanied by goal-setting (yielding 13% savings) and c) a simple indicator device that signaled to homeowners when the outside temperature was low enough that they could turn off their air conditioner (saving 15.7%). The authors concluded that the signaling device was more effective than simple energy use feedback in modifying behavior because the light had a very simple, clear message. They do not discuss that the signal – a blinking blue light in the kitchen – could only be disabled by turning off the air conditioner.

Numerous studies have been done on the energy reduction potential of information provided by energy use monitors, the vast majority in households. A 2005 review of 38 field intervention studies from the 70s and 80s (Abrahamse et al 2005), included *antecedent* interventions (educational campaigns) as well as *consequence* interventions (pricing, discounts, or rewards). They found that when information or education was provided, this did improve knowledge levels, but not necessarily behavior change without a device to act as a reminder. They also concluded that more frequent feedback leads to more behavior change, as does the addition of social-motivational mechanisms. In a similar comparative analysis, Darby (2006) found that the simple presence of a monitoring device produced savings that range from 5% to 15% and pointed out a number of important success factors. For instance, they note that new behaviors must be reinforced long enough to become routine in order to persist (they specified a three month period); they also suggest that information one has to seek (for instance, an online dashboard) is much less successful than direct, in-person feedback; and finally, the type and frequency of feedback should be tailored to the type of behavior change it is intended to inspire.

Although available studies deal with bulk energy reductions in households, the principles of how feedback facilitates targeted behavior change are worth exploring in a commercial context. We are aware of just one study that specifically investigates the use of information and education to modify specific control habits in a commercial office setting (Owen, McMurchy and Pape-Salmon 2010). At the Jack Davis Building, Pulse Energy compared energy use and behavior patterns before and after a lighting retrofit in which automatic lighting controls with occupancy and photosensors were compared to simple light switches plus email prompts reminding occupants to turn their lights off when they leave for lunch. They found that during the campaign, lighting use in the areas of the office that received manual control and active prompting was reduced by half, 12% better than the technology-based approach; however, people went back to their previous, more wasteful habits after the campaign was over. The research team recommended that a long-term plan for sustained energy-

saving practices in office buildings must involve setting new norms through company or organizational policy, empowering internal champions, removing barriers by giving people simple switch-type controls, and providing customized information so that occupants see immediate feedback on their actions. Although this is the only study about active behavior prompting we found, it is important to note that the goals of this system were simple energy reduction rather than ongoing, optimal operational management.

5.0 SUMMARY

The common thread that links the relevant post-occupancy evaluations and case studies in mixed-mode and naturally-ventilated buildings is that users need to be better educated about their building's environmental control systems, and building designers and managers need to better understand building users. Even as high performance buildings become more mainstream along with ideas about greater personal control, connection with the outdoors and adaptability, the means of transforming these ideas into an operational reality remains lacking. Ongoing research is making more tangible the complex dynamics of adaptive behaviors so that designers might better harvest the technical benefits of manual window use in their designs, and avoid liabilities. What post-occupancy studies teach us, however, is that it is not just access to environmental controls that can lead to a reduction in energy use, but the habits and interest of occupants, as well as the extent to which they understand their building may influence adaptive actions significantly.

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