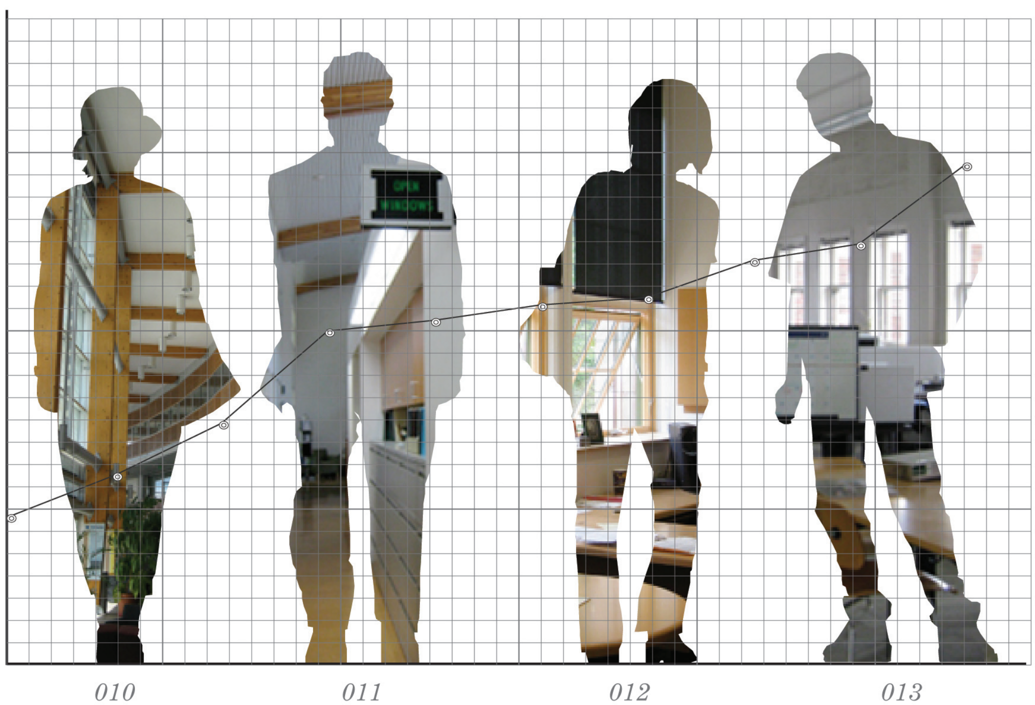


# Occupant Response to Window Control Signaling Systems

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MS Thesis, Dept. of Architecture, UC Berkeley 2011 http://escholarship.org/uc/item/8043748x

Occupant Response to Window Control Signaling Systems

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A thesis submitted in partial satisfaction of the
requirements for the degree of

Master of Science in Architecture
in the Graduate Division of the University of California, Berkeley

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Spring 2011

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## Acknowledgements

Thanks are due to a number of people who kept my research and my wits on track. In particular, Lindsay Baker, whose wonderful friendship, conversations and her own research helped me develop and finish the study. The good ideas and encouragement from David Fannon as I tried to make sense of things also deserves special thanks, and I am eternally grateful to Professor Gail Brager for her continued, enthusiastic support and mentorship, and to the guidance of Professors Cris Benton, Ed Arens and Alice Agogino.

This project was made possible by funding and support from the Center for the Built Environment and the Department of Architecture's Chester Miller Fellowship. Above all, this project owes its existence to the contributions of dozens of individuals who took time out of their schedule to answer my questions, provide me with project leads, and walk me around their buildings. In particular, Cole Roberts at Arup, Allan Daly and Gwelen Paliaga at Taylor Engineering, and Matthew Longsine at WSP Flack + Kurtz were singularly responsible for the broad scope this project was able to achieve.

# 1 Introduction

Designs for low-energy office buildings increasingly incorporate operable windows for the benefits of personal control, environmental quality, and architectural value. “Mixed-mode” design, which combines the use of natural ventilation and mechanical cooling, posits a “best of both worlds” opportunity to achieve superior energy performance as well as comfort, satisfaction and occupant health. There is a great deal of literature establishing a strong theoretical basis for this perspective. Operable windows offer improved indoor air quality  (Seppanen and Fisk, 2001) and increased occupant satisfaction from greater personal control and connection to the outdoor environment (Brager and Baker, 2008). They also have the potential for energy savings based on downsizing cooling equipment and/or offsetting fan-driven ventilation (Daly 2002; Rowe 2003; Ogden et al 2004; Emmerich and Crum 2005).

The benefits of operable windows are acknowledged by national building standards based on the adaptive comfort theory (Brager and de Dear 1998a), and the Leadership in Energy and Environmental Design (LEED) rating system has embraced the operable window as a workplace quality amenity. Designers are limited in the tools they can use to fully account for the benefits of operable windows in their designs. For example, U.S. design standards assume that adaptive comfort does not apply in buildings when an air conditioning system is operating. In addition, although there are proposed models for incorporating window use behavior into energy simulation, integrating human behavior into mechanical system design is inherently problematic. For these reasons, designers who pursue mixed-mode design lack the ability to be very aggressive about using manually-operated windows for energy efficiency. Additionally, like other architectural decisions, operable windows are not necessarily proposed based on measurable benefits. There is an important symbolic rationale, and where operable windows are installed, client and architect often share the same values and beliefs about their benefits.

Typically, mixed-mode buildings are classified as either "concurrent," in which operable windows and active cooling can occur in the same place at the same time; "changeover," in which the two modes occur in the same place but at different times; or "zoned," in which some select areas of the building are isolated and naturally-ventilated. In practice however, there is a wide range of technologies and control strategies that are used to balance the benefits of operable windows (Brager, Borgeson and Lee, 2008). The strategies range from the fully manual to the fully automatic.

To understand the diversity of control options, it is important first to distinguish between the different functions of natural ventilation. Other than providing fresh air, natural ventilation can refer to the use of outside air either a) to provide increased air movement for comfort; b) to lower the indoor temperature by introducing cooler outside air; or c) to cool the structure, by utilizing night-time ventilation and thermal mass. Mixed-mode buildings can employ any combination of these functions, at different times and in different spaces within a single building. Ideally, a building with operable windows, particularly manual ones, will be designed to avoid excessive internal gains by external shading, night ventilation, and thermal mass to dampen or buffer against indoor swings.

It is also critical to note that decisions regarding natural ventilation control are made concurrently with the selection of cooling and air delivery technologies that are to be coupled with the operable windows. This decision-making process is driven by several factors, including design philosophies and architectural ideas, programmatic goals, budgetary constraints, site context, and climate.

## 1.1 Statement of the Problem

The goal of a mixed-mode control strategy is to achieve an optimal operating schedule that invokes mechanical cooling only when conditions are not appropriate for natural ventilation. 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 providing unreliable ventilation rates. However, if windows are automated for natural ventilation, the building design loses the comfort benefits, amenity, appeal and robustness of manually-controlled windows.

On the fully-automated end of the spectrum, some designers prefer using computer-actuated windows or vents because they are more reliable and easy to control. But they can also raise costs and remove much of the amenity windows usually provide. The more sophisticated and automated the control solution, the more the building runs the risk of installation, operations and maintenance issues. Another, more clean and simple approach, is to install controls that shut off the HVAC system in response to occupants opening a window. However, this strategy only works in buildings where each occupied space – a private office, for instance – is thermally compartmentalized with its own individual control system, usually a prohibitive cost outside of certain building types (like dormitories). Some buildings in which this strategy has been used with a conventional office zoning scheme have had to deactivate the system. Window-HVAC interlock also relies on the occupants understanding the best times to open and close windows. On the fully manual end of the spectrum, the building design does its best to reduce loads and provide high-efficiency cooling and ventilation systems, and occupants are allowed to use their windows as they please. This approach maximizes personal control but also raises the potential for energy waste and balancing issues.

Signaling devices that inform occupants about when to open and close their windows (such as red/green lights or lighted signs) have become a popular, low-cost solution that addresses the shortcomings of other control strategies in balancing the benefits of manual and automatic control. Although this approach has exciting potential in its mix of automation and manual control by way of an occupant feedback mechanism, little research has been done to characterize how these systems operate in practice, and whether they influence how occupants use their windows.

### 1.2 Objectives

The over-arching objective of this project is to identify key issues associated with window signaling as a natural ventilation control strategy. These key issues may relate either to the design of the system (control sequence, installation strategy) or to human and situational factors that influence occupant response. This project takes a broad look at window signaling systems in existing buildings in the U.S. Through interviews, site visits and occupant survey, we investigated 16 projects across the country to better understand a) why signaling controls were implemented in the project; b) how “open windows” mode was defined; and c) the extent to which the signals play a role in window use behaviors.

Because there is virtually no previous research about window signaling systems, this study combines different forms of both qualitative and quantitative subjective data, and offers a number of secondary contributions. The first is the development of a framework for categorizing the design rationale and control strategies of the 16 mixed-mode buildings that took part in the study. Another secondary contribution is the development of a survey module that asks for occupant input on the control logic of mixed-mode buildings. Overall, the study adds substantially to systematic post-occupancy data that is available for mixed-mode buildings in the U.S., both in terms of input from occupants of the buildings as well as written case study information (Appendix C).

### 1.3 Significance

The results from this project are intended primarily to inform designers of best practices when considering signaling as a way to manage window use. In addition, signaling systems provide a unique opportunity to investigate the ability for informational devices (or occupant education, more broadly) to bring design objectives and occupant control behaviors into better alignment. Recent research suggests that occupant understanding of unconventional systems in low-energy buildings in particular is often low (Brown, Dowlatabadi, and Cole 2009). Concurrent with this debate is a growing interest in the use of building information systems, including energy dashboards and other “feedback” devices, to encourage occupants in commercial buildings to conserve energy. The use of feedback devices to prompt specific actions is a small but emerging area of research. But in buildings with this type of device, the importance of occupant education and active participation is made explicit in the design, creating a unique opportunity to explore the relationship between information and occupant control behaviors.

# 2 Background

Window signaling controls occur within a design paradigm in which building operations is a shared responsibility between the building's energy management system and its occupants. The decision to use operable windows alongside a mechanical cooling system in an office environment rests on beliefs about the value of operable windows and a faith in the idea that occupants will actively participate in maintaining indoor environmental quality (compared to a conventional, sealed office environment). Assuming these ideas hold true, the energy efficiency of such a building becomes a function of how well the HVAC system is controlled to integrate with manual window operation. Because optimizing for natural ventilation and accounting for human behavior are both very difficult, understanding the performance of mixed-mode buildings is complex. One central issue is determining the relative merits of manual versus automatic control. Informational controls propose a compromise between the two, asserting that information from the building can effectively influence behavior while retaining the fundamental benefits of manually-operated windows.

This topic addresses two active fields of research. The first involves ongoing attempts to characterize and account for window control behavior in energy models. While this project is not intended to contribute to behavior models, understanding previous research about how and why people use windows is central to documenting the influence of signaling systems. The second area of research relevant to this project includes studies looking at the relationship between occupant behavior, information feedback, and energy efficiency in buildings. This chapter reviews the current state of knowledge regarding the following:

2.1 The rational for operable windows
2.2 Integrating operable windows and mechanical cooling
2.3 Factors that drive window use
2.4 Feedback, knowledge, and informed behavior

## 2.1 The rationale for operable windows

This section reviews the known benefits of operable windows, and reasons they are incorporated into contemporary commercial buildings.

### *2.1.1 Symbolic value*

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 (gasous pollutants, particulates, sounds (noise), temperature, humidity, air movement, light transmission, view, and precipitation). Whereas fixed windows assume one is trying to create a homogenous, neutral, “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 and 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 20$^{th}$ 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.

### *2.1.2 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.

### *2.1.3 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 $CO^2$ to rely on them to provide themselves with adequate ventilation while they are doing other things.

### *2.1.4 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 2.7ºF 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 2.2), and it has been equally challenging to generate reliable behavior models and optimization tools that are needed to reap the potential benefits (Section 2.3).

## 2.2 Integrating operable windows with a mechanical cooling system

The concept of mixed-mode cooling was originally proposed by Max Fordham and Partners, revised by Bill 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.

Bill 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,” according to the technological solutions that have been typically achieved in real 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 2.1 Window and Mechanical System Options for Mixed-Mode Buildings

| | **Window Systems** | **Mechanical Systems** |
|---|---|---|
| Increasing cost and/or complexity → | **Simple Manual Operable Window**<br>The most basic and common way to allow natural ventilation. Usually refers to view-level windows.<br><br>**Multi-element operable window**<br>More expensive but sometimes more preferred to allow more precise control over ventilation, air movement and heat exhaust functions of windows<br><br>**Automated operable window**<br>Actuators control some or all elements, may be used exclusively for night ventilation, may or may not have manual over-ride.<br><br>**Advanced Natural Ventilation (ANV)**<br>Used by Bordass et al (1998) to describe large, complex buildings with sophisticated automated natural ventilation systems. | **Minimal "Background" Ventilation**<br>Trickle ventilators, stack assist fans and other low-energy devices that induce a minimal amount of ventilation.<br><br>**Mechanical (economizer) Ventilation**<br>Outside air (no refrigeration) centrally delivered to larger, more complex buildings<br><br>**Static Cooling**<br>Radiant cooling panels, chilled beams<br><br>**Single zone air conditioning**<br>Window or wall AC units, PTACs, RTUs with one system serving one zone.<br><br>**Distributed Air Conditioning**<br>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.<br><br>**Central Air Conditioning**<br>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. |

(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.

### *2.2.1 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 (Torcellini 2006). Furthermore, the advantages of mixed-mode dictate that design strategies 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 when operating in a 'free-running' (passive) 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.

Other post-occupancy studies focus on the success of combining automatic and manual control solutions. In the UK, the PROBE project represents perhaps the most comprehensive attempt to characterize how well mixed-mode design ideas materialize in operation. The principal finding from this work is that buildings that have more automated and complex natural 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.

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 risks becoming uncomfortable, but there is also a higher potential for thermal storage to play a role in regulating loads. The author proposes "intelligent" temperature control that allows the average indoor temperature to rise 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, particularly in North America, do not provide a good way for designers to account for these benefits, because they are difficult to reliably quantify. Furthermore, there is little that has been done to extend the lessons learned from UK studies to the U.S.  As the next section describes, mixed-mode performance is tied up in the psychological, social and logistical factors relating to how people use windows.

## 2.3 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, how behavior is influenced, and how control interfaces contribute to a break-down in building legibility and efficient operation (section 2.4).

Historically, window behavior has been modeled with very limited evidence from the field. Assumptions about behavior are made based on either occupancy or on 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.

### *2.3.1 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 on 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.

### *2.3.2 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 or simply habit. 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 Laussane, 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.

### *2.3.3 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).

## 2.4 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 2.3), 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.

### *2.4.1 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 the current study insomuch as occupant response to window signaling is conceived as "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 audience, appealing to the social norms and/or tangible benefits familiar to the user (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.

### *2.4.2 Legibility and User-Centered Design*

The simplicity and legibility of a building design to users is a major factor that affects behavioral outcomes. Bordass and Leamann (2007) establish a set of usability criteria to evaluate lighting and thermal-related controls, based on the following variables:

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 corresponds to wayfinding or 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 2.3.2, much of the literature, operates under the assumption that people predominantly take actions as an adaptive (reactive) response, 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, as several studies point out (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.

### *2.4.3 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 knowledge and 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).

### *2.4.4 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 perior), 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 use their windows instead of 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 energy reduction, whereas the signaling controls in this study are less about energy conservation and more about ongoing operational management.

## 2.5 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.

# 3 Methods

As stated in chapter 1, the over-arching objective of this project is to identify key issues associated with window signaling as a natural ventilation control strategy. Because these systems have not yet been studied, the most important issues may relate either to the design of the system (control sequence, installation strategy) or to human and situational factors that influence occupant response. Therefore, I chose a multi-method approach, combining occupant surveys, expert interviews and site observations, to collect information that investigates the technical strategies employed as well as the human dimensions of the systems in operation.

### 3.1 Learning from Occupants

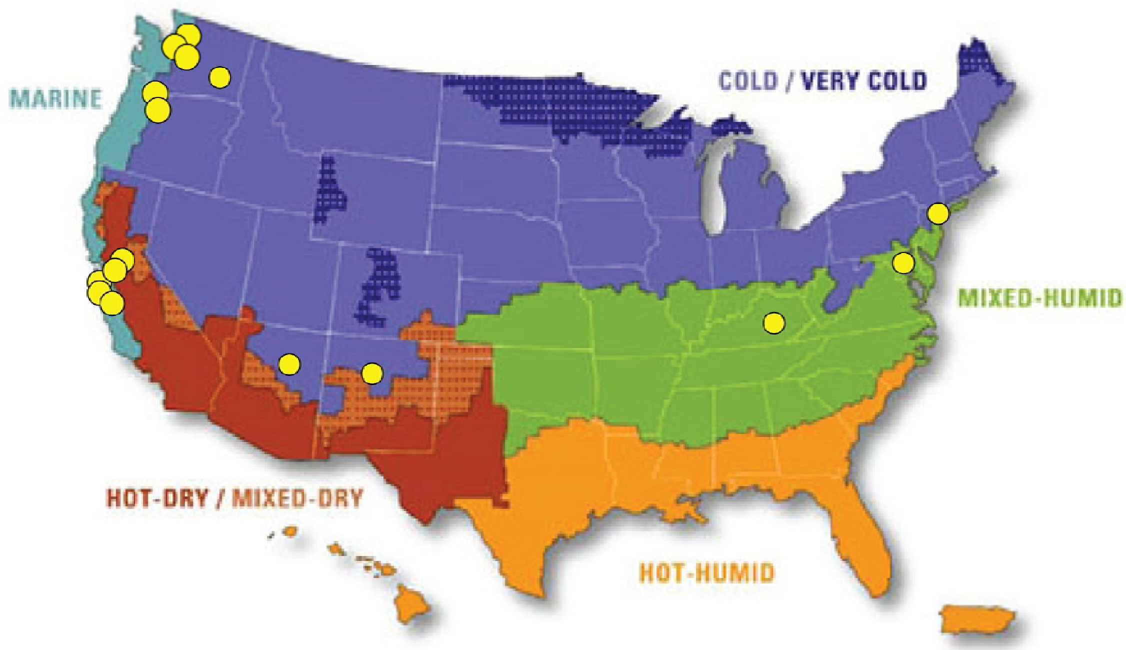
As shown in the previous chapter, studies into human dimensions of building operations run the gamut of study methodologies; but most commonly, they include some form of occupant survey and/or physical measurements and behavior monitoring. For example, these methods have successfully been used to record the comfort impacts of a control intervention, the reasons for taking an action, or to compare manual and automatic control responses (e.g. Inkarojrit and Paliaga 2004; Inoue,1988). Longitudinal field studies would be suitable for future investigations into signaling controls, but are beyond the scope and timeline of the current study. Evaluating how occupants interact with window signals first requires describing the contextual factors, some of which reach back to the design phase. This study follows the model of other types of multi-method post-occupancy studies (Bordass and Leamann 1993, 1998; Brown and Cole 2009) that combine surveys with expert interviews, on-site observations and other professional assessments to describe the complex dynamics at play among a building's human, mechanical and passive control systems, which can be difficult to anticipate.

### 3.2 Building selection

In an initial recruitment phase we cast a wide net to identify any building with a visual method for prompting or informing user-controlled—rather than building automation system (BAS) controlled—building operations. We identified 16 office and mixed-use buildings in the U.S., drawing from existing databases of high performance buildings and by reaching out to the Center for the Built Environment industry partner network.

This study was restricted to office spaces in North America with full-time occupants, where a visual signaling device linked to window use is installed. User-based control systems targeting building managers or transient occupants (including the Aldo Leopold Center, and Berkeley Civic Center) were not included. Although email, web interfaces, and word-of-mouth methods were left out of the study, findings about educational strategies that reinforce the visual signals in each building is an important element of the discussion.

**Figure 3.1 Locations of 16 Study Buildings**




Basemap: US Department of Energy

## 3.3 Survey Development

Occupant surveys are typically used for research purposes to measure comfort satisfaction as an indication of indoor environmental quality. Less often, surveys include questions that ask occupants to report their own behavior as an indication of the building's overall operational effectiveness, for example to indicate how frequently they use a given feature (like a window), or to rate their level of personal control. The two major databases of building occupant satisfaction data widely used by researchers are inconsistent in making this type of assessment. The Building Use Studies (BUS) survey instrument, developed in 1981 in the UK, asks occupants to rate the degree of personal control over heating, lighting, cooling, ventilation and noise on a seven point scale. It then asks how frequently they take actions that influence these five factors, and how they would rate the accessibility, usability and responsiveness of controls available to them.

This study builds on the core Indoor Environmental Quality survey produced by the Center for the Built Environment (CBE), which is not designed with the same focus on usability. The purpose of the CBE survey is "to assess the performance of a building, identify areas needing improvement, and provide useful feedback to designers and operators about specific aspects of building design features and operating strategies." (Zagreus et al 2004) In addition to assessing The core CBE survey asks occupants to tick the personal controls they have access to, but does not include ratings of satisfaction with these controls. Additional modules about workplace adjustability, operable windows, ceiling fans and window blinds do include these questions but they not make up a usable portion of the database. This limits the ability of the current study to compare and benchmark certain control satisfaction results against other types of buildings.

An operable windows module within the CBE survey was developed for a 2004 study on window use at the Berkeley Civic Center (Paliaga 2004), and is offered to clients of the general survey for an additional fee. The module has been used in a very limited number (~5) of benchmarked office buildings in the CBE database prior to this study and in 60 recent school surveys. A central contribution of the current study was to expand the information about occupant interactions with windows in the CBE survey database, tripling the number of office buildings with operable windows, mostly mixed-mode.

**Table 3.1 Methods used in 16 study buildings**

| Building | Nickname | Location | Interview | Visit | Survey |
|---|---|---|---|---|---|
| 654 Minnesota Ave, UCSF | UCSF | San Francisco, CA | ✓ | ✓ | ✓ |
| Orinda City Hall | Orinda | Orinda, CA | ✓ | ✓ | ✓ |
| NBBJ Architects Offices | NBBJ | Seattle, WA | ✓ | ✓ | ✓ |
| Savery Hall, U of Washington | Savery | Seattle WA | ✓ | ✓ | ✓ |
| Boora Architects Offices | Boora | Portland, OR | ✓ | ✓ | ✓ |
| ZGF Architects Offices | ZGF | Portland, OR | ✓ | ✓ | ✓ |
| Kroon Hall, Yale School of Forestry | Kroon | New Haven, CT | ✓ | ✓ | ✓ |
| ARD Facility, Northern Arizona U | ARD | Flagstaff, AZ | ✓ | ✓ | ✓ |
| Compton Union Building, WSU | CUB | Pullman, WA | ✓ | | ✓ |
| Lincoln Hall, Berea College | Lincoln | Berea, KY | ✓ | | ✓ |
| Kirsch Center, de Anza College | Kirsch | Cupertino, CA | ✓ | ✓ | |
| Hewlett Foundation | Hewlett | Menlo Park, CA | ✓ | ✓ | |
| Zoomazium, Woodland Park Zoo | Zoom | Seattle, WA | ✓ | ✓ | |
| Thornburg Headquarters | Thornburg | Santa Fe, NM | ✓ | ✓ | |
| Boalt Hall, UC Berkeley | Boalt | Berkeley, CA | ✓ | ✓ | |
| Chesapeake Bay Foundation | CBF | Annapolis, MD | ✓ | | |

### *3.3.1 About the CBE survey*

The Center for the Built Environment (CBE) developed a web-based occupant questionnaire and online reporting tools as a quick and inexpensive means to gather occupant feedback information on nine categories of indoor environmental quality (IEQ), including thermal and visual comfort as well as workplace amenity. (Zagreus et al 2004)

The survey is invitation-based, sent to building occupants via email from a building or office manager. The core survey takes roughly 10-15 minutes to complete, and responses are totally anonymous. Core questions includes multiple choice questions for basic workspace facts and 7-point likert scale questions used for individual evaluation of environmental conditions and building features. Four or Five-point likert scales are typically used to evaluate the frequency something occurs or an action is taken.

Administration of the survey lasts two weeks, including at least one reminder to raise response rates. The target response rate for this study was >65% in buildings with fewer than 200 occupants, or a minimum of 100 responses (no building received less than 50%, which is the standard target for the core CBE survey implementation procedure). Incentives in the form of three $25 Amazon.com gift certificate were offered using the web-based instrument if building management expressed concern about the timing of the survey or the ability to draw responses.

### *3.3.2 Survey Pilot*

In fall, 2009 we developed and pilot-tested a version of the operable windows survey module that included additional questions about window signals (Appendix A). In the survey we asked occupants to report:

1. How frequently they actively respond to the “open” and “close” signals;
2. How likely they are to open the window even in “close” mode;
3. Whether the signals interfere with their sense of personal control; and
4. To describe any conflicts that arise between the system and their own preferences.

The pilot survey was based in part on lessons learned from a set of questions on window signals included in an earlier survey at the Hewlett Foundation. Writing and revising the questions was an iterative process that took place in collaboration with other CBE researchers, and included input from designers and staff associated with the study buildings and familiar with the key issues. The survey was issued to Orinda City Hall staff in late 2009. The most difficult question to refine was occupant feedback about the "logic" of the signal modes. This question was the only question substantially modified, converted to an open-ended question in the final module.

### 3.4 Data Collection

A framework to integrate different strands of subjective data is provided by an "embedded" comparative case study model, where analysis is done at multiple levels and then compared across cases:

**Table 3.2 Embedded Case Study Methodology**

| Analysis Level | Data |
|---|---|
| **Level 1: Occupant tendencies and attitudes**<br>• Occupant survey<br>• Informal occupant interviews on site | • The extent to which signals play a role in window use behavior<br>• Trends in willingness to disregard signals<br>• Document most common reasons for disregarding signals |
| **Level 2: Building attributes**<br>• Design team interviews<br>• Building manager/operator interviews<br>• Site observations | • Diversity of building attributes<br>• Range of design intentions and control strategies<br>• Education/management framework |
| **Level 3: Cross- case comparison** | • Control algorithm classification<br>• Relative importance of project attributes (office type, culture, interface type, placement, education, etc)<br>• Common interfering circumstances<br>• Individual case study narratives |

The schedule for collecting occupant and building-level data evolved somewhat over the first few months of the project. For instance, site visits and conversations with professionals were necessary to fine-tune the survey instrument and interview guides. Ultimately, however, surveys were conducted first, and then interviews were combined with follow-up conversations about the survey results, on site if possible. For those buildings where formal interviews were conducted before the survey, a shorter, follow-up interview was scheduled to discuss findings.

### *3.4.1 Survey Implementation*

Other than the pilot survey at Orinda City Hall, which is included in our results, surveys were conducted in the summer between May and August 2010. The intention was to highlight behavior during warm weather (this was specified in the questions). Because of the academic schedule, campus buildings were surveyed in the late spring; unfortunately, 2010 had an unusually long winter, so survey results at Savery Hall and Kroon Hall in particular were more biased toward the heating season than what would have been ideal, and survey results are augmented by conversations with building management that extended through the summer.

We were unable to conduct surveys in six of the 16 buildings. This is because either a) fewer than 10 occupants occupy the office space (three buildings); b) the buildings have been studied extensively and there was no interest in a second survey (2 buildings); or c) we simply could not sell the idea (1 building). Many of the buildings are mixed-use; in these buildings, only the full time office employees were surveyed.

### *3.4.2 Interviews*

For all 16 buildings, we contacted at least one member from the design team (architect and/or engineer) and at least one representative of the building management team (building coordinator, manager or operator) to understand the original intent of installing window signaling controls, how the signals are programmed, and any relevant operating issues. Building documentation, including system description, as-designed sequence of operations and/or building diagrams and plans, were made available for six of the buildings.

Appendix B includes a full interview guide. Building manager interviews took place in person during site visits where possible, but most of the interviews occurred by phone. The individuals most knowledgeable about the design process and operation of each building differed dramatically case-to-case. In many cases, compiling answering the interview questions was piece-meal; for example, a building manager who was the initial point of contact turned out to know little about building operations, and would refer me to an off-site controls contractor. Interviews were implemented informally, and in some cases developed into an ongoing conversation.

After the survey results were recorded, results were discussed with members of the design team as well as the main facilities manager as a part of the interviews. Each interviewee was asked what factors they think contribute the most to the survey results.

Ultimately we invited all interviewees to review the accuracy of the final case study narrative and the validity of our conclusions about each building.

### *3.4.3 Site Visits*

I was able to visit 13 of the 16 buildings to record general impressions and observations about the office spaces and the placement of the signaling devices in context. The three I was not able to visit were simply too expensive to get to. During the site visits, I conducted a few brief informal interviews with occupants where I was able to get permission (22 interviews in all, 3-5 in six of the buildings). Ideally, this form of occupant feedback would have comprised a larger portion of the research. Appendix B shows a 2-page template was developed to summarize the key features of each building in a way that can be easily compared to others.

## 3.5 Limitations of the Study

Occupant questionnaires provide a practical, quick, inexpensive and relatively noninvasive way to collect a large amount of data about that can be benchmarked and analyzed statistically. However, surveys have a number of limitations. The notion of “satisfaction” as a metric of performance has been called into question, since it is impossible to disassociate reported satisfaction from occupants’ own coping behaviors and routines (e.g. are occupants satisfied with or without their space-heater?), let alone attitudes (Vischer 2008). Furthermore, occupants’ self-assessments of behavior can be very different from their actual behavior. Lutzenhiser (1993) notes that people have a tendency to over-represent their technical competencies and report behaviors that are “better” than actual (i.e. lower-than actual thermostat settings), even if they known the actual settings are being recorded. Most importantly however, surveys by themselves do not fully capture situational, social and psychological factors that are known to influence how people experience buildings.

Because the survey data set has numerous mediating variables and weak control, the data collected in this study is not intended to identify generalizable correlations between specific building attributes and level of response. The survey data serves primarily as a basis for showing the range of responses across buildings and to provide standardized feedback about the benefits and challenges of the system from the occupants’ perspective.

The value of this study rests in the quality of the narratives constructed for each building (Appendix C). Conclusions that are drawn base on comparing case studies depends on how well subjective information was triangulated, for example, categorizing the design intent for each project. During the study, access to key members of the design team, design documents and as-built control sequences, representative survey responses, and representative or thorough observations, photos and occupant perspectives during site visits was inconsistent building to building. The most important limitations are explained within the narrative offered for each. The case studies that we feel are the best documented include 654 Minnesota Ave, Thornburg Headquarters, ARD Facility, NBBJ offices, Savery Hall, Orinda City Hall and Boora Architects. The least documented are Boalt Hall, Zoomazium, Kirsch Center for Environmental Studies, Hewlett Foundation, and the Chesapeake Bay Foundation. This is primarily because these buildings were already studied or surveyed in detail and/or were too small or specialized in program. For some buildings, such as Lincoln Hall, Chesapeake Bay Foundation and Hewlett Foundation, the interviews were skewed towards the present management since design team members were difficult to reach (usually because too much time had passed).

# 4 Comparison of Signaling Strategies

This chapter summarizes the "level 2, building attributes" component of the study. It explores the diversity of control applications we found, within the context of the design objectives and circumstances specific to each project (such as size, occupant type, cooling system and climate). Understanding the diversity of design intents and operational issues is important to interpret the occupant level results presented in Chapter 5.

## 4.1 Reasons for Choosing Signaling Controls

Although literature on mixed-mode buildings discusses signaling controls (a.k.a. "informational controls") as a "changeover" strategy in lieu of sensors, actuators and other computer-automated controls, we found signaling systems to span a range of control concepts in practice. The common theme is that the signals are conceived as a sustainable design feature. But comparing applications reveals differences in how the design team understood the priorities and limitations in achieving the benefits of operable windows. From our interviews we found three primary reasons a signaling device was chosen:

1. **Moderating personal control**
   The client or architect values operable windows as a workplace amenity, but they are a hard sell to engineers or facilities managers without some measure of oversight for manual window use.

2. **Cost-effective natural ventilation**
   The design team intended for windows to offset mechanical cooling and ventilation, but window actuators or HVAC lock-out controls were deemed too expensive and/or value engineered out of the project. Three projects decided on a signaling strategy post-design development.

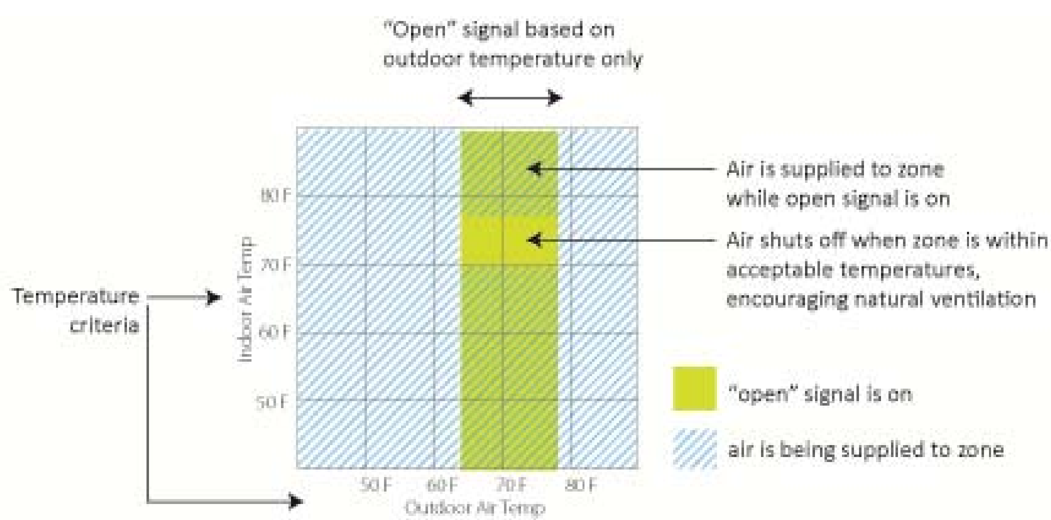
3. **"Green" message**
   The client or design team thought the signals would highlight operable windows to occupants or visitors. All projects claim one of the above two options as the primary reason for installing the system; however, the visibility factor had equal importance in three projects.

## 4.2 Defining "Open Window" Mode

Whether the decision to use operable windows was driven more by occupant satisfaction or by energy reduction translated loosely into how the "open" and "close" signals were defined in the building's sequence of operations. We were able to collect the as-designed control algorithms for each of the 16 buildings, and we were able to verify the as-operated sequence in all but four of the buildings.(Refer to Appendix C for details on key projects.)

We developed a graphic tool (Figure 4.1) to visualize the differences among control strategies based on the main temperature criteria employed (outdoor temperature displayed on the x-axis and indoor temperature is displayed on the y-axis). The green shaded region indicates the setpoints defining when the "open" signal is on. Outside of this shaded region, the "open" signal is off and the "close signal" is on (if there is one). The blue, hatched region shows the setpoints determining when air is mechanically supplied to the zone (either outside air or conditioned). Where the diagram is not hatched, the air supply fan is off and windows are relied upon exclusively for ventilation. Note that outside air is modulated based on demand control in some

**Figure 4.1 Sample Control Algorithm Diagram**



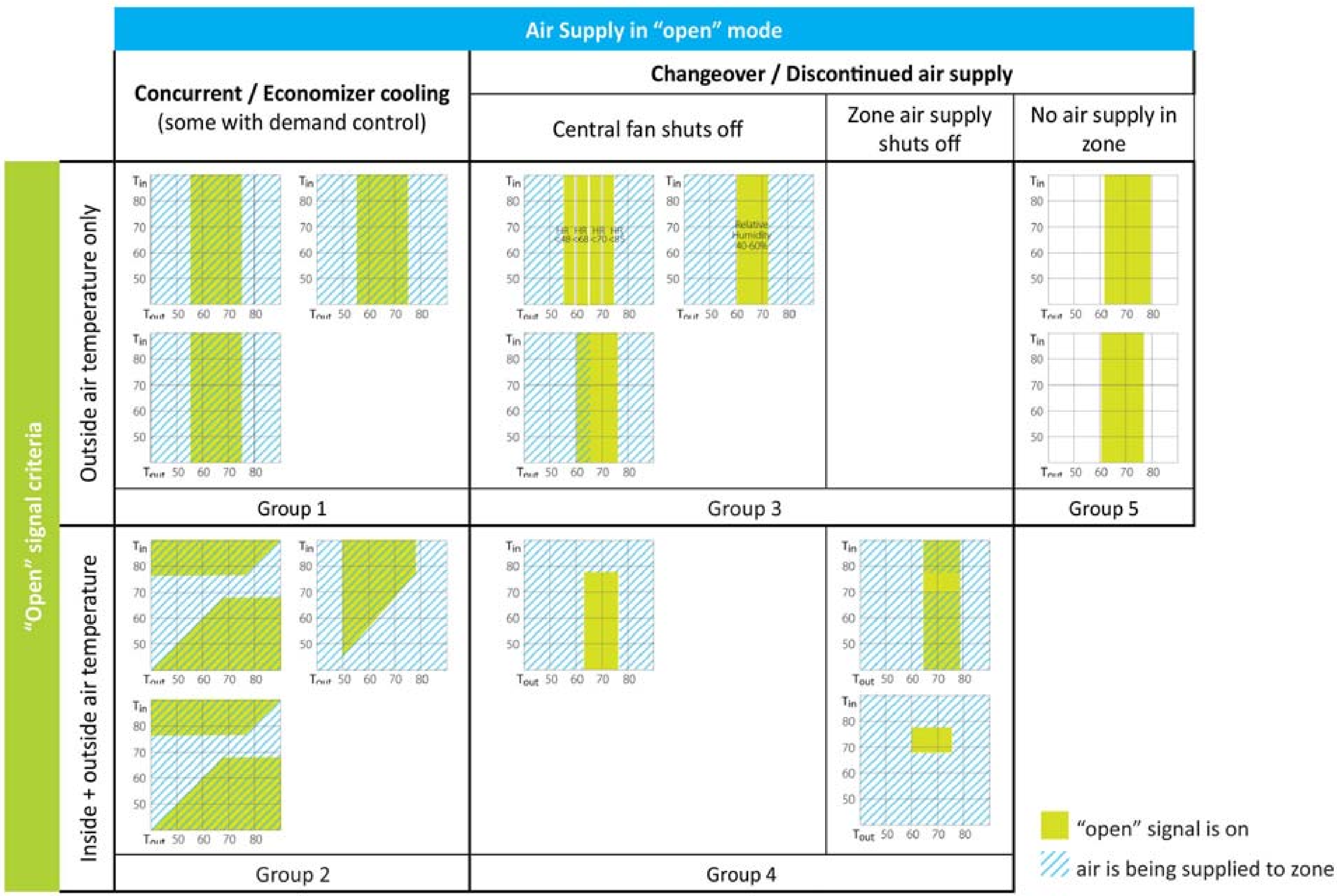

buildings.

In all but one project, the algorithm for "open" mode was written based on outdoor and indoor temperature criteria. In other words, the operation of the signals is related to but technically independent from the HVAC system operation. The exception is Thornburg Headquarters in Santa Fe, NM, in which the "open" signal was tied directly to chilled and hot water supply “enable” commands. In four buildings, humidity, wind speed and $CO_2$ were additional environmental criteria for “open” mode.

Figure 4.2 compares the diagrams of the control criteria for 15 buildings (not including Thornburg). Using this scheme we can distinguish five general approaches (Groups 1-5) related to whether indoor temperature input criteria was used (the two rows), and whether mechanical air supply was regulated during “open” mode (the four columns). If the mechanical system continues to supply air during “open” mode (first column, Groups 1 and 2), this is similar to a “concurrent” approach, where the windows are essentially supplementing the building’s economizer mode (thus the green area overlaps with the blue hatch).

If the mechanical air supply is discontinued (middle two columns, Groups 3 and 4), we may refer to this as a “changeover” approach, where the windows are intended to serve all of the building’s cooling and ventilation requirements while in “open” mode. (Note: one example in group 4 combines both changeover and concurrent operating strategies, depending on the state of the combined indoor and outdoor temperatures). The last column, Group 5, distinguishes strategies in which the windows are relied upon exclusively for ventilation These buildings have no mechanical ventilation in the perimeter zones, and the windows are designed to supplant active cooling via fan coil units and radiant panels, respectively, when possible. Note that even though these buildings have no mechanical ventilation in “open” mode, similar to the “changeover” approaches, these buildings more technically “concurrent” by design.

Figure 4.2 Comparison of Control Sequences



## 4.3 Control strategies in operation

### *4.3.1 Group 1: Concurrent air supply; outdoor temperature control.*

In this group of projects, the buildings rely on an air-side economizer and a conventional, compressor-chilled water system for cooling. The "open" signal is designed to coincide with the building's normal economizer cycle, typically using an outdoor temperature range of 55°F – 75°F to approximate this mode, so there is little conflict between bringing in outside air through the ducted system or directly through the windows.

In these projects, the building operates more or less the same regardless of whether people open their windows, although some energy savings does result if open windows reduces the amount of air that supply and relief fans need to move. If windows help to meet the cooling setpoint, then a lower volume of air can be supplied; open windows would also reduce the need for the relief fan to maintain static pressure. However, these energy savings are somewhat of a "bonus" in these buildings; by and large, the windows were included primarily as an amenity, and mechanical systems are responsible for maintaining environmental quality, and temperature setpoints are kept within a fairly conventional range. In all three, red-green signals were used as a mechanism *mainly to prevent windows from being opened*, or left open, when they shouldn't be (in other words, the red or "closed" mode was most important).

**Table 4.1 Cases in Group 1**

| Building | Loc | Year | # People | Perimeter program | Occupant type | Cooling and air systems |
|---|---|---|---|---|---|---|
| 1. UCSF | CA | 2007 | 150 | Open office | University Staff | Central chiller, overhead air distribution |
| 2. Boalt | CA | 2009 | 8 | Open office, classroom | Law students | Central chiller, overhead air distribution |
| 3. ZGF | OR | 2009 | 175 | Open office | Architects | Central chiller, underfloor air distribution |

### *4.3.2 Group 2: Concurrent air supply; outdoor + indoor temperature control.*

This group of buildings resembles those in Group 1 in that "open" mode is intended to coincide with the building's normal economizer mode. But in these cases, the control algorithm for "open" mode is more sophisticated, where a relationship between the outdoor temperature and coincident indoor space temperature (or return air temperature) must be satisfied for the "open" signal to go on. Demand control is also used in one of the buildings to minimize mechanical ventilation air during green mode to maximize the energy benefit of natural ventilation. In all of these buildings, however, it is unclear how often the green light is on. In all but Thornburg, the "close" signal is reportedly on most of the time despite being located in ideal climates. For example, insufficient heating in the core office spaces in the Hewlett Foundation has reduced the number of hours the building spends in economizer mode. At the ARD Facility and Kirsch Center for Environmental Studies, the control sequence suggests that the "open" signal goes on only when the building's indoor temperature rises above the setpoint; which doesn't happen if the mechanical system is working. Unfortunately, we were unable to verify this or attribute the performance of the signals to the control strategy.

**Table 4.2 Cases in Group 2**

| Building | Loc | Year | # People | Perimeter program | Occupant type | Cooling and air systems |
|---|---|---|---|---|---|---|
| 4. Thornburg | NM | 2004 | 175 | Private and open office | Financial group | Evaporative cooler, chiller, underfloor air distribution |
| 5. Kirsch | CA | 2005 | 8 | Private office, classroom | University Faculty (Enviro mission) | Central chiller, underfloor air distribution |
| 6. ARD | AZ | 2007 | 50 | Private office | Environmental Research | Central chiller, underfloor air distribution |
| 7. Hewlett | CA | 2002 | 150 | Private office | Foundation | Evaporative cooler, Ice storage, underfloor air distribution |

### *4.3.3 Group 3: Changeover/Discontinued air supply; Outdoor temperature control.*

These projects are designed to switch completely from a mechanical cooling mode to a fully passive mode by shutting down the central air handler within an acceptable outdoor temperature range. As in Group 1, because the "open" mode is controlled by outdoor conditions alone, the signals are relatively predictable and reliable, assuming the instruments that take these measurements are working. Because mechanical air supply is discontinued based on outdoor temperature only, occupant behavior does not impact the building's operating status, but it may result in uncomfortable indoor conditions if a sufficient number of people do not actually open the windows, or if solar gain in the building is higher than expected. Building form, upper-level automated openings and thermal mass are all used to minimize this impact. At Chesapeake Bay Foundation, MIT and NREL researchers found issues with solar control and overheating, and recommended that the upper and lower outdoor temperature setpoints for "open" mode be lowered. (Griffith et al, 2005; Chang, 2003) At the Zoomazium, an environmental education center at the Seattle Zoo, the algorithm includes a small range of outdoor air temperatures in which the green light is on but air supply is still enabled. This might be useful if there's an assumption that people won't open their windows at the lower acceptable outdoor temperatures.

**Table 4.3 Cases in Group 3**

| Building | Loc | Year | # People | Perimeter program | Occupant type | Cooling and air systems |
|---|---|---|---|---|---|---|
| 8. Lincoln | KY | 2002 | 60 | Private office | University Faculty | District chilled water, overhead air distribution |
| 9. CBF | MD | 2000 | 50 | Open office | Foundation (Enviro mission) | Ground source heat pump, overhead air distribution |
| 10. Kroon | CT | 2009 | 60 | Private office | University Faculty (Enviro mission) | Ground source heat pump, underfloor air distribution |
| 11. Zoom | WA | 2003 | 3 | Shared office | Administrative Staff | Rooftop packaged AC Underfloor air distribution |

#### *4.3.4 Group 4: Discontinued air supply; Outdoor + Indoor temperature control*

Similar to Group 3 buildings, these three projects aspired from the outset to rely on passive cooling and ventilation for as many hours as possible throughout the year. At Savery Hall and NBBJ Architects offices (both in Seattle), the signaling system was a late-stage design decision once it was determined that 100% natural ventilation wasn't feasible and automated controls were too costly. Cost and the desire for simplicity also drove the decision to install a signal at Orinda City Hall.

These buildings differ from buildings in Group 3 simply because the natural ventilation mode includes an indoor temperature setpoint that must be satisfied for the building (or zone) to remain in a passive mode. The control strategy at Orinda City Hall, however, can be considered a hybrid of group 1 and 2 approaches, since the "open" signal is tied to outdoor temperature only. If indoor temperature setpoints are met, the zone will operate in a passive mode, relying on the windows exclusively for ventilation. In all three buildings however, because there is an indoor temperature setpoint, occupant participation does impact how long a given zone remains in a passive mode, depending again on the rate of internal gains and thermal lag factors. If occupants do not act on the "open" signal, the indoor temperature may rise more quickly, and mechanical conditioning will be initiated. When in natural ventilation mode, windows are relied upon exclusively for fresh air at NBBJ and Orinda City Hall; at Savery hall, a $CO_2$ alarm triggers minimum mechanical air supply to the zone, switching the light from green to red.

In these buildings, the range of acceptable outside temperatures is generally warmer than in other cases but still fairly broad, with 60°F-63°F being the acceptable minimum, and 78°F the maximum. The maximum acceptable indoor temperature is the same in all cases (78°F); whereas the minimum indoor setpoint is treated differently in each building. At NBBJ, there is none; window use is allowed as long as the indoor temperature does not exceed 78°F. At Savery Hall, the system asks occupants to shut their window if the indoor temperature falls below the heating setpoint of 68°F. At Orinda, the signal does not change, but the mechanical system is allowed to supply heated air below 68°F, which is adjustable down to 64°F.

Functionally, it is clear that this group includes both concurrent and changeover operating strategies, and in some ways can be viewed as a more or less conventional control strategy that uses a higher cooling setpoint, with windows provided to relieve discomfort between, roughly, 72°F and 78°F. Relying on a high setpoint for useful natural ventilation requires buy-in from occupants and the building operator. At Savery Hall and NBBJ, the building operator has managed to maintain a high cooling setpoint of 78°F. At Orinda City Hall, the building operator adjusts the cooling setpoint quite a bit based on season and comfort expectations from occupants; during hot summer months, the setpoint is a more conventional 72°F, while during milder periods the setpoint is 74°F – 76°F.

**Table 4.4 Cases in Group 4**

| Building | Loc | Year | # People | Perimeter program | Occupant type | Cooling and air systems |
|---|---|---|---|---|---|---|
| 12. NBBJ | WA | 2003 | 315 | Open office | Architects | Central chiller, Underfloor air distribution |
| 13. Savery | WA | 2009 | 200 | Private office, classroom | University Faculty | VRF heat pump, overhead air distribution |
| 14. Orinda | CA | 2007 | 40 | Private and shared office | Municipal government. | Evaporative cooler, overhead air distribution |

#### *4.3.5 Group 5. Decoupled cooling and ventilation*

At the Compton Union Building (CUB) and Boora Architects office, air supply is decoupled from the hydronic heating and cooling systems in the perimeter zones, and no air is supplied to these spaces other than via the windows and infiltration from the core. At CUB, radiant panels are controlled centrally based on outdoor air temperature, and a setpoint of 76°F initiates the chilled water and "close" signal simultaneously. In this building, failure to use the windows according to the signals does have potential comfort *and* energy consequences since the radiant panels can't cool people as effectively if the windows are open when they shouldn't be, as they try to compensate for warmer indoor temperatures. Condensation risk is handled by an alarm system that regulates the supply water temperature if the dew point rises. In a sense, the control solution has a "change-over" intent, although the energy risks are not considered to be serious. The initial lower setpoint for "open" mode of 60°F was, however, deemed too cold and adjusted up to 71°F, reducing the ability for the windows to contribute substantially to cooling, especially in situations were internal gains are high but outdoor temperatures are moderate and would have contributed to cooling.

At Boora, heating and cooling is provided via a three-pipe system to perimeter fan coil units, and “open” mode for windows coincides with a fairly wide and warm temperature range (62°F – 80°F). Because control is localized, coordinating how occupants use windows, ceiling fans, and their local fan coil units to enhance both comfort andenergy performance is, importantly, a matter of education beyond the “open” signals alone.

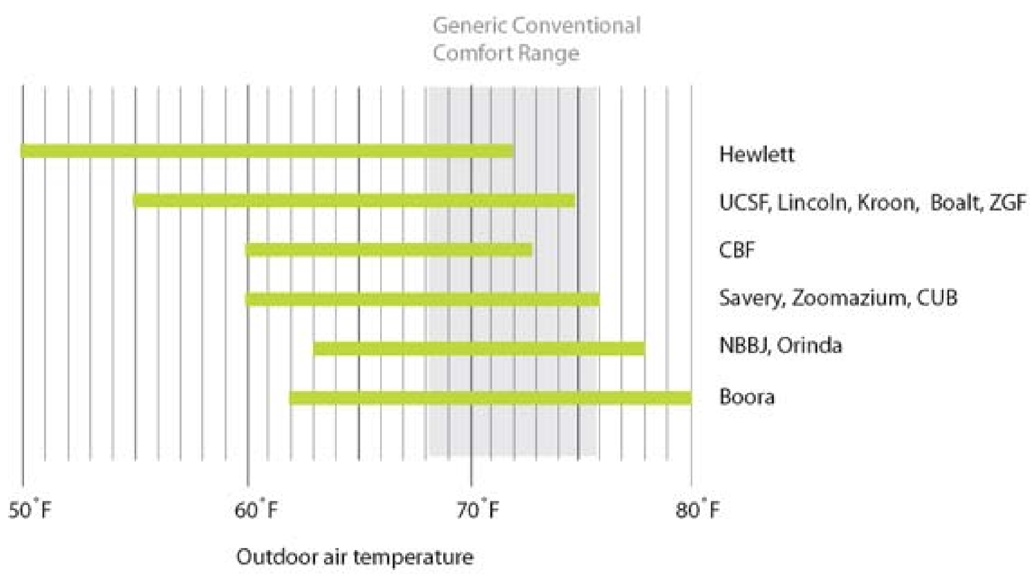
**Table 4.5 Cases in Group 5**

| Building | Loc | Year | # People | Perimeter program | Occupant type | Cooling and air systems |
|---|---|---|---|---|---|---|
| 15. CUB | WA | 2008 | 25 | Open office | University Staff | Radiant panels |
| 16. Boora | OR | 2008 | 60 | Open office | Architects | Perimeter fan coil units |

## 4.4 Determining outdoor temperature setpoints

Figure 4.3 shows the variation in acceptable outdoor temperature ranges for “open” mode. The chart roughly differentiates strategies in which open windows are understood as part of the economizer mode (allowing window use at very cool temperatures), and strategies that adopt adaptive comfort principles (allowing

**Figure 4.3 Variation in Acceptable Outdoor Temperature Ranges for Opening Windows**




higher indoor temperatures). Note these strategies are not mutually exclusive. Naturally, the setpoints also differ according to building size, climate, internal loads and system design.

## 4.5 Humidity control

As discussed, environmental parameters other than temperature are included in control sequences for only three projects. At Kroon Hall, Lincoln Hall and Chesapeake Bay Foundation, "open" mode is over-ridden if humidity is too high. At Kroon Hall wind speed must also be below 15 miles per hour for a period of five minutes for the green light to go on. Other buildings that associate window use with the building's economizer (all on the west-coast) use outside temperature as a proxy for simplicity, even if the economizer has enthalpy control. Depending on climate and cooling system type, it may make sense to tie the open and close signals directly to the mechanism that initiates active cooling (chilled water supply) rather than outdoor or indoor temperatures, as is the case at Thornburg Headquarters. The downside to this approach is managing frequent cycling of the chilled water supply during the swing seasons. Because of this issue, the green light at Thornburg is disabled completely between November and April.

## 4.6 Air quality control

At Lincoln Hall, a separate blue light indicates to occupants if $CO_2$ levels are high enough to warrant opening the windows for air quality reasons. We did not ask the occupants specifically about their response to this signal. In some buildings that associate windows with economizer mode, demand-control is used to modulate fan speed for efficiency and air quality. Only in one building, Savery Hall, does $CO_2$ influence the status of the red and green light. In this situation, $CO_2$ sensors in each zone may over-ride natural ventilation mode and trigger air supply, switching the indicator from green to red.

For buildings in which air supply is shut off in "open" mode (changeover approach), all workstation zones are within 20 feet of the perimeter, and windows are assumed to be adequate for ventilation.

## 4.7 Signal Design and Placement

As shown in Figure 4, there are nearly as many signal types as there are buildings. Interviews revealed that in most cases there was little discussion about the design of the signaling device. The decision to go with a red/green light, a single green light or "open windows" sign was usually a matter of "off-the-cuff" judgment, sometimes influenced by cost or previous experience. For the vast majority of interviewees, providing "guidance," as opposed to a directive, was a high priority, but this was addressed explicitly in only one case: in which there one design team opted for an amber light over the more commanding "red."

Of the 16 projects, eight use un-labeled red-green or amber-green indicator lights; three use indicator lights with explanatory text, two use un-labeled on/off green indicators, and three use on/off “open windows” signs. The survey did not find any relationship between the presence of text and the percentage of occupants to report being aware of the signals. In terms of occupant response, our results suggest that all interface types were more or less equally likely to be overlooked unless occupants were given a compelling reason to regard them by way of orientations, periodic emails, or regular, less formal reminders from the building or office manager (see next section).

The decision to place the devices in workstations or common areas was also in most cases a matter of designers’ best judgment and/or cost savings. Several design teams elected to place the signals in places where occupants walk while others thought visibility from as many workstations as possible was preferable. In our survey, one of the most common comments was that occupants reported being more likely to use the signals if they could see them from their desk.

**Figure 4.4 Signaling Device Designs**

### 4.8 Education of Occupants

A number of education and reinforcement methods were used to communicate the meaning of the signals. We identified three "tiers" of educational strategies. In the first tier, the majority of projects relied upon an initial staff notice, usually in the form of an orientation given by the design team or building manager, which described the signaling system in the context of all of the other "sustainable" features of the building. In two cases, the initial notice came in the form of an information card. A new-hire orientation with the building manager is placed in the next tier, providing a more targeted and one-on-one explanation of the controls (windows, fans, thermostats, etc) available to occupants, even if this only happens once. In the highest tier, a building or office manager is active in an ongoing discussion with occupants, either in person or by email, regarding what is going on with the building (e.g. reminders when the summer makes itself official). For the most part, awareness of the system is highest where there is personal or ongoing contact such as this, even if it is just on a seasonal basis. In other cases, such as in Boora Architects' offices, a high level of knowledge and positive attitude regarding the signals most likely relates to the fact that many of the staff were involved in the design of the space. Not all ongoing reinforcement is effective. Emails sent automatically by the building management system can easily be regarded as spam and ignored, particularly if they are received more often than a few times a week, according to occupants at Kroon Hall.

**Table 4.6 Education approaches used in study buildings**

| Building | Num. People | Perimeter program | One-time staff notice | Ongoing discussion | New hire orientation | Info. card | Auto email |
|---|---|---|---|---|---|---|---|
| 1. Thornburg† | 175 | Private/ open office | | ✓ | | | |
| 2. UCSF | 150 | Open office | ✓ | | | | |
| 3. Boalt | 8 | Open office, classrm | | | | | |
| 4. ZGF*† | 175 | Open office | ✓ | | | | |
| 5. Lincoln | 60 | Private office | | | ✓ | | |
| 6. CUB | 25 | Open office | ✓ | | | | |
| 7. Boora* | 60 | Open office | ✓ | | | | |
| 8. CBF | 50 | Open office | ✓ | | | | |
| 9. Kroon | 60 | Private office | ✓ | | | | ✓ |
| 10. Zoom | 3 | Shared office | | ✓ | ✓ | | |
| 11. Kirsch | 8 | Private office, classrm | ✓ | ✓ | | | |
| 12. ARD | 50 | Private office | | | | | |
| 13. Hewlett† | 150 | Private office | ✓ | | ✓ | | |
| 14. NBBJ*† | 315 | Open office | ✓ | ✓ | | | |
| 15. Savery | 200 | Private office, classrm | | | | ✓ | |
| 16. Orinda† | 40 | Private and shared office | ✓ | | | ✓ | |

* Indicates occupants are architects and are thus more likely to be knowledgeable about the office design
† Indicates on-site building operator

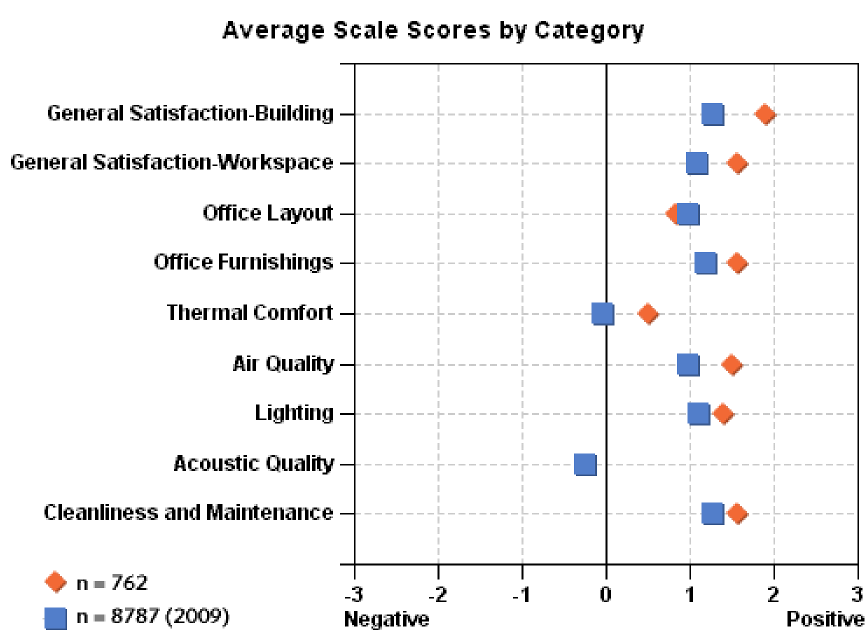
# 5 Occupant Response

We evaluated how engaged occupants are in observing the signaling systems, including how "actively" they respond to the signals and how likely they are to disobey the signals. We were able to survey occupants in 10 of the 16 buildings, and we conducted a few brief, informal interviews during site visits in six of the buildings. As shown in Tables 4.1-4.5, the type of organization and the number of occupants we surveyed varied widely building to building. Also note that the survey asked occupants to report their own behavior, and these responses were not necessarily reflective of actual behavior, but are still useful to compare buildings with similar attributes and understand the range of responses.

## 5.1 General Comfort Satisfaction

Indoor environmental quality assessment for the buildings in this study represent a range of occupant satisfaction scores, as shown in Figures 5.1-5.3. Figure 5.1 shows the average performance of the buildings included in the study (including those surveyed previously) compared to all buildings of a similar vintage (constructed since 2000) and the scores show a consistent, minor improvement on average, particularly

**Figure 5.1 Average occupant satisfaction scores compared to CBE IEQ survey database**



in general satisfaction and air quality.  These results coincide with the findings of Brager and Baker (2008), who use a sub-set of this data to demonstrate high occupant satisfaction scores for mixed-mode buildings. Their findings are reproduced in Figures 5.2 and 5.3 including the added records generated for this study (mixed-mode buildings shown as black circles and other mixed-mode buildings depicted as white diamonds, both sets compared to the curve for the entire CBE database as compiled in late 2009). The new records occupy a similar range of the distribution curves, with much wider distribution in the thermal comfort category. For the majority of projects, air quality scores seem promising. It should be noted that the base curve for these figures includes the entire CBE database, not just buildings of the same vintage.

**Figure 5.2 Thermal comfort benchmark: buildings with signals and all mixed-mode buildings**

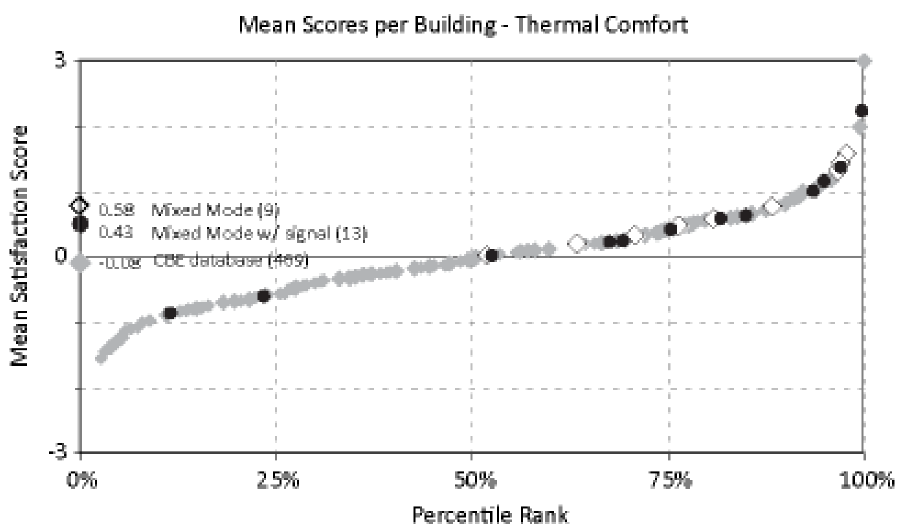
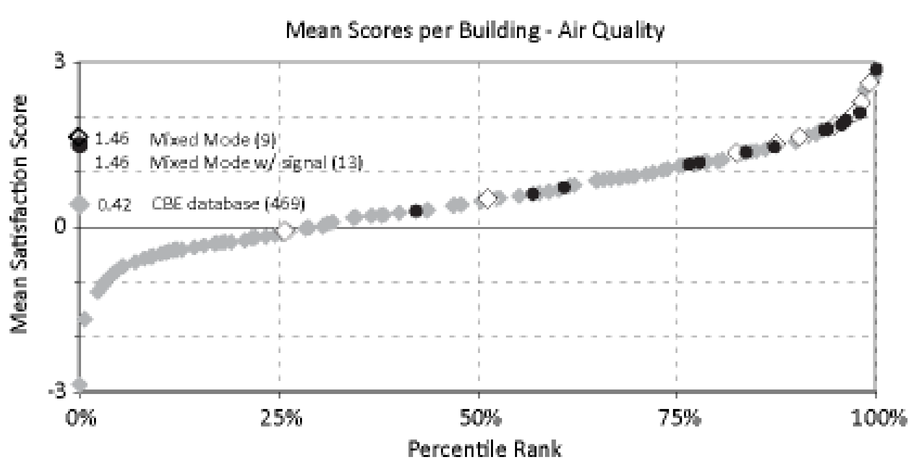



**Figure 5.3 Perceived indoor air quality: buildings with signals and all mixed-mode buildings**



The survey data does not send a strong enough signal of the perceived thermal comfort or air quality benefits of operable windows, even at this high level. Upon closer analysis of the data, there was no relationship found between general workspace satisfaction or comfort satisfaction and how occupants responded to questions regarding the windows or the signals.

### 5.2 Active Response to “Open” and “Close” signals

Figures 5.4 and 5.5 show the percent of occupants in each building that report acting on the signals after they notice the status has changed. Each bar represents all responses for one building, and the buildings are ordered from most active in “open” mode to least active in “open mode” according to mean response. The mean is based on numerical values assigned to each answers, from 1.0 (never opens) to 4.0 (always opens). “Not aware” responses are not counted in the mean. We are defining “active” occupants as those who report adjusting the window “always” or “usually.

Figure 5.5 shows that in most buildings, a consistent minority – 10-20% of respondents – report actively opening their window when the “open” signal is on, with very few saying they “always” act. This pattern seems to be independent of what control strategy and interface is used, and the percentage of respondents who say they are unaware. There are three outstanding buildings in which over 50% of occupants report being active and with very low percentages of respondents in the "not aware" category. These are NBBJ Architects in Seattle, Boora Architects in Portland, and Lincoln Hall at Berea College in Kentucky, and they share only one characteristic: they are the three in which internal management is actively engaged in educating occupants. In the case of Boora Architects, there is less direct discussion about the signaling system among staff, but it is a smaller office and most employees are very familiar with the system if not directly involved in the project. These results may suggest that, in the absence of a more consistent education effort, there are likely to be a minority of people who figure out, or remember, what the system is for and find it to be useful or important. It could also be an affect of the survey question itself, in which respondents are reminded of the system and provide a "good behavior" response.

**Figure 5.4 Occupant Response to "Open" Signal**

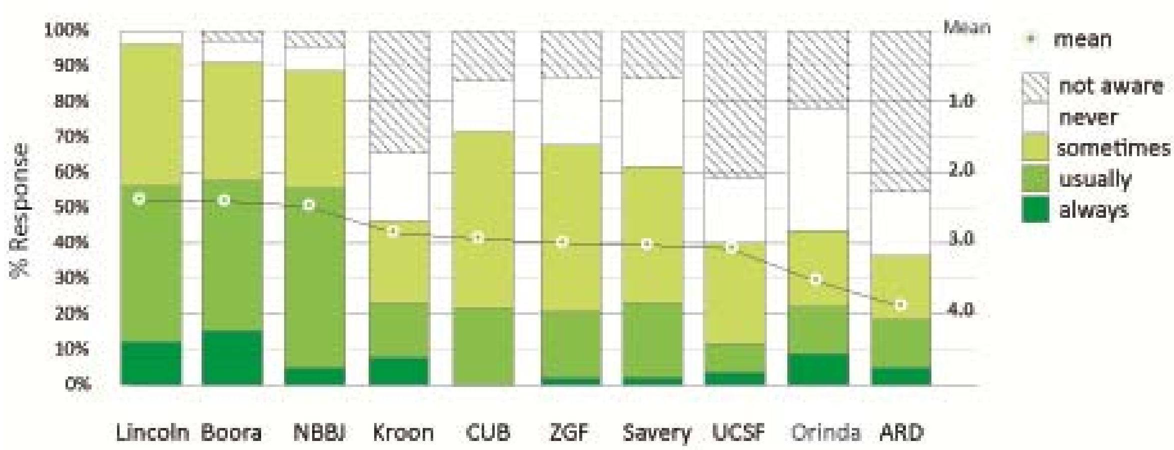
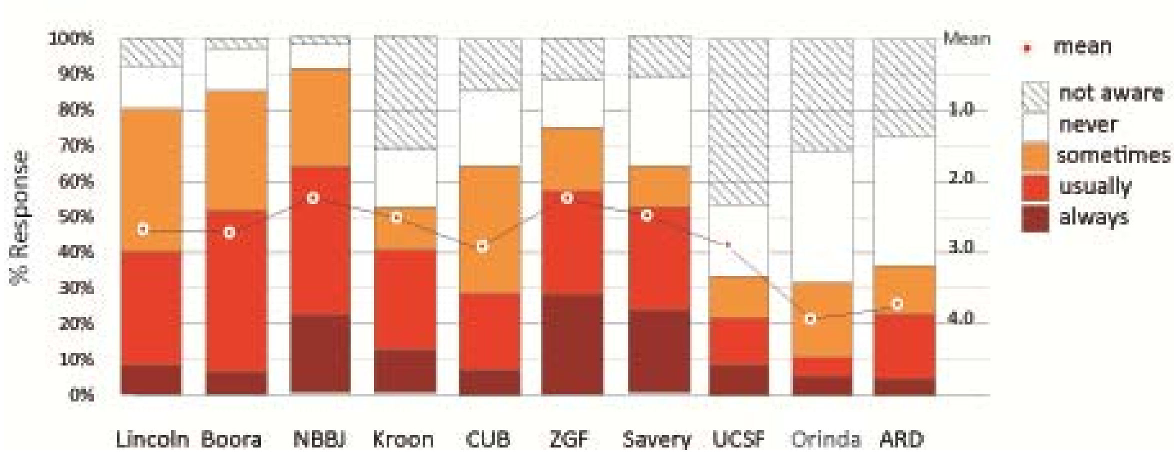



**Figure 5.5 Occupant Response to "Close" Signal**




Overall, the mean responses for acting on the "close" signal are higher and more variable (**Error! Reference source not found.**). The projects for which “closing” responses diverge significantly from the “opening” responses include those with on/off “green only” signals, which exhibit lower response rates (Lincoln Hall, Boora Architects, and Orinda City Hall), and those in which the importance of closing windows was particularly emphasized to occupants, which exhibit higher response rates (ZGF Architects and Savery Hall).

The survey results are as problematic as they are promising. For any given building, including those with the highest “active” response rates, there are about as many people who are unaware or generally ambivalent about the system as there are those who pay attention and actively participate. This varies somewhat based on the type of office and education occupants received as well as their general interest and knowledge level;

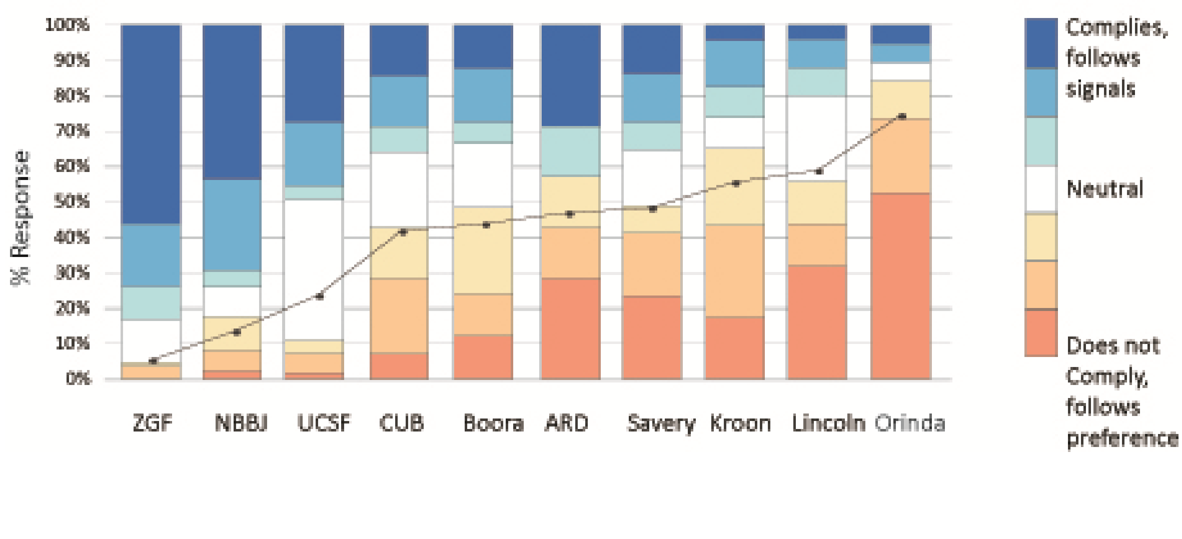
but no building achieved a mean response rate to either "close" or "open" signals as low as 2.0 ("usually"). The risks of this general ambivalence are reduced somewhat in open office spaces (as discussed in more detail later), where the 'active' users end up taking responsibility for a group of coworkers who share window access. It is also easier for building managers to walk through and correct for windows accidentally left open.

### 5.3 Willingness to Act Against the "Close" Signal

Occupants were also asked how likely they would be to open a window if they want to, even if they know the signal indicates otherwise. In Figure 5.6, the buildings are re-ordered from most compliant to least compliant. For this question, responses in the buildings represent a full spectrum of tendencies, from over 70% reporting being compliant in one building, to less than 10% in another. With a few exceptions, generally 40-60% of occupants in any given building report adjusting windows as they see fit.

Given that most design teams underscored the importance of protecting occupants' sense of personal control, these results do not necessarily indicate the "success" of each system. Rather, the wide distribution points to the importance of identifying the most common conflicts and personal factors that determine why someone responds the way they do, and then determining which of these factors are in the control of the design team or building management (or even should be).

**Figure 5.6 Willingness to Disregard the Signals**

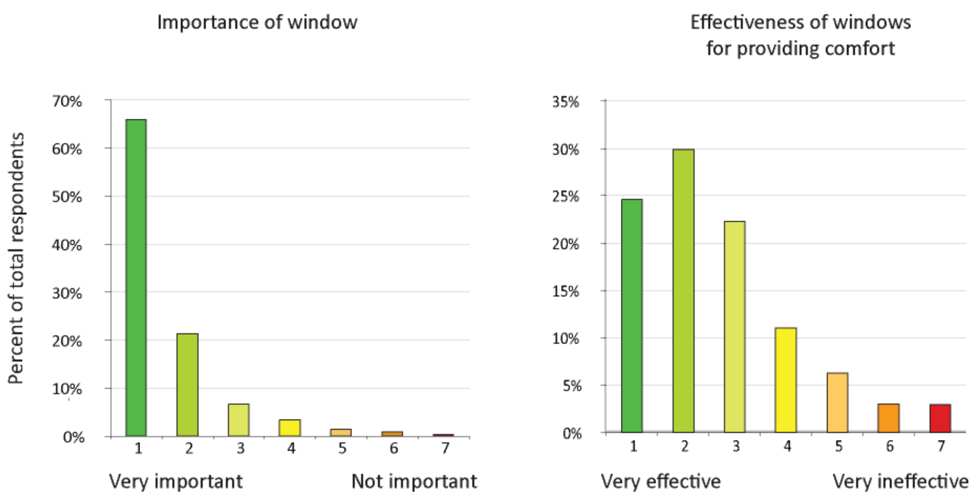


## 5.4 Factors that contribute to disregarding the signal

### *5.4.1 Personal reasons for using windows*

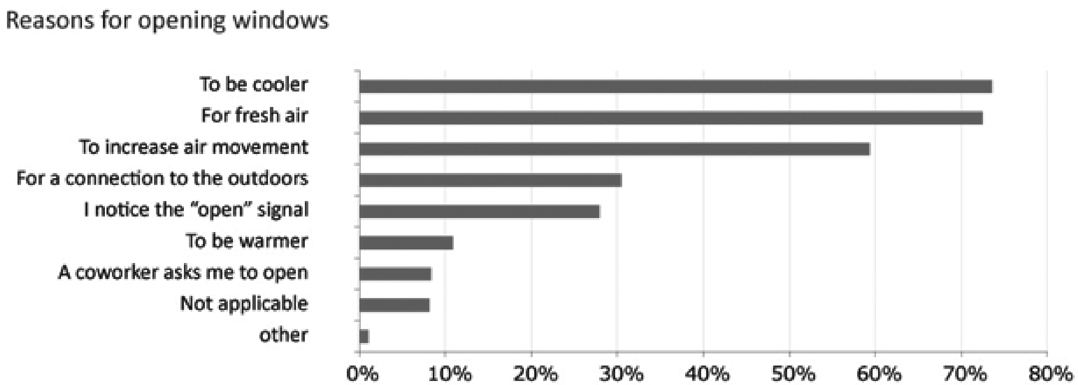
Our survey revealed that, across all buildings, most people value having operable windows very highly and consider windows to be an effective way to relieve discomfort (Figure 5.7).

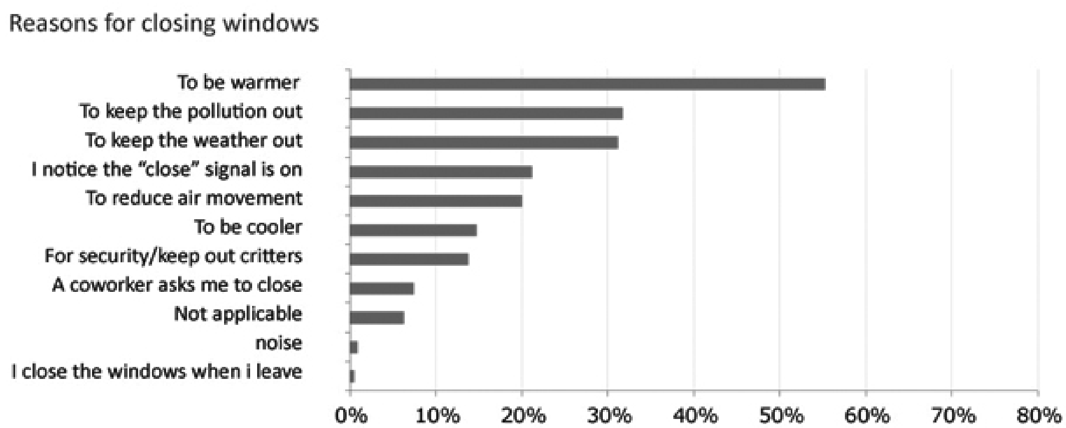
**Figure 5.7 Occupants' Satisfaction with Windows**




However, this positive attitude is not necessarily associated with a regular awareness or frequent use of windows, much less an appreciation for the encouragement that the "open" signal offers. Based on brief interviews with 22 occupants in six of the buildings, 15 (70%) said that the signals don't play any significant role in how they use windows. The most common reason was simply a tendency not to pay attention to windows – or the signals - because they are generally comfortable and focused on other things at work. Corroborating these findings, a similar sizable minority of survey respondents (30%) included the signals as a reason they opened their windows, on average; however, this average varies widely across buildings.

**Figure 5.8 Reasons for Opening and Closing Windows**




Of the seven people interviewed who said the signals *did* play a role in how they use their windows, four expressed a general tendency to like to have their windows open on a daily basis, and as a result were more likely to see the "open" signal as a "good reminder" or "a treat." Likewise, they were more likely to acknowledge the "close" signal (or wonder why it was on). Others found particular value in following directions, whether it was an opportunity to take a break from work, a reminder that it was nice outside, or a belief that following the system is important for the operation of the building. In the survey, 30% of respondents in each building cited a "connection to the outdoors" as a reason they open windows[1].

[1] In previous studies that used occupant surveys to understand window control factors, psychological factors are typically not included (e.g. Warren and Perkins, 1984)

### *5.4.2 Office Type*

Survey results uncovered a significant divide between the responses of people in open vs. private offices, as shown in Figures 5.9 through 5.12. Overall, people in private offices are less likely to actively respond to the signals, even though they generally have better access to both windows and an indicator installed in their personal space. There is also a strong correlation between office type and one's willingness to disobey the signals, private office inhabitants being less compliant. There are a number of possible explanations. During interviews with occupants, a few open-office workers commented that the signals acted as a "neutral third party," giving permission to window-users who would otherwise be concerned about disturbing their coworkers. In fact, the vast majority of survey respondents who said the signals enhanced their sense of personal control were located in open offices (Figure 5.10), while those who said the signals interfered were predominantly in private offices. In a sense, signaling systems may work in open offices by leveraging the behavior of those who regularly use windows, even if they are a minority.

**Figure 5.9 Open vs Private Offices: Willingness to Disregard the Signals**

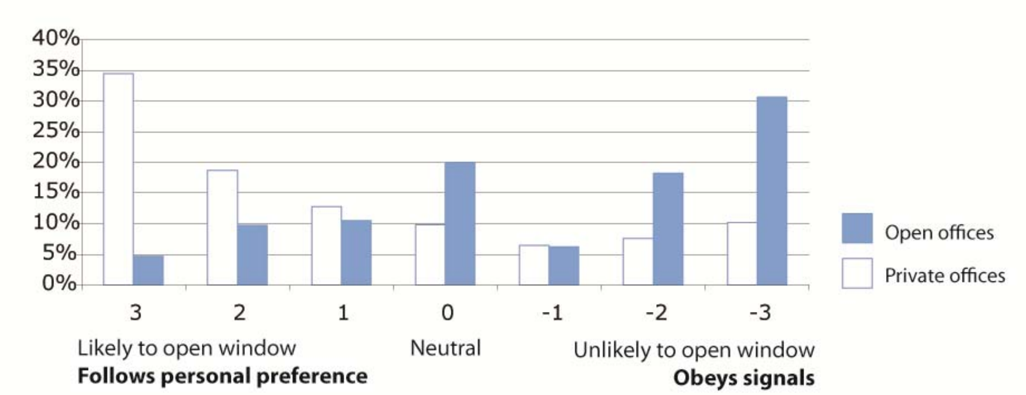



**Figure 5.10 Open vs. Private Offices: Personal Control**

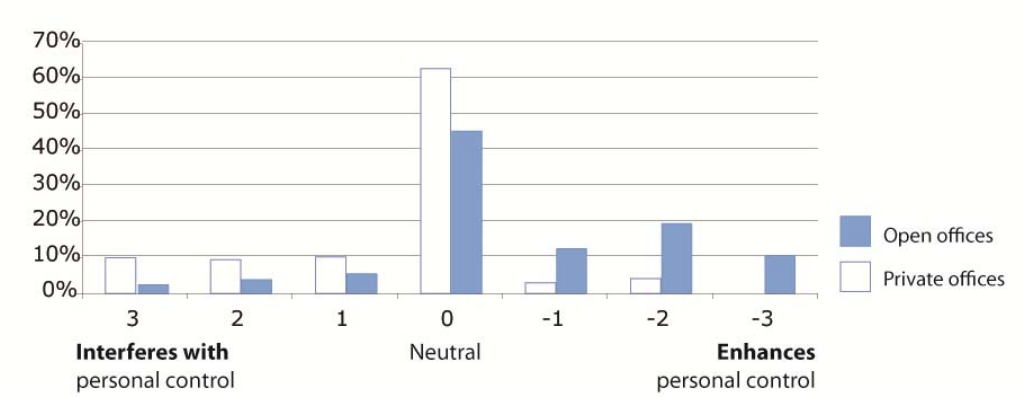



**Figure 5.11 Effectiveness of Windows**

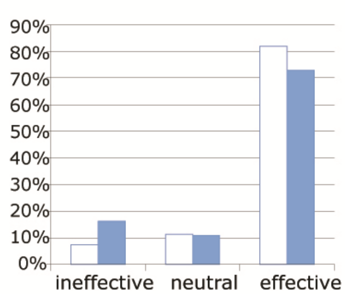
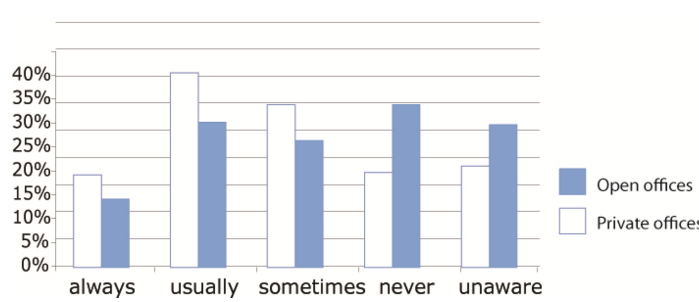



**Figure 5.12 Frequency of window use**



### *5.4.3 Reported conflicts*

In the survey, we asked occupants to comment on whether the signals coincided with their "own sense of when to open/close windows," and reviewed, coded and tallied the most common issues. A total of 274 comments were offered (roughly 20% of total survey participants), and responses were normalized by the number of occupants surveyed in each building. Of the weighted total, 35% dismissed the devices in some way, either remarking that they don't let the signals dictate their behavior, or that the signals easily go un-noticed. The rest were more constructive; roughly 40% critiqued the logic of the signals, and another 20% noted interfering circumstances such as difficult window hardware, wind, dust and noise. The most common comments are as follows:

**A. The "close" signal is on too often.** Next to simply not paying attention, the most recurring reported issue (15% of comments) was that the "close" signal was frequently on at times that seemed nice enough to use windows. In five buildings, there were reports that the "close" signal was "always on." Although we were unable to verify whether the number of hours spent in "open" mode really seemed unreasonable, in all five cases it does appear that a malfunction, mis-translation of the design intent, or adjustment in response to unrelated HVAC service issues, was responsible.

For buildings in which the signals are functioning as intended, this type of comment usually referred to the space being too warm and stuffy during times windows were not allowed. Another recurring complaint was that air conditioning would come on too early; that is, occupants thought the "open" signal turned off when it still seemed nice enough outside. Most of these occurred in buildings with high (78 F) cooling setpoints. These kinds of reported conflicts are at the heart of adaptive comfort in mixed-mode buildings and worthy of further research. These comments suggest that some occupants adjust their thermal preferences based not only on season and workspace conditions but also on their understanding of how the building operates.

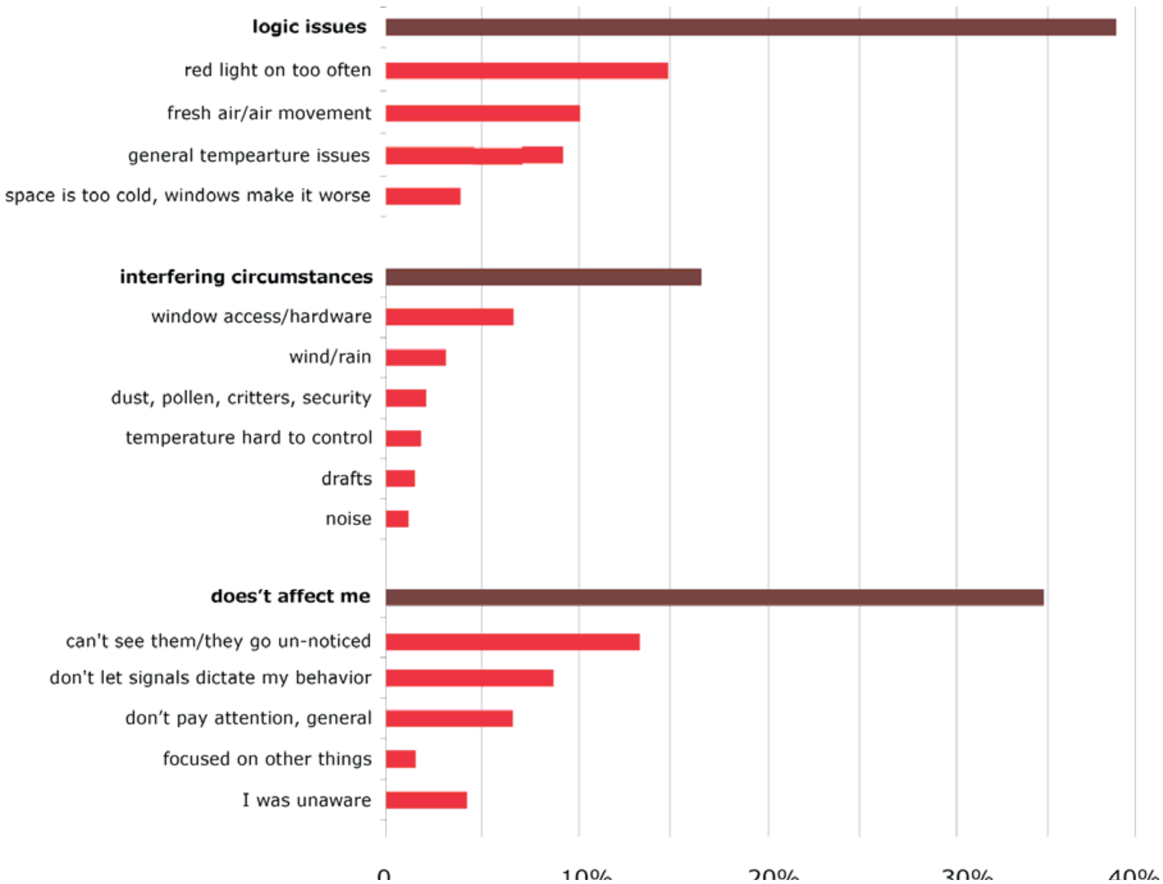
**B. Fresh Air.** Ten percent of comments referred to a conflict of wanting fresh air when the "close" signal was on. In most cases, air movement and fresh air were coupled in the comment, but the perception of stuffiness and need for fresh air was the dominant factor. In the results from our survey as well as other survey-based studies, air quality is an equally important reason for opening windows as temperature. However, air quality perception is complex and more difficult to assess in measurable terms than temperature, and it has been excluded as an independent variable from window control models. Research has shown that a perception of "stuffiness" is influenced by air movement, humidity and temperature (Fang et al 2000; Arens et al 2008).

More research is needed to determine whether increased air movement or $CO_2$ over-rides in the control algorithm for signaling systems would effectively manage these conflicts.

**C. Visibility from workstations.** As noted earlier, over 10% of those who offered comments remarked that they may pay more attention to the signals if they were more visible from individual workstations. Our analysis was not detailed enough to correlate survey responses and distance from or orientation to a signaling device. However, given our findings that most people tend not to pay attention to their windows as they go about their workday, its seems reasonable that a highly visible device would serve as a reminder, assuming occupants already find value in the system.

**D. Unique situations.** Most of the comments, even if they are not shared by other respondents in the study, point to the diversity of attitudes and preferences among office occupants as well as the range of local circumstances that affect comfort and can not be anticipated by a single control algorithm or window-opening policy. Aside from personal disposition, mood and personality, we documented extrinsic interfering circumstances including the location of furniture, the location of the thermostat, the presence of drafts from floor air diffusers (noted by several occupants), proximity to the façade, conditions directly outside (such as noise, wind, or pollen), surface temperatures, and direct sun exposure. In theory, these circumstances are the very justification for providing measures of personal control like operable windows. However, in many buildings, how the meaning of the signals is described to occupants does not go far enough to make allowances for these circumstances.

**Figure 5.13 Top Conflicts Reported in Open-Ended Survey Questions**



# 6 Summary and Conclusions

Signaling controls for operable windows are an unusually explicit way of negotiating between occupant behavior and automatic control in buildings. This study provides a closer look at both the range of circumstances to anticipate when designing with operable windows as well as how successful an information system is in moving occupant behavior towards design team expectations. Building designers who are considering signaling controls should be comfortable with the idea that the number of people who reliably ("usually" or "always") respond – to either "close" or "open" signals – is not likely to exceed 50%. This is in the best case, in which occupants are exposed to a higher degree of education than the normative initial meeting or notice. Otherwise, a smaller percentage (10-20%) of reported active participation is typical in "open" mode. Response in "close" mode is more varied.

Based on survey responses and informal interviews with occupants, we think it's reasonable to conclude that signals are generally disregarded because the majority of office inhabitants have a tendency not to pay attention to their windows unless they're uncomfortable. When comfortable, they are likely to maintain the status quo and not react to the signals; and when they are uncomfortable, it matters little what the signals say anyway. It is perhaps counter-intuitive that the minority of occupants who have stronger psychological motivations for using windows (such as a "connection to the outdoors") are the ones who may be more naturally active "window-users," and more likely to pay attention to the signals.

Given the right circumstances, however, our findings also show that it is possible to get occupants who normally wouldn't think about their windows *to start doing so*. We find that such a change in behavior is most likely associated with an increase in personal control, since those who follow the signals do so because they have discovered personal value in the system. To improve the success of a signaling system, we highlight the following key considerations.

## 6.1 Linking the signals with tangible benefits.

In the majority of projects, the signals were presented to occupants as a "green" feature designed to save energy by providing natural ventilation and/or avoiding energy waste. Our findings seem to align with the numerous studies that have found energy-saving behavior to be seldom motivated by generic values like "saving energy," and that programs to influence behavior are most successful when designed from the perspective of the audience, appealing to the social norms and/or tangible benefits familiar to the user (Abrahamse 2005; Gardener and Stern 1996; McKenzie-Mohr and Smith 1999; Stern 2002; Campbell et al. 2000; Staats et al. 2004).

Connecting the meaning of the signal to “green building” is not likely, by itself, to substantially influence the majority of occupants. This may be particularly true in private offices, where there is less social reinforcement of “doing good” or “breaking the rules.” Examples of personal benefits that occupants volunteered in our survey and interviews, which could be better incorporated in the “message” or education about these signals, include:

- a better understanding of how to use windows for comfort, separating air movement and cooling benefits (i.e. “if it’s warmer than 80F, opening the window may make you more uncomfortable.”)
- the ability to *avoid* discomfort (“if you let the cool air in now, it will prevent overheating later”),
- the opportunity to take a mental break from work by going to open the window, and
- an enhanced knowledge of the outdoor environment.

### 6.2 Leveraging behavior of “window-users.”

The idea that a significant minority (25-30%) of office inhabitants may have a psychological motivation to use windows is worth further attention. In an open office, although there were a greater number of people who reported acting on the signals and having an enhanced sense of personal control compared to private offices, these responses still represented a minority. In fact, overall, people in open offices reported using their windows *less frequently* than did people in private offices. Presumably, people with private access to a window will use it whenever they want, whereas window use in open offices is inherently more tied to the signals or other directives from coworkers. Therefore, signaling systems are more successful in open offices not necessarily because they prompt a kind of socially-reinforced collective effort in which everybody gets up and becomes frequent window users (the “army mentality,” in the words of one building manager describing the intent of the signal). Rather, I posit that the potential in an open office space may have more to do with the ability of a signal to validate and leverage the behavior of those who naturally like to have their windows open. There also may be a greater discouraging effect from opening the windows in “close” mode in open offices.

## 6.3 Visibility from individual workstations.

Assuming people have found value in the system, direct visual access to the signal is also important for taking action. Many occupants said explicitly in the survey that they would probably use the signals more if they could see them from where they sat. This is one rationale behind the PC desktop indicator strategy, used at ZGF Architects Portland offices, and also at the National Renewable Energy Laboratory's Research Support Facility (not in this study). From a small sample of interviews at ZGF, it seems this signal was easily overlooked because it blended too well with other task bar icons. Thus, what is considered "visible" at any given site can be highly contextual.

## 6.4 Climate and routine

The study was not designed to determine whether occupant response differs substantially in mild climates versus more extreme climates, or in response to weather at a particular time (which would involve a much more detailed on-site field study). And while these may certainly have some influence, our findings suggest that occupant culture and system reliability are probably even more influential to how people regard the devices. Once culture and reliability are established, however, climate remains an important factor in determining the routine of opening and closing schedules, which may be more or less in sync with personal preferences. For instance, for buildings in extreme climates, the green light may only come on for part of the day in the spring and fall and is red for much of the rest of the year. If occupants see "close" mode as the norm, they may come to regard the windows as inoperable. Likewise, in areas with pronounced swing seasons, where temperature variability throughout the day is unpredictable, we found examples of occupants ignoring the system if called on to make more than one or two adjustments over the course of a day.

## 6.5 Control logic

The type of control logic is probably less important than the consistency with which it coincides with the design intent *as communicated to occupants*. Whether the windows are allowed concurrently or as a part of a changeover strategy, is likely to be a function of the design team and owner's wishes and priorities. For either approach, however, the case studies reveal a number of further considerations:

### *6.5.1 Economizer logic and minimum acceptable temperatures*

For buildings in mild, dry climates, controlling signals based on outdoor temperature is a clear, simple strategy. It is a reasonable proxy for when outside air can serve the building, and it can be informative to occupants. The potential downside is that the control of the quantity of airflow is not as precise as with an economizer. In a large office space, it can be uncomfortably cool to open windows at 55°F or 60°F, particularly if there is wind, even if this may minimize internal gains and cooling needs later in the day.

The "windows-as-economizer" approach takes two forms in our set of case studies. Group 1 buildings allow the use of windows during economizer mode, offering some supplementary benefit depending on the sophistication of air supply zoning and demand control. The chief advantage of this approach is its resilience to the uncertainties of occupant participation. The conditioning system has been selected for maximum efficiency, and any further energy savings is a bonus. However, participation (i.e., opening windows when acceptable) is not likely to be high, since the mechanical system keeps the space comfortable within fairly conventional limits. In places where there is higher participation, open windows during "close" mode pose a greater liability. In sum, greater energy savings comes with substantially greater management with this approach.

Windows are also sometimes used *in place* of the economizer – that is, they are entirely relied upon for cooling over a similar outdoor temperature range. The Zoomazium and the Chesapeake Bay Foundation offer extreme examples of this approach, in which occupants are considered human actuators for large banks of windows that are not immediately adjacent to the workspace. At NBBJ, the system is more about providing guidance for personal window use according to an "economizer" rationale. At 63°F (outside), when 100% outside air is ideal to cool the building, the central fan shuts off and the building enters a "free-running" mode until either the indoor or outdoor temperature reaches 78°F. The staff are told to open the clerestory level windows first, and they are generally well-informed and relatively responsive to the system. This seems a reasonable approach that is worth further monitoring; unfortunately, the overall thermal comfort score in this building is low due to complaints of overcooling, related to both the windows and the underfloor air system.

### *6.5.2 Upper setpoints for cooling system "changeover"*

In setting a maximum indoor temperature for natural ventilation, the NBBJ strategy is related to those used at Savery Hall and Orinda City Hall, in which passive operations are based ultimately on *indoor* temperature criteria. This approach differs from economizer-driven control logic in two ways: first, outside air is still supplied to the zone by the air handler when temperatures may be too low for occupants' taste. Secondly, the energy savings from natural ventilation in these buildings relies primarily on maintaining a high indoor comfort limit, based on an interpretation of the adaptive comfort principle. In other words, windows are provided to relieve discomfort and displace mechanical cooling between roughly 72°F and 78°F (indoor). CUB and Boora operate under similar expectations (with 76°F and 82°F upper limits, respectively). If occupants do not adapt to and find the higher setpoint acceptable, or if they do not actively use their windows, these buildings run the risk of operating more like fully-conditioned (though highly efficient) buildings. Fortunately, this occurred in only one case; in fact, comments from NBBJ staff suggested that their 78°F setpoint could be pushed higher, perhaps due to their climate, Seattle, in which a connection to warm, sunny weather might be highly valued.

#### *6.5.3 Localized control*

The combination of windows with other local thermal control features was not very common. Savery Hall, Orinda City Hall and Boora were the only three examples that each allowed for ventilation and cooling control by zone (every 2-3 workstations/offices). These cases reveal advantages and potential pitfalls of providing local control. First and foremost is the potential to modulate operating modes based on local conditions or personal preferences. At NBBJ by contrast, overheating in one location has the potential to initiate mechanical cooling for an entire floor. However, realizing the potential of local control involves the assumption that occupants will decide to use their windows (and/or ceiling fans) and thermostats in the right sequence. Signals alone can't influence these decisions, but they can provide useful guidance if designed well. There is also the risk of increased complexity with local control. At Savery hall, variable refrigerant flow (VRF) heat pumps were an appropriate solution for encouraging natural ventilation while handling variable loads through the large, heavily partitioned building. However, by tying the signal to VRF operation zone by zone, it is common for adjacent spaces to be in different signal modes, and for signals to cycle frequently. Orinda City Hall avoids this by linking the signals only to outside temperature, communicating to occupants that the potential is available, while the VAV fans modulate between zero and full speed as necessary.

#### *6.5.4 Combining signals with thermal mass and other control strategies*

There are several controls that could theoretically be combined with signaling systems to enhance the use of natural ventilation, including sensors or actuators that could provide alarms or automatic overrides in order to address windows left open over night or during critical periods. In practice, however, none of the study buildings involved such controls because they were deemed too expensive. Instead, the use of thermal mass to dampen or buffer against temperature swings and reduce loads (as in Kroon Hall, Orinda City Hall) stands out as the most robust way to increase the viability of manually-operated windows, given the inevitable diversity of occupant tendencies and unique circumstances.

### 6.6 Management

Ultimately signaling controls are balancing the dual objectives of enhanced comfort through manually operated windows, and improved energy-efficiency. As the case studies show, building designers are often faced with tradeoffs between these objectives and resolve them in many different ways. None of the designers we interviewed ever assumed that everyone in the building would follow the signals perfectly. By necessity, each building is designed with low-energy systems and/or other passive features (night cooling for instance) so that window use transgressions don't pose any serious performance risks. As one building manager put it (echoed by other designers and operators we interviewed), "if you're serious about natural ventilation, you can't leave it up to the occupants." So why propose a signaling systems at all, and how is money and time best invested?

Based on what we have observed, we think the answer is to take advantage of signaling systems as an informational device supporting an explicit internal policy, rather than thinking of them as being just another part of the building's controls. The policy should be based on what occupants need to know about the features they have access to (windows, fans, thermostats) and environmental conditions so that *their* needs are met, rather than the building's needs. Assuming the building is designed well, these would coincide.

For example, Stanford's Yang and Yamazaki Energy and Environment Building (Y2E2), a large faculty office building in Palo Alto, CA, opted out of a signaling system in favor of a simple word-of-mouth policy. In Palo Alto, natural ventilation is adequate most of the year except for summer days that can get too hot in the afternoon; so, the design team has disseminated the message that "if it is above 80°F outside, please don't open your window." This is similar to the policy established at ZGF (although the two buildings have very different conditioning strategies). The implication is that, even if occupants are not following the policy to be "green," they learn over time that it is best for their own comfort. Staff at Kroon Hall learned this lesson on their own as well, without looking at the signals. In these buildings, a simple digital read of outdoor and indoor temperature may suffice, similar to what is placed on ZGF staff computers. At Boora, the approach is more legible, with a digital temperature monitor wired to each "open windows" sign and installed by the window at eye-level. At Y2E2, staff must access an online dashboard system to figure out what the operating status is, a strategy which is still more informed by the objective of "getting people to do good for the environment" rather than simply making a building design legible to its users, (even though the dashboard solution is certainly less Pavlovian than indicator lights).

There are a number of reasons that a signaling system should be secondary to a management strategy. First, as has been shown by others (Brown and Dowlatabadi 2009), the occupant learning curve for unconventional building systems in office spaces in particular is steep, and some strategies, such as wider dead-bands, may require a shift in occupant expectations or routines. Secondly, internal policy and education is the only way to address the unforeseen interactions among thermal, visual, acoustic, and other conditions and preferences unique to a specific workstation. A few examples of messages that a signal could represent:

"*the red light means that your air conditioner is operating when it might not need to be – if this is what you prefer, please make sure the window is closed. Also, remember you have a ceiling fan*"

or, "*it's 5:00, before you leave please make sure your window is closed so it's not freezing when we all come in tomorrow morning*."

This reinforcement probably needs to be ongoing and not too frequent. Only some messages can reasonably be tied to a signaling device.

Finally, interest level appears to be a key factor in getting occupants to use the signals. For example, the survey results showed that architects scored high while city officials scored low. Furthermore, about half of the buildings house organizations that have an environmental mission. Ideally, window use policies should be tailored to the values of the occupants via management.

## 6.7 Future Work

We see this study as one step forward in the ongoing inquiries into occupant behavior in mixed-mode buildings, and what appears to be the first systematic study of signaling devices. Digging deeper into quantifying how much behavior is influenced by signals, or how much signaling devices impact fan and/or cooling energy requires field studies of a strong sample of buildings that are generic enough in size and use, and are working as designed. The buildings in this study together provide a useful set of best practices for implementing signaling controls, but no project stands out as a model application for one reason or another, and setting up a controlled study would probably require some initial interventions. For instance, one building's control strategy may be particularly robust, but the signals are not visible to occupants; or occupants are particularly well-informed and engaged with the system, but the control sequence happens to be faulty or confusing.

This project combined multiple methods in order to collect as much information as possible about a technology that has been little studied. Future research could go in several directions:

- Monitoring of actual window use behavior to better understand the influence of a signaling device compared to other environmental stimuli or physical characteristics in an office (open, private, distance form window).
- Intervention studies that monitor window use behavior before and after targeted policies, campaigns or interfaces are introduced (may or may not be associated with a signal)
- Field monitoring of fan operation in "open" mode resulting from window use compared to demand control ventilation or compared to window-HVAC interlock controls
- Field studies incorporating both physical measurements and surveys to test acceptable upper temperature limits in natural ventilation mode
- Investigating the use of signals in combination with other building information feedback tools, such as dashboard systems.

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## Appendix A: Survey Module

Below is the text of the questions that were added as a self-contained module to the existing CBE Indoor Environmental Quality survey http://www.cbesurvey.org Like the core survey, questions are a combination of multiple choice and those that ask the respondent to rate an attribute on a 7-point scale. Text was modified according to the type of control system, for instance instead of "green light" and "red light" the text might read "the 'open windows' sign is on" or "the 'open windows' sign is off," etc.

### Opening and Closing Windows

**Please identify the reasons why you open the window(s) in or near your workspace.** (check all that apply)

- ☐ To feel cooler
- ☐ To feel warmer
- ☐ To increase air movement
- ☐ For fresh air
- ☐ To feel a connection with the outdoors or adjacent spaces
- ☐ A co-worker requests that I open the window
- ☐ I notice the window indicator lights are green
- ☐ Not Applicable, I never open the window(s)
- ☐ Other: ________

**Please identify the reasons why you close the window(s) in your or near your workspace.** (check all that apply)

- ☐ To feel cooler
- ☐ To feel warmer
- ☐ To reduce air movement
- ☐ To keep out smells, noise or pollution
- ☐ To keep the weather out
- ☐ For safety or security reasons
- ☐ A co-worker requests that I close the window
- ☐ I notice that the window indicator lights are amber
- ☐ Not Applicable, I never close the window(s)
- ☐ Other: ________

## Operable Windows - Use Patterns

**Excluding rainy/cold times of year, how often do you typically adjust the window(s)?**

- ◯ Daily (typically every day)
- ◯ Weekly (1-3 times a week)
- ◯ Monthly (1-3 times a month)
- ◯ Less than once a month
- ◯ Never

**Excluding rainy/cold times of year, approximately how much time during the day do you keep the window(s) open?**

- ◯ The whole day
- ◯ Half of the day
- ◯ 1-2 hours a day
- ◯ Less than 1 hour a day
- ◯ Never (I don't open my window)

**How often do leave the windows open over night?**

- ◯ Daily (typically every day)
- ◯ Weekly (1-3 times a week)
- ◯ Monthly (1-3 times a month)
- ◯ Less than once a month
- ◯ Never

**If you don't tend to use your windows, what are the main reasons? (check all that apply)**

- ☐ Window is difficult/confusing to operate
- ☐ Office layout or furniture makes it inconvenient to use the window
- ☐ It is often too noisy outside
- ☐ Blinds or shades are often down/in the way
- ☐ I am uncertain about when opening windows is okay, easier to keep them closed
- ☐ I don't want to disturb my co-workers
- ☐ I am usually comfortable and seldom feel the need to open the window
- ☐ I am simply not in the habit of using my window
- ☐ Not applicable (I use my window regularly)
- ☐ Other: __________

**To what degree does the building management encourage or discourage the use of operable windows?**

Encourage ◯ ◯ ◯ ◯ ◯ ◯ ◯ Discourage

## Operable Windows - Green/Amber Indicators

**This building has a green/amber light system to notify you when conditions are appropriate to open and close windows. When you notice that the light is green, how often do you respond by opening the window(s)?**

- Always
- Usually
- Sometimes
- Never
- I have not noticed/can't tell when the light is green

**When you notice that the light is amber, how often do you respond by closing the window(s)?**

- Always
- Usually
- Sometimes
- Never
- I have not noticed/can't tell when the light is amber

**How often do the lights conflict with your own sense of when to open windows, or with your own preferences? (Excluding rainy/cold times of year)**

- Always
- Usually
- Sometimes
- Never
- I don't know

Please explain

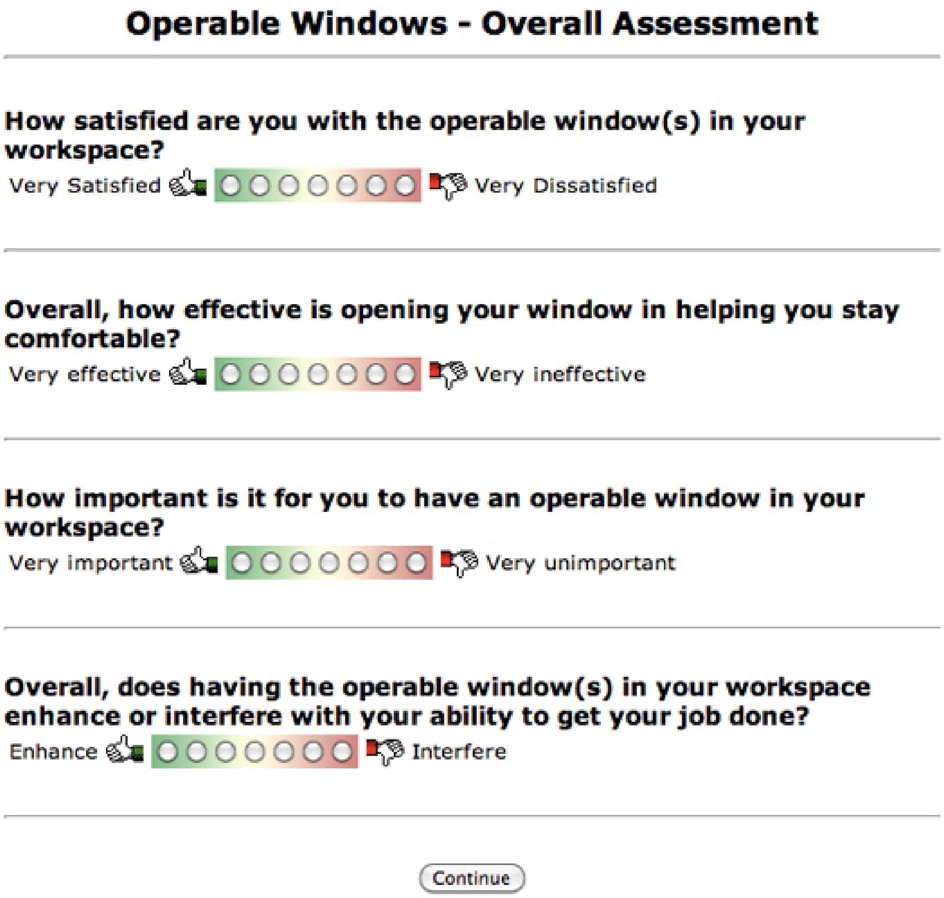
**If you want to open a window when the light is amber (indicating that it's not the right time), how likely are you to open the window?**

Highly Likely ○ ○ ○ ○ ○ ○ ○ Highly Unlikely

**Do the green/amber lights enhance or interfere with your sense of personal control?**

Enhances ○ ○ ○ ○ ○ ○ ○ Interferes

**Please describe any other issues related to the operable windows or green/amber lights that are important to you.**



## Operable Windows - Overall Assessment

**How satisfied are you with the operable window(s) in your workspace?**

Very Satisfied ○ ○ ○ ○ ○ ○ ○ Very Dissatisfied

**Overall, how effective is opening your window in helping you stay comfortable?**

Very effective ○ ○ ○ ○ ○ ○ ○ Very ineffective

**How important is it for you to have an operable window in your workspace?**

Very important ○ ○ ○ ○ ○ ○ ○ Very unimportant

**Overall, does having the operable window(s) in your workspace enhance or interfere with your ability to get your job done?**

Enhance ○ ○ ○ ○ ○ ○ ○ Interfere

Continue

## Appendix B: Interview Guide

For each building, the following template was constructed. Interviews were not conducted in every category for every building, but each building had at least one design team member and one on-site management position represented in the interview results. The same questions were asked of all individuals where appropriate.

| | | | | |
|---|---|---|---|---|
| Contact ID | | | | |
| Date | | | | |
| Describe how the building works.<br>What were the main design goals of the project?<br>What was the main reason for/ idea behind using a mixed-mode strategy? | | | | |
| How would you describe the purpose of the indicator? | | | | |
| How were decisions made about design/placement of the devices? | | | | |
| What are "open" mode criteria, what happens in "open" mode? | | | | |
| When does green light tend to go on/off? | | | | |
| Is the building operating as intended? What are main complaints/hurdles? | | | | |
| Do people use their windows? | | | | |
| Are people aware of the system/follow it? | | | | |
| How were/are occupants informed? | | | | |
| Lessons learned/stories | | | | |

## Window Signaling Systems: Case Study Summaries
Appendix C

### Group 1 Concurrent air supply, outdoor temperature control

1. 654 Minnesota Avenue, UCSF, San Francisco CA
2. Boalt Hall, University of California Berkeley, Berkeley California
3. ZGF Architects Offices, Portland, OR

### Group 2 Concurrent air supply, outdoor + indoor temperature control

4. Thornburg Headquarters, Santa Fe, NM
5. Kirsch Center for Enviromental Studies, De Anza College, Cupertino, CA
6. Applied Research and Development (ARD) Facility, Northern Arizona University, Flagstaff, AZ
7 . William and Flora Hewlett Foundation Building, Menlo Park, CA

### Group 3 Discontinued air supply, outdoor temperature control

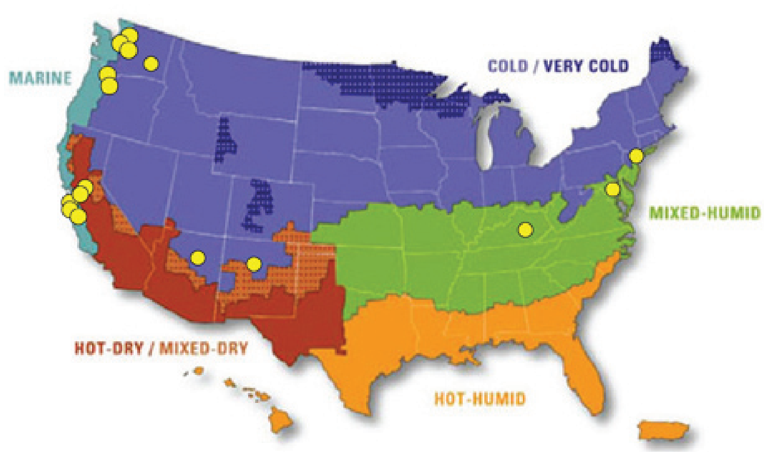
8. Lincoln Hall, Berea College, Berea, KY
9. Phillip Merrill Chesapeak Bay Foundation Building, Annapolis, MD
10. Kroon Hall, Yale University School of Forestry Building, New Haven, CT
11. Zoomazium, Woodland Park Zoo, Seattle, WA

### Group 4 Discontinued air supply, outdoor + indoor temperature control

12. NBBJ Architects Offices, Seattle WA
13. Savery Hall, University of Washington, Seattle WA
14. Orinda City Hall, Orinda, CA *This could also be considered a variation of Group 1 or Group 3 building

### Group 5 Decoupled cooling and ventilation

15. Compton Union Building (CUB), Washington State University, Pullman, WA
16. Boora Architects Offices, Portland OR



# 1. 654 Minnesota Avenue, UCSF, San Francisco CA

Group 1 Concurrent air supply, outdoor temperature control

| | |
|---|---|
| **Project Scope** | Owner-occupied adaptive re-use of 1980s industrial building with operable windows |
| **Architect** | STUDIOS Architecture |
| **Mechanical Engineer** | Taylor Engineering |
| **Year Completed** | 2008 |
| **Perimeter Program** | Large open office plan, three workstations from window |
| **Occupants** | 150 |

| **Intent of Signals** |
|---|
| To moderate personal window control. Window use is allowed when outdoor temperatures are between 55-75° F (roughly the building's normal economizer cycle), and discouraged otherwise. |

*Red/green signals are located overhead in corridors, with other utilities*

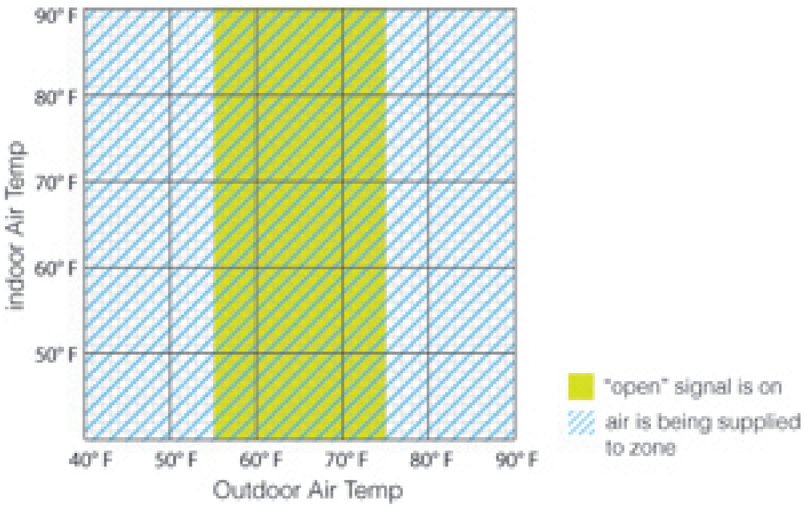
## System Description

This project exemplifies the type of application in which the design team wanted to provide operable windows primarily as a personal control amenity for occupants. The existing industrial building had original operable windows, and the central goal of the project was to be as low-energy as possible. But the depth of the floor plates made it difficult to justify a dependence on the operable windows for air supply entirely. In a climate where a large percentage of operating hours are spent in economizer mode, however, keeping the windows operable was a reasonable gesture towards a more flexible, adaptable envelope. The signals were installed to maintain some measure of oversight and discourage open windows at times the HVAC system is actively cooling or heating. A set of red/green lights is suspended from the ceiling at either end of each circulation corridor. Placards that explain the meaning of the red and green lights were planned but ultimately rejected during project close-out. As a result, only the occupants who were present for an initial building orientation were directly informed about the system. Many others didn't notice the presence of the lights.

*Typical operable window adjacent to workstation.*

## Operating Conditions and Occupant Response

Based on interviews, site observations and survey responses, the lights function well and the green light is on at times that make sense, but the occupants are generally disengaged from




the routine of operating windows, either because they are unaware, busy, comfortable, physically removed from the window, or off-site, where many staff spend a good portion of their workdays. Because comfort satisfaction is very high, and the building operates as it would otherwise when the green light is on, there is little reason or incentive to reinforce the system. By and large, preventing energy waste during the red light mode is a more direct energy consequence, and the most important oversight issues include people leaving their windows open and the light turns red. Survey results show that over 40% of occupants are unaware of the system. In other projects where little has been done to educate, the responsibility has been assumed by the office manager, who goes around at the end of the day or when the light turns red to make sure windows are closed. Fortunately, because the space has an open plan and the windows aren't used very much, this places little burden on the building or its users.

# 2. Boalt Hall, UC Berkeley, Berkeley CA

Group 1 Concurrent air supply, outdoor temperature control

| | |
|---|---|
| **Project Scope** | Renovation |
| **Architect** | Ratcliff |
| **Mechanical Engineer** | Taylor Engineering |
| **Year Completed** | 2009 |
| **Perimeter Program** | Small open office, classrooms, lounge |
| **Occupants** | 2-3 full-time, mostly transient |

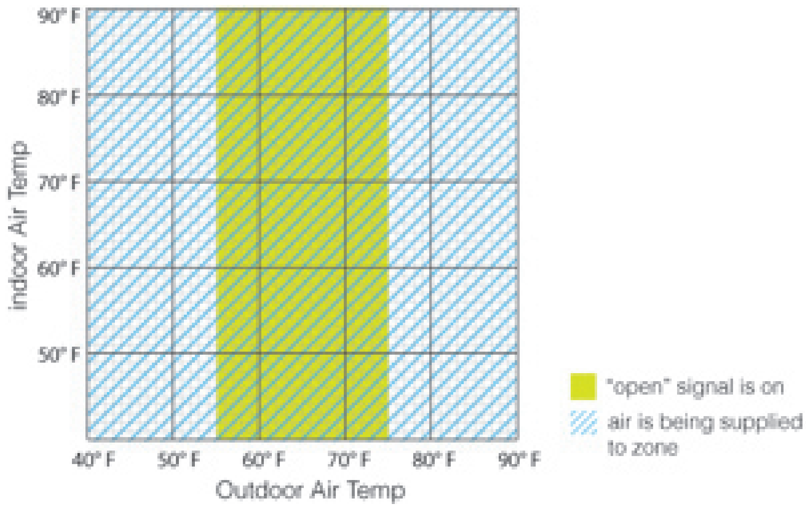
| **Intent of Signals** |
|---|
| To regulate manual window use. Window use is allowed when outdoor temperatures are between 55-75°F (roughly the building's normal economizer cycle), and discouraged otherwise. |

## System Description

During a recent renovation of Boalt Hall, operable windows were installed on the first floor, which contains two classrooms, a student lounge area, and the California law review office. The windows face south and west onto the public courtyard and busy plaza bounded by Bancroft ave, Wurster Hall, and Boalt. For security reasons, the windows open only four inches. The windows were installed to earn an additional LEED credit for increased thermal control. Because the building was to be mechanically cooled and ventilated, a set of red and green lights was installed to help avoid energy waste, or in the words of the engineer, provide "a way out of a bad situation." They are placed just above head height next to each bay of windows.

## Operating Conditions and Occupant Response

Because the space is occupied by student staff with irregular schedules and annual turn-over, we chose not to study this building in detail. However, we interviewed students on multiple occasions to get a feel for how much the windows are used. Although the people we spoke with were unaware what the signals were for, (there is no signage associated with them and they didn't recall receiving an email), they were very enthusiastic about the idea once they learned about it. Even though the windows don't open very far, the blinds are often drawn and it is noisy outside, the students we interviewed said that the windows do get used, because they like the fresh air and connection to the outdoors.


90° F
80° F
70° F
60° F
50° F
Indoor Air Temp
40° F
50° F
60° F
70° F
80° F
90° F
Outdoor Air Temp
"open" signal is on
air is being supplied to zone

# 3. ZGF Architects, Portland, OR

Group 1 Concurrent air supply, outdoor temperature control

| | |
|---|---|
| **Project Scope** | Mixed use office/residential high-rise in downtown urban area designed by primary tenants |
| **Architect** | ZGF Architects |
| **Mechanical Engineer** | Stantec |
| **Year Completed** | 2008 |
| **Perimeter Program** | Large open office plan, 2 workstations deep |
| **Occupants** | 245 |

| **Intent of Signals** |
|---|
| To regulate manual window use. Window use is allowed when outdoor temperatures are between 55-75°F (roughly the building's normal economizer cycle), and discouraged otherwise. |

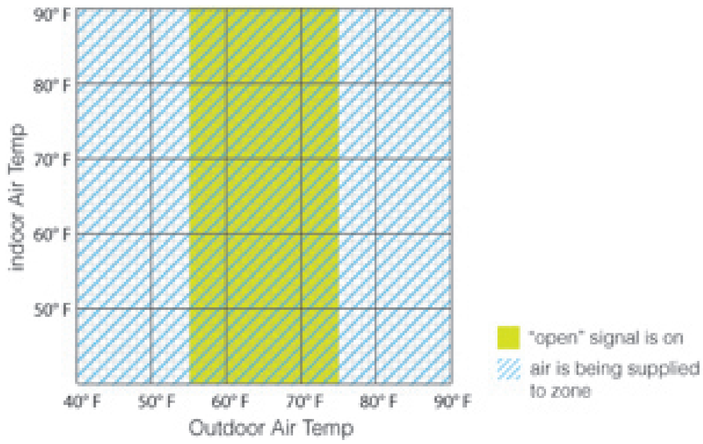
## System Description

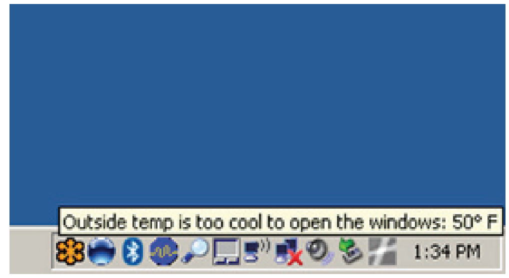
In this project, the building was originally designed without a signaling system. The central idea was to provide a low-energy under-floor air distribution system and operable windows for personal control, given Portland's mild climate. The signaling system came about after a heat wave soon after move-in, when management noticed that staff were using the windows when it was too hot outside. The design team decided on a policy to inform and remind occupants about efficient window use based on outside air temperature. A digital indicator icon mounted on each occupant's PC taskbar was chosen, with blue (too cold), green (okay to open windows) and red (too warm) icons. The team decided against a "pop-up" notification to minimize the nuisance or "spam" factor.

*Operable slender awning windows are removed a few feet from workstation clusters*

## Operating Conditions

No interview was conducted with the building operator and we are unaware of any major commissioning issues regarding the cooling and air distribution systems.




## Occupant Response

654 Minnesota Ave (case #1) and ZGF offices recieved almost identical thermal comfort and air quality satisfaction scores. However, compared to the occupants at 654 Minnesota in San Francisco, staff at ZGF are more active window users, perhaps due to office culture, schedules, or more variable thermal conditions within the office. There were several complaints of overcooling in this building, attributed either to local drafts or to the set-points for "green light" mode being too broad. The level of knowledge and interest of the occupants is revealed in their survey comments; many put forth conflicting theories or proposals for how the system could be more effective.

Similar to Boora Architects (see Group 2) and NBBJ Architects (see Group 4), this project benefits from an occupant group that is relatively well-informed about the system (and potentially proud of their new space) compared to other buildings in the study. ZGF has the highest percentage of respondents (25%) who report "always" acting on the red or blue icons (55% responded in the categories of always + usually, which is second place). These results are promising considering the stated intent of the icons, which is to enlist staff in keeping an eye on outdoor temperature when the windows are open. However, because the building is larger and ZGF staff are more active window-users compared to those in 654 Minnesota, there could be higher risks associated with the equally large percentage of staff (~50%) who remain fairly ambivalent about or unaware of the system.

# 4. Thornburg Headquarters, Santa Fe, NM

Group 2. Concurrent air supply, outdoor and indoor temperature control

| | |
|---|---|
| **Project Scope** | 110,000 square-foot, 3-story office building in suburban area |
| **Architect** | Legoretta + Legoretta; Dekker/Perich/ Sabatini Architects (Architect of Record) |
| **Mechanical Engineer** | Arup (Design Engineer); Bridges and Paxton Consulting Engineers (Engineer of Record) |
| **Year Completed** | 2009 |
| **Perimeter Program** | Private offices and open office bays 2 workstations deep |
| **Occupants** | 195 |

| **Intent of Signals** |
|---|
| To remind occupants that the building has low-energy systems and they have the opportunity to use their windows. Window use is allowed in the building as long as there is not a call for chilled water between the months of April and November |

## System Description

The local climate of Santa Fe is well suited to natural ventilation, but requires active cooling for significant periods as daily temperature can vary by as much as 30 degrees with high seasonal variation. In developing a mixed-mode system for the building, the design team was able to meet most of the cooling loads with evaporative cooling, and provided additional conventional chilled water to meet the few hundred hours per year evaporative cooling would be insufficient. The green indicator light used at Thornburg ultimately became a way to celebrate the building's low-energy design and to encourage people to use their windows when the building is either in evaporative cooling or economizer modes. Some members of the design team emphasized the psychological benefit of reminding occupants that they do not work in a sealed office environment, a message that was unique to this case.

*Typical private and open office areas*

## Operating Conditions

Thornburg is the only case in which the control commands for the window indicator are tied directly to the commands for the mechanical system's operation. The building maintains fairly conventional heating and cooling setpoints of 72° and 75° F. Occupants do not have local thermostat control but can control

*There is no control sequence diagram for this project*

air flow at local floor air diffusers. Initially, the green window signal was set to be normally "off," unless the economizer was enabled (outside air temperature must be below 65° F and at least two degrees below the return air temperature). This caused the lights to cycle on and off as the building modulated between modes. It was particularly confusing in one central area of the building, where cross-over within a double-height space connecting floors served by different air handlers made it difficult to control temperature. To address this problem, the control for the lights was set to default to "on" in all modes, unless there was a call for chilled or hot water. This provided some measure of coordination among the lights, but the consequence of this solution was the possibility for the green light to turn on during the heating season, when hot water supply cycled off and air was simply recirculated. As a result, the building operations team decided to disable the green light completely between the months of November and April, during which period they presumed no one would miss their windows.

## Occupant Response

We were not able to survey occupants in this building, but a few informal interviews suggest that, despite the intent of making natural ventilation legible in the building, many people are still not in the habit of using their windows. One issue is the placement of the furniture next to the window in such a way that the hardware is out of reach without a special device that was fashioned by the building manager. However, access is probably not the primary reason; more commonly, it seemed that occupants are generally busy and comfortable, and don't feel the need to use them. A sizable minority do appreciate the connection to the outdoors, as we found in other buildings. In the open office spaces, there is more conversation about adjusting windows and blinds, but this depends on the group of people sharing access.

Although there was no initial orientation about the system and no signage accompanying the green light, the building manager communicates regularly via email about the system; he finds the green light useful as a way to communicate what the building is doing generally. Based on talking to staff, they seem to

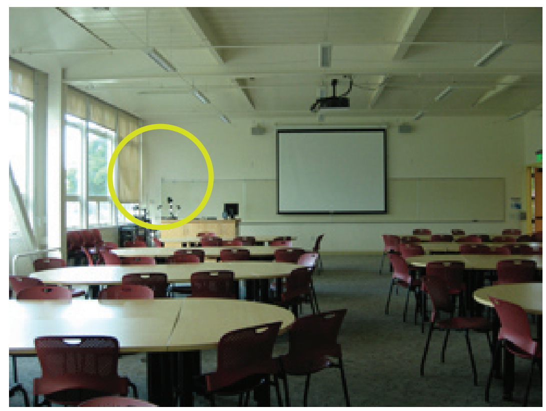
# 5. Kirsch Center for Environmental Studies, de Anza College, Cupertino, CA

Group 2. Concurrent air supply, outdoor and indoor temperature control

| | |
|---|---|
| **Project Scope** | 22,000 ft$^2$ classroom and faculty office building in campus/suburban area |
| **Architect** | Van der Ryn Architects (Design archtiect) and VBN Architects |
| **Mechanical Engineer** | ARUP |
| **Year Completed** | 2005 |
| **Perimeter Program** | private offices, classrooms, student lounge |
| **Occupants** | 8 |

**Intent of Signals**

The purpose of the signals is two-fold: to keep the windows closed while the building is being actively heated or cooled, and to make the natural ventilation strategy visible to students and other occupants.



*A red/green light with instructional text is mouted at eye level on the wall next to each window in private offices, classrooms, and shared worspaces. In the classrooms, they are mounted next to the thermostat and blind controls.*

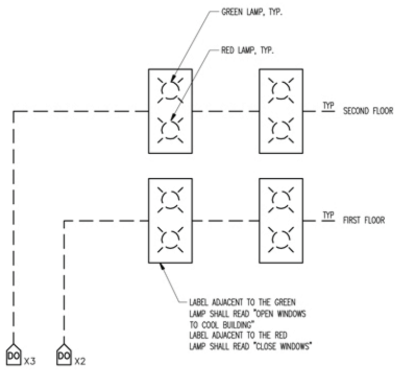
## System Description

The building design is split into east and west wings, with radiant slab cooling in the west wing and underfloor conditioned air on the east. A core goal for the project was to provide a "teachable" building with highly visible efficiency features. Operable windows were a part of the original design proposal, but campus facilities staff were skeptical, arguing that acutators were necessary to keep pressure and temperature balanced. The signals were selected as a compromise, providing some measure of oversight to prevent windows from being left open.

## Operating Conditions

The Kirsch Center has been celebrated as an example of successful high performance design, and achieved among the highest occupant satisfaction scores in the CBE survey database out of roughly 400 buildings (conducted in 2005; we did not run another survey for this study).

The operation of the signaling system itself is less clear, particularly how much time the building spends in "open" mode. According to the design engineer, the original intent was for the light to be green "most of the time"




SEQUENCE OF OPERATION

THE INDICATOR LAMPS ARE INTENDED TO ASSIST THE BUILDING OCCUPANTS AND MAINTENANCE STAFF TO KNOW WHEN TO OPEN THE BUILDING UP FOR VENTILATION AND WHEN TO CLOSE IT DOWN. ILLUMINATE THE UPPER GREEN LAMP WHEN ANY OF THE FOLLOWING ARE TRUE:

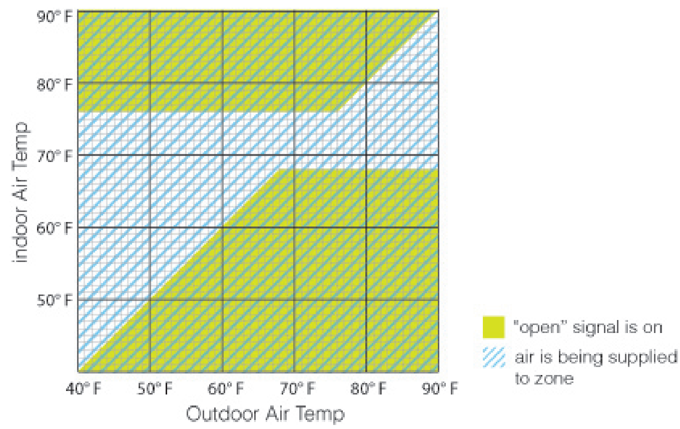
1. BETWEEN THE HOURS OF [6pm] AND [6am] THE INSIDE TEMPERATURE IN THE PARENT SPACE IS HIGHER THAN THE OUTSIDE TEMPERATURE AND THE OUTSIDE TEMPERATURE IS [50°F] OR GREATER.

2. BETWEEN THE HOURS OF [6am] AND [6pm]

   A. THE INTERNAL TEMP IS ABOVE THE MAXIMUM ADAPTIVE COMFORT TEMP AND OUTSIDE TEMP IS BELOW INDOOR TEMP.

   B. THE INTERNAL TEMP IS BELOW THE MINIMUM ADAPTIVE COMFORT TEMP AND OUTSIDE TEMP IS ABOVE INDOOR TEMP.

ILLUMINATE THE LOWER RED LAMP WHENEVER THE UPPER GREEN LAMP IS NOT ILLUMINATED.


because the climate is so mild. But the signals seem to work primarily in the swing seasons during the evenings. According to the controls contractor, the signals are not intended to work during the summer months while the chilled water plant is serving the building. As written in the design documents, the control algorithm is designed to encourage natural ventilation when outdoor temperatures are either warm or cool enough to meet indoor needs, and indoor temperatures exceed the adaptive comfort range. For this condition to be met however, the mechanical systems must allow the building to float beyond the established comfot setpoints. In this building and the ARD facility (next case), which was designed the same way, a mis-translation of this principle may be causing the "close" signal to be on more.

Occupant Response

The building has approximately 8 full-time staff with variable schedules, in one private office cluster. The building is otherwise occupied by transient users (teachers and students). From talking to one teacher who uses the classrooms, knowledge about the signals varies. One student staffing an information desk said she was aware of the system and would go to open the windows when the light turned green, although this didn't happen often. Because there are few full-time staff, communication and reinforcement about the signs happens mostly verbally, or "by example." A few faculty take the lead in informing students and teachers about the system, emphasizing that the signals "are a should, not a shall." Because of frequent confclits, private office occupants have been told that it probably makes little difference how they use their windows, but to close their office door anyway if they want to open their window while the light is red.

The "teaching tool" aspect given the academic setting is unique to this project, and it introduces questions about what is exactly being taught, since it is unclear to users of the building how the signals are programmed. The building manager (who is a faculty liaison, not campus facilities staff) said she wished she had better access to the building controls and as-built design documents.

## 6. Applied Research and Development Facility, Northern Arizona University, Flagstaff AZ

Group 2. Concurrent air supply, outdoor and indoor temperature control

| | |
|---|---|
| **Project Scope** | 56,000 ft2, 4-story building housing faculty offices, classrooms and a student lounge area |
| **Architect** | Hopkins Architects and Centerbrook Architects and Planners |
| **Mechanical Engineer** | ARUP |
| **Year Completed** | 2009 |
| **Perimeter Program** | Private and shared enclosed offices, open student lounge on fourth floor |
| **Occupants** | 60 |

| **Intent of Signals** |
|---|
| As stated in the sequence of operations: “The indicator lamps are intended to inform the building occupants when it is appropriate to open the building’s northwest perimeter windows to improve comfort conditions in the space and when it is inappropriate to open them” |

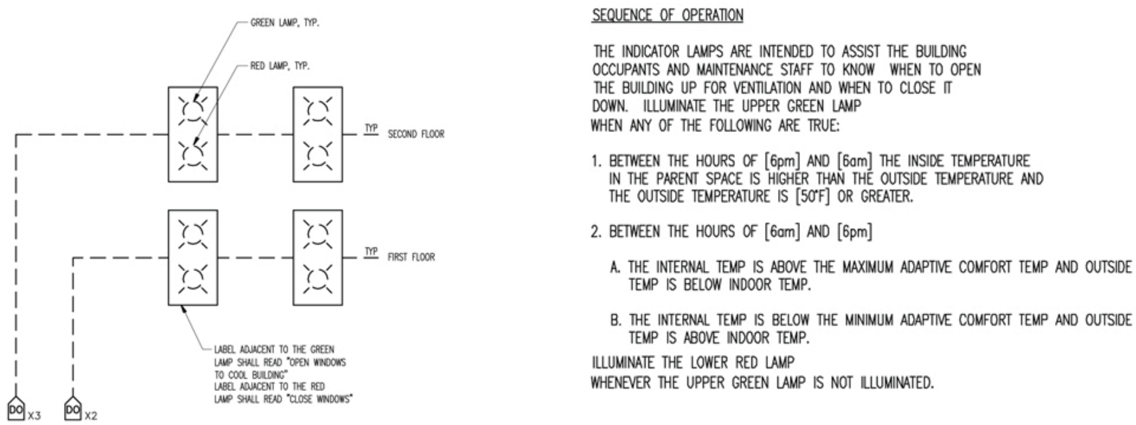
*The atrium provides a termal buffer for the north-facing offices*

*Signals are located below the window in ecah private office*

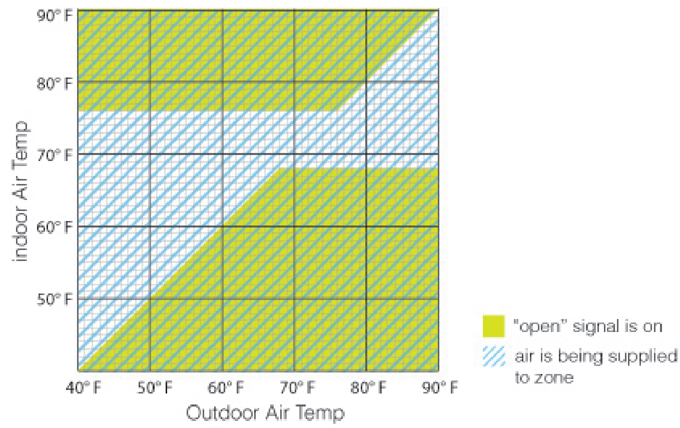
### System Description

The ARD facility has narrow floorplates that curve to the south, with private offices lining the north facade and open offices three workstations deep situated in the core. The south facade encloses a triple-height gallery space that acts as a thermal buffer for the building, with well-designed exterior solar control and exposed thermal mass. The gallery is naturally ventilated and has a supplemental zoned radiant floor system that is separate from the primary heating and cooling circuits in the rest of the building. Natural ventilation louvers operate in stages to maintain the temperature in the gallery between 68 and 79 F and $CO_2$ levels below 900 ppm. The radiant floor is operated in cooling mode based on predictive temperature controls and a wide deadband (65-80) so that pre-cooling of the slab and natural ventilation do the most work to maintain comfort.

The labs and office spaces are served by 5 air handling units. In cooling mode, the economizer, evaporative cooling coil and cooling coil modulate in sequence to achieve a supply air temperature of 65 F. Back-up chilled water is available between April and October when outside air temperature is above 65 F. Air is delivered via an underfloor plenum and motorized VAV diffusers are controlled by room temperature sensors with an override for $CO_2$ detection (700 ppm setpoint). Because the atrium and the








office areas are served by independent systems, the windows serve different functions: in the atrium, they are primarily for night ventilation, while in the offices they are intended for local supplemental cooling and ventilation.  In theory, using the windows would offset fan energy by allowing the demand-controlled VAV system to modulate air supply in response.

## Operating Conditions and Occupant Response

The ARD facility houses several different university departments and environmental research groups. Comments about the windows in our survey suggested over-arching control issues, rather than persistent comfort complaints. Due to the success of the gallery design and Flagstaff's sunny, mild, dry climate, thermal comfort may not always be an issue; but when there are comfort concerns, the reliability and responsiveness of controls do not meet occupant expectations. The primary example noted by the building manager referred to the lighting controls, which malfunction frequently and are managed by an off-site controls contractor in Phoenix. Occupants of this building are the least satisfied with their windows as well as their the windows' ability to provide comfort (55% dissatisfied, 40% say window is only somewhat effective); this does not mean that dissatisfaction is widespread, but there are various interfering factors, including difficulty controlling the windows on windy days, as noted by several people.

This building also received the lowest scores in terms of occupants' "active" response to the signals. Most people who offered comments about the signals said that the red light is "always on" (the others said the signals weren't visible to them, they hadn't been told about them, or the system was flawed because stuffiness was an important factor). Like the Kirsch Center, which was designed the same way, a mis-translation of the control algorithm may be causing the "close" signal to be on too often, but we were unable to confirm the as-built controls.

# 7. William and Flora Hewlett Foundation

Group 2. Concurrent air supply, outdoor and indoor temperature control

| | |
|---|---|
| **Project Scope** | 48,000 ft2, 2-story building |
| **Architect** | BH Bocook, Architects, Inc |
| **Mechanical Engineer** | Critchfield Mechanical, Inc |
| **Year Completed** | 2002 |
| **Perimeter Program** | Private offices |
| **Occupants** | 150 |

| **Intent of Signals** |
|---|
| The purpose of the indicators are to improve the efficiency of the building by keeping people from opening windows when the building is actively heating or cooling the building. |

## System Description

Cooling is provided by an evaporative cooling and ice storage system to reduce peak demand. Two air handlers supply conditioned air to each wing of the building via an underfloor plenum with manually-operable floor diffusers. In the perimeter zones, heating coils are placed in the raised floor.

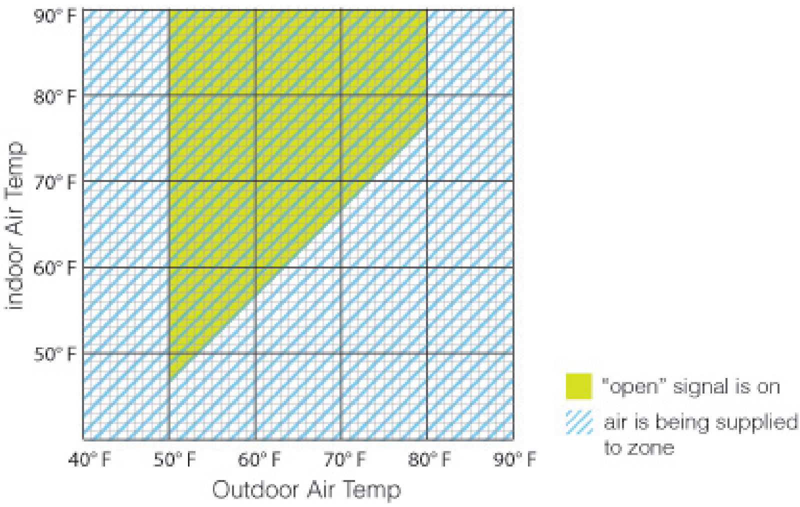

*Signals are installed in the circulation areas between perimeter and core offices*

The operable windows were one of several features that are meant to give people more control over their environment, creating a more domestic, “family” feel for the building. In the building controls, the windows were considered as part of the building’s economizer cycle. The design documents state that, when sensors determine that the return air is warmer than the outside air and the outside air is between 50 and 78 degrees Fahrenheit, the BMS initiates an economizer mode, simultaneously opening clerestory windows for stack-driven exhaust and initiating the green light.

## Operating Conditions and Occupant Response

An earlier occupant survey of this building in 2004 revealed that thermal comfort satisfaction was relatively poor (52% satisfied). The survey also happened to ask some custom questions about the signaling systems, and discovered that many people reported the light to be red most of the time, or “always.”  Although we were not able to survey

*Typical perimeter office*




occupants again or monitor the hours spent in green mode, this issue seems to persist. Again, we were unable to confirm the as-built control sequence, but the problem seems to stem from ongoing challenges the building management team has had heating the building, particularly the core. It could be that the economizer is over-sized, requiring outside air to be heated to address comfort complaints in the core. As stated by the building manager, “because the building is always doing something, the light is not often green.”

We were unable to administer a second survey or interview occupants, but the building operations staff are above average in their interaction with occupants and understanding of comfort conditions. Each new hire is given a building orientation with the building manager when they move into their office. They are told that there are five ways to effect room temperature in each office, particularly in the perimeter offices. Occupants can adjust the air flow or placement of their floor diffusers, adjust the windows and blinds, or request a change in the zone set point. People are informed of the red/green light system, encouraged to use their windows, and are instructed to close the window at the end of the day. They are not encouraged to check the red/green light system throughout they day to dictate their behavior, because “people should feel like they can open the window if they want to.” There is a policy that asks occupants to close their door if they wanted to open the window when the light was red. But the building manager also wanted to be clear that the window signals are by and large seen as a “nice idea” that, like other design ideas, when confronted with the reality of how people work don’t play a big role in how people use the building. In the 2002 survey, most comments regarding the lights reflected a general awareness and respect for the idea amidst ambivalence about acting on it. However, one peculiar comment unveiled the complete thought process of a conscientous window-user when presented with conflict:

“I assume the red light means that energy is being used to modify the temparature inside and therefore if I open my window it will waste energy. Even so I open the window frequently, but when I do this I close the office door. However I don’t like the way that the closed door separates me from co-workers. So I put a sign on the door to let them know they can come in any time. But having the door closed is still very isolating, even though it is glass. I would open the window more if the light were green more and if I didn’t feel I needed to close the door, ie. if I knew that opening the windown wouldn’t waste energy.”

# 8. Lincoln Hall, Berea College, Berea, KY

Group 3 Discontinued air supply, outdoor temperature control

| | |
|---|---|
| **Project Scope** | Gut rehab and modernization of historic campus building |
| **Architect** | EOP Architects |
| **Mechanical Engineer** | CMTA Engineering Consultants |
| **Year Completed** | 2002 |
| **Perimeter Program** | Private and shared enclosed offices |
| **Occupants** | 50 |

| **Intent of Signals** |
|---|
| To remind occupants to use their windows on warm days, to maximize hours the building can be served by outside air only, and to minimize air conditioning, particularly during swing seasons. |

*Photos courtesy EOP Architects*

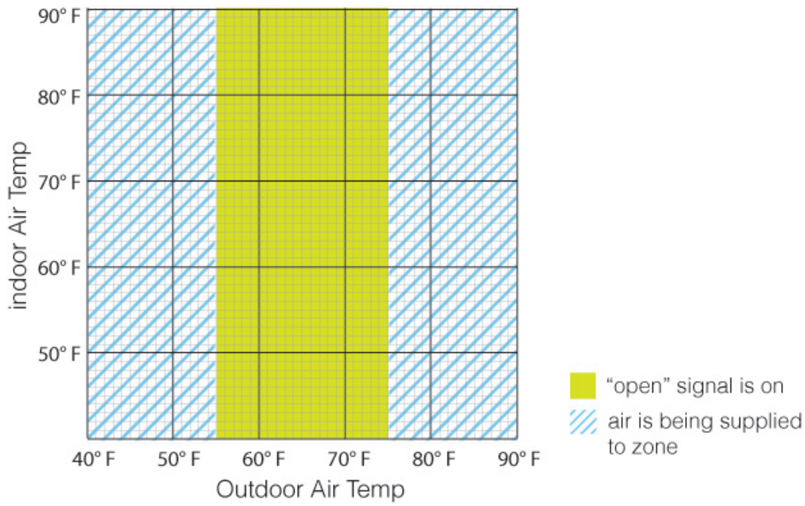
## System Description

After a minor collapse of the central interior in 2001, Berea college decided to fully renovate the building, taking advantage of the new, unplanned central atrium to enhance natural ventilation. Lincoln Hall was renovated when the campus switched from coal-fired central steam boilers to new central natural gas boilers and central chillers. During the renovation the building was fitted with a new central air handling system with local thermostats and VAV boxes in each room that regulate overhead air supply based on demand ($CO_2$). The building is designed to save 30% over ASHARE standard 90.1-1999, primarily by shutting the air handling system down and prompting occupants to open their windows within given outdoor temperature and humidity limits (55-75 is assumed, not confirmed). Because of Kentucky's climate, the benefits occur primarily during the swing seasons.

## Operating Conditions and Occupant Response

Staff in Lincoln Hall are very well informed about the green light system in the building. They are each given a personal orientation about the system and

*We were unable to collect images of the office and the green light signal.*




the importance of using windows to offset air conditioning. This is most likely the reason over 50% of occupants surveyed reported “always” or “usually” responding to the green light. This level of training is the only commonality linking the three buildings that achieved this level of success. However, comfort issues from overheating are recurring and fairly common based on survey comments, and so when the light is red, occupants operate the windows as they see fit to stay comfortable regardless of what the green light says. This could be a failure to emphasize the importance of keeping the window closed when the red light is on; however, one occupant reported indoor temperatures as high as 83 degrees, even with the green light on, and two occupants reported that the green light is routinely not on when it seems comfortable outside and its too hot inside. We were not able to discern what this discomfort can be attributed to, but given the high humidity in Kentucky, it could be reaching the limits of mixed-mode applications. It would be important to understand whether this problem persists during the summer when chilled water is available, or if it’s just a swing-season problem. When windows are needed, window use is also complicated by a few window access problems (people climbing on fixed furniture in at least two offices), pollen issues that seem like they could be serious, and sometimes noise. A couple people were troubled by the necessity of the windows given that pollen was such a problem.

# 9. Chesapeake Bay Foundation, Annapolis MD

Group 3 Discontinued air supply, outdoor temperature control

| | |
|---|---|
| **Project Scope** | 32,000 ft2 2-story office building for environmental protection organization, first LEED Platinum building in the US |
| **Architect** | Smithgroup |
| **Mechanical Engineer** | Smithgroup |
| **Year Completed** | 2000 |
| **Perimeter Program** | Open offices |
| **Occupants** | 105 |

| **Intent of Signals** |
|---|
| To enlist the occupants in operating the building for natural ventilation in lieu of window actuators |

*Photo: Smithgroup*

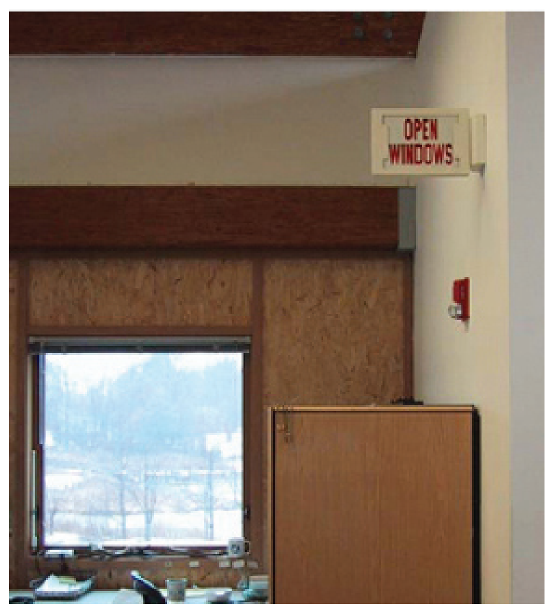
## System Description

Chesapeake Bay Foundation is the earliest and most well-known application of window signaling systems in the U.S. The idea of using operable windows to passively cool the building was identified during schematic design. The team did some modeling to estimate what percent of the year natural ventilation could serve the building (10%, mostly during swing seasons was the expectation; this turned out to be conservative). The client couldn't afford motorized controls so the engineer proposed a modified exit sign as a low-tech, subtle way to compel users to participate. The value of engaging occupants was an unspoken understanding between the design team and the client and never questioned.

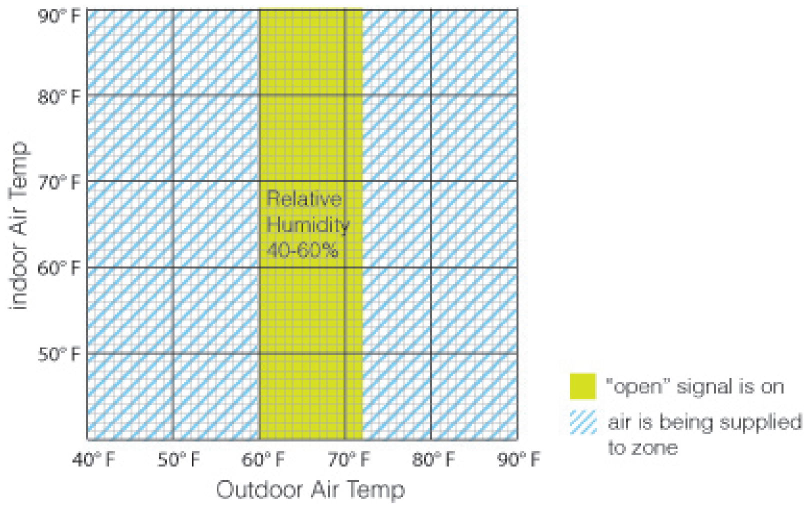
The windows are cranked casements, four on one crank, one crank every ten feet. Twelve people share access to a crank. The idea was an "army mentality" where the occupants were meant to be very active in responding to the signs, according to the building manager.

## Operating Conditions and Occupant Response

We were unable to conduct a site visit or survey; however, this building was previously surveyed by the




*Photos from: NREL 2004*




CBE, and the operation of the signaling system was studied by the National Renewable Energy Laboratory, who found little persistence in occupant response to the signs; and by a graduate student at MIT, who recommended shifting the "open" signal setpoints down to 46-72 F to compensate for internal gains. (Chang, 2002)

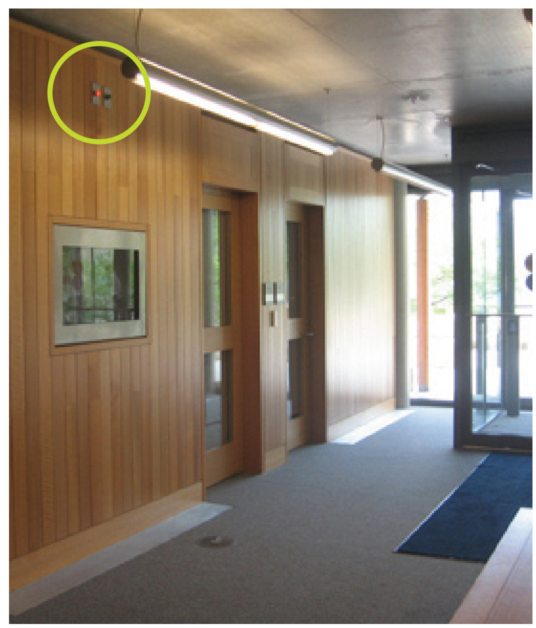
The person in charge of operating the building during the first several years of its life did a lot to tweak the setpoints and worked with staff to see how low wide he could set the comfort range without having people complain. Thanks in part to the diligence of the building operator in continuous monitoring and tuning the building systems, the building is acclaimed as exceeding its energy saving goals, spending more hours than anticipated in natural ventilation mode. However, researchers we spoke with who have worked on the building agree that, based on anecdotal evidence, occupants have not been persistent in acting on the signals.

# 10. Kroon Hall, Yale School of Forestry, New Haven, CT

Group 3 Discontinued air supply, outdoor temperature control

| | |
|---|---|
| **Project Scope** | 56,000 ft2, 4-story building housing faculty offices, classrooms and a student lounge area |
| **Architect** | Hopkins Architects and Centerbrook Architects and Planners |
| **Mechanical Engineer** | Arup |
| **Year Completed** | 2009 |
| **Perimeter Program** | Private and shared enclosed offices, open student lounge on fourth floor |
| **Occupants** | 60 |

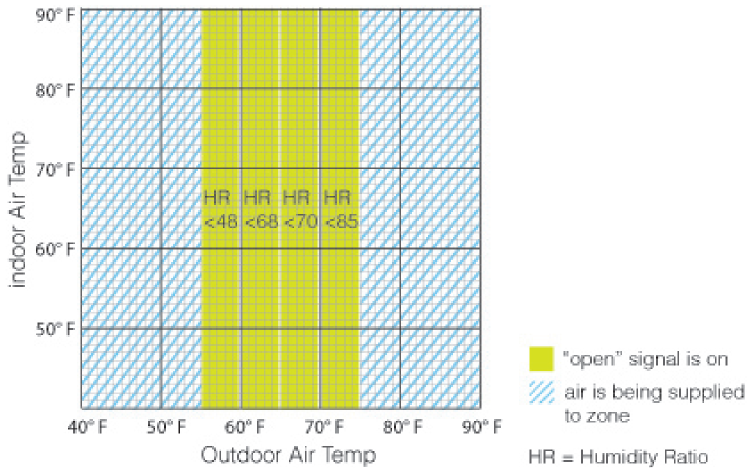
| **Intent of Signals** |
|---|
| To allow the building to be purely naturally ventilated given outdoor air temperature, humidity and wind conditions. Signals intended to inform occupants about what the building is doing, but building operates independently of occupant behavior. |



*Signals are installed at either end of each floor in public circulation areas.*

## System Description

The design goals for Kroon Hall stemmed from an ambition to push the envelope of sustainable design practices and create a building that did not rely on the campus' chilled water or steam system. Narrow floor plates, effective exterior shading and the use of thermal mass was intended to keep cooling loads down. The building is served by four air handlers, which are coupled to ground-source heat pumps and deliver conditioned air via and under-floor plenum. Three of the four air handlers serve the office spaces with windows, and the central fans shut off during natural ventilation mode, reducing overall power consumption from 30 kW to 8 kW. Natural ventilation mode falls between 55 and 75 F outside air temperature, depending on humidity and wind speed criteria, and these conditions are all monitored by a dedicated weather station. The fourth air handler serves the classrooms, operates full-time, and slows to provide minimum outdoor air based on $CO_2$ levels. A set of green and amber lights, notifying occupants of natural ventilation mode, are installed in the central corridors at either end of each floor. They are installed high on




*Typical office "tilt-turn" window*

the wall and are not accompanied by signage. However, the system emails staff automatically when the building enters and leaves "green light" mode.

## Operating Conditions and Occupant Response

By design, this project is similar to the cases in group 1, except that the operable windows are intended to essentially replace the building's economizer cycle in spaces where people have daily access to windows. However, this building differs from the buildings in group 4 because occupant behavior has no bearing on the status of the lights or the supply of air to the zone. If people fail to open their windows during the "open" mode, the consequences are comfort-related only, and survey results and informal interviews suggest that the mass of the building seems to do a good job regulating indoor temperatures. Whether or not occupants follow the green light is not of great concern to the building operator. However, similar to other buildings in Group 3, failure to observe the amber light could cause serious temperature control problems since the climate experiences both cold and hot-humid extremes.

When the system is working, Kroon Hall spends most of its operating hours in natural ventilation/"green light" mode during the swing seasons (April, May, September, October). However, the red light was on for the majority of 2010, either due to commissioning issues with the ground-loop system that resulted in adjustments to the humidity set-points, or a malfunctioning of the weather station. We were unable to confirm which one, but the weather station seems the most likely culprit.

The simplicity of the building's overall design and the control logic for the green light provide a good model for future mixed-mode buildings with signaling controls. However, there are a number of lessons to be learned. First, the signals themselves are very easy to miss, especially for staff working in the middle of the hallway. According to staff interviews, email notifications turn into spam if received on a daily basis, as is the case during a typical fall day. In general, similar to Savery Hall, occupants are given very little reason to take the system seriously given that they are situated in their own, private offices, and have experienced other commissioning issues with the building. As a result, active response to the green and amber lights, awareness levels, and willingness to comply with the red light are all among the lowest in the study, despite overall positive indoor environmental quality satisfaction.

# 11. Zoomazium, Woodland Park Zoo, Seattle WA

Group 3 Discontinued air supply, outdoor temperature control

| | |
|---|---|
| **Project Scope** | 8,500 ft2 Interactive natural science exhibit space |
| **Architect** | Mithun |
| **Mechanical Engineer** | Flack + Kurtz |
| **Year Completed** | 2006 |
| **Perimeter Program** | Interactive nature “play space” |
| **Occupants** | 1 full-time office staff, mostly transient staff and visitors. |

| **Intent of Signals** |
|---|
| To instruct staff to open manually operated windows intended to supplement automatic windows for natural ventilation and cooling. |

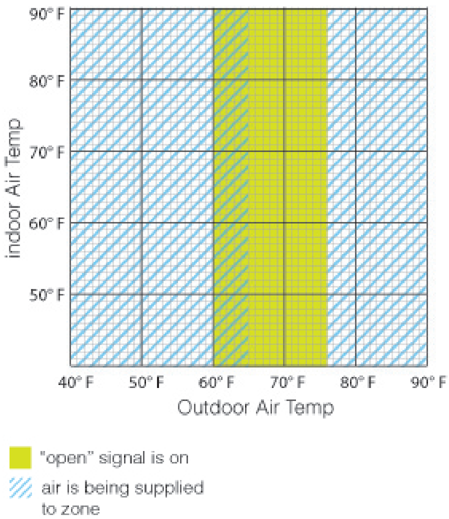


## System Description

The Zoomazium was designed to take advantage of the building’s small program and Seattle’s cool climate and use natural ventilation as much as possible. The building is served by a constant volume, variable temperature air handling unit and heat pump that delivers air via an underfloor plenum. The system maintains a cooling setpoint of 78 F and a heating setpoint of 72 F with a 4 degree deadband. When the outdoor temperature is between 60 F and 76 F, the green light turns on, indicating that opening the windows is allowed. When outdoor temperatures reach 66F, the air handler is disabled completely, and motorized transom level windows open to promote natural ventilation. The building also features a nigh flush mode between 1:00 and 4:00 am if the outdoor temperature is below 72 F and the indoor temperature is above 70 F.

## Operating Conditions and Occupant Response

Because of the building’s unique program, we did not focus on this building in the study, but a few anecdotes from zoo staff and the building manager provide interesting lessons learned. Because of the nature of




Excerpt from Sequence of Operations, 2005

3.6 MANUAL OPERABLE WINDOW INDICATOR LIGHTS.
A. The Operable window indicator lights shall operate as follows:
1. When the outside air temperature is between 60°F (adj.) and 76°F (adj.) the green light shall be on and the amber light shall be off.
2. At all other times the amber light shall be on and the green light shall be off.

*We weren't able to obtain a photo of the office space.*

the building, staff see opening the windows as a part of their job, so the lights seldom go un-heeded; however, given the demands of the child-oriented, public interactive space, opening the windows can become a nusiance. Staff said they were confused about why all the windows could not be automated, and they reported that the sytem works best in the summer, when the window opening task hits a predictable routine with one or more adjustments; during the swing seasons, when outdoor temperatures fluctuate more throughout the day, the signals can go on and off several times during the day, which gets cumbersome and annoying.

# 12. NBBJ Architects, Seattle WA

Group 4 Discontinued air supply, outdoor temperature control

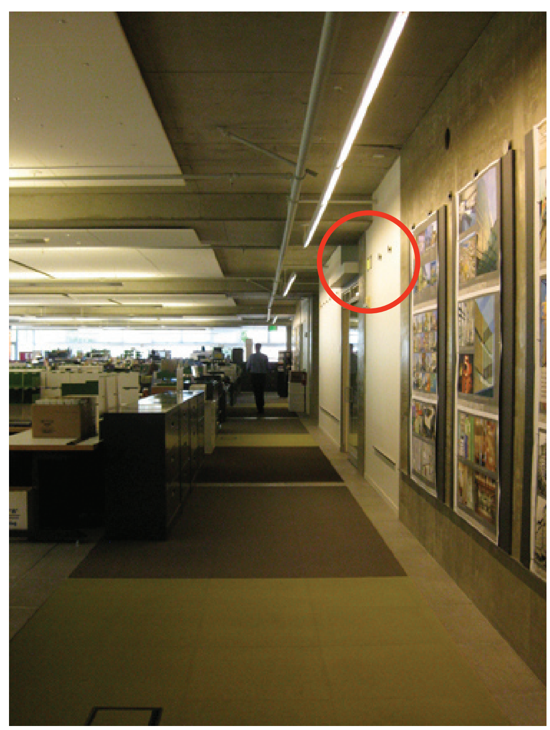
| | |
|---|---|
| **Project Scope** | New 5-story office/mixed-use development, designed by primary tenants, 2 floors leased to other tenants |
| **Architect** | NBBJ Architects |
| **Mechanical Engineer** | WSP Flack and Kurtz |
| **Year Completed** | 2008 |
| **Perimeter Program** | Large open office plan, three workstations deep |
| **Occupants** | 315 |

| **Intent of Signals** |
|---|
| Operable windows and signaling system are intended to provide cost-effective natural ventilation, and use HVAC energy only when necessary. Central air handler shuts off and window use is encouraged between 63-78°F outdoor temperature, or when indoor temperatures reach 78°, whichever comes first. |

*Window banks include view-level and clerestory operable windows.*

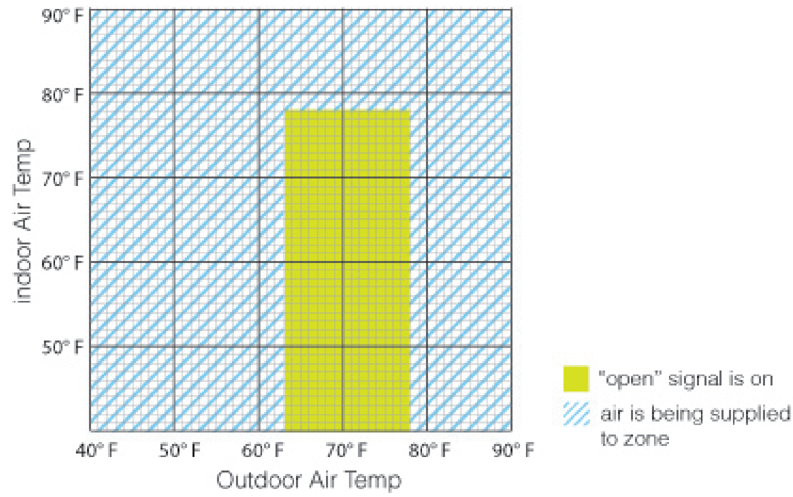
## System Description

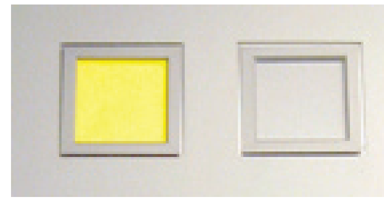
NBBJ Architects worked closely with the property developer and building engineer to push for an aggressive low-energy design that was 100% naturally ventilated. When the building owner discovered risk associated with leasing office space that didn't have air conditioning, the project shifted to a deep plan design with exterior fixed shades and a central air handling system serving all spaces via an under-floor plenum. The idea is that the building is naturally ventilated most of the year except for a few days when AC is needed. A low-profile green/amber light system is installed on the wall of the circulation corridor facing the office spaces, and is intended to enlist occupants in manually operating windows in place of a fan-powered economizer cycle. It was the first project where the engineers proposed a signaling system on such a large scale.



## Operating Conditions and Occupant Response

In this project, the occupants include the architects involved in defining the goals of the project, and the building operator and office management are in close



*These signals were the most stylized in the study.*

partnership educating occupants about the system and addressing issues as they arise. As a result, survey results show very high awareness and active response rates (over 50% reporting "always" or "usually" acting on the green light).

Interestingly, occupant survey results show that the nuisance factor is also low; staff are not only more compliant but also more positive about the system than in other buildings, and are more likely to report that the system enhances their sense of personal control rather than interfering with it. Informal interviews in this and other buildings suggest this may be because signals favor window users in shared office settings who would otherwise be concerned about disturbing their coworkers.

From the perspective of management, however, the system is not flexible enough to meet the diverse expectations and preferences of different people in a large, open office, and speaking with occupants on site suggested general apathy about the system. Although survey results are positive, several comments point out ways the system could be improved. The main issue raised was a general over-cooling of the space and the complaint that the building shifts over to air conditioning mode too quickly. Indeed, because two floors are controlled by one air supply system, any one zone that reaches the relatively low indoor set-point of 78°F initiates the HVAC system throughout the spaces served by that air handler. Savery Hall and Boora Architects offices, which are also located in the Pacific Northwest and designed for natural ventilation, attempt upper set-points of 80-82°F. The width of the dead-band also affects how disruptive the signals are during the work-day. Survey comments suggested that the signals are a nuisance if the windows have to be adjusted more than twice a day, which happens during the swing seasons. Complicated window hardware and the tendency for windows to be left open over night were also concerns.

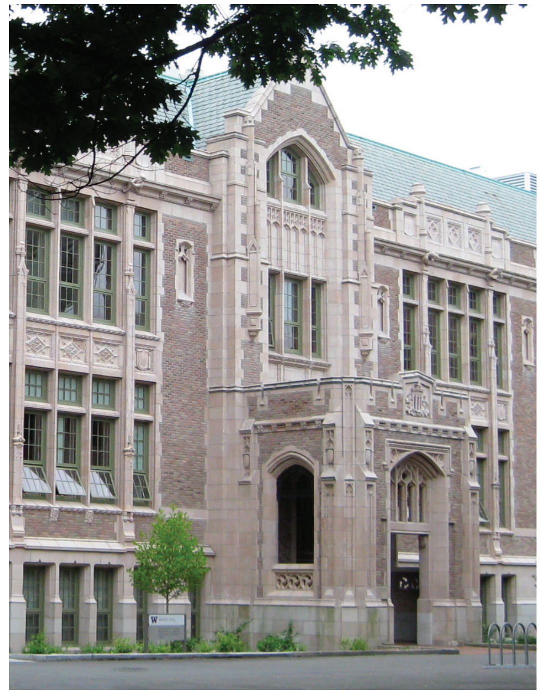
Overall, the success of the system in a building where there have been a number of operational and comfort issues points to the significance of occupant knowledge, culture and values in achieving design intent.

## 13. Savery Hall, University of Washington, Seattle WA

Group 4 Discontinued air supply, outdoor temperature control

| | |
|---|---|
| **Project Scope** | Owner-occupied historic gut renovation/ modernization |
| **Architect** | SRG Partnership |
| **Mechanical Engineer** | Wood-Harbinger |
| **Year Completed** | 2009 |
| **Perimeter Program** | Private faculty offices and classrooms |
| **Occupants** | 120 |

| **Intent of Signals** |
|---|
| To provide cost-effective natural ventilation, using HVAC energy only when necessary. Window use is allowed when outdoor temperature is within 60° and 75°F and indoor temperatures are within the comfort setpoints (68°-82° F). Once the cooling mode is initiated, the VRF will cool to 2° below the setpoint, allowing the green light to cycle back on. |

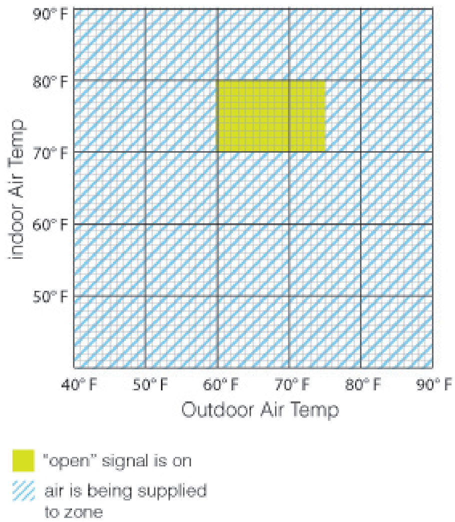


### System Description

During a recent gut renovation and modernization, the design team for Savery Hall was dedicated to enhancing natural ventilation to avoid the installation of a large air handling system. However, a number of circumstances made 100% natural ventilation difficult, including east-west exposure and restrictions on exterior solar control because of the building's historic status. When CFD analysis showed risk of overheating on peak summer days, the design team decided to incorporate a small VAV system with distributed variable refrigerant flow (VRF) units for cooling and heating. To minimize the operation of the VRF system in cooling mode, red-green light indicators were installed to encourage occupants to use their windows. The signals are installed near or above the door to each office space and classroom and are accompanied by placards that explain the purpose of the red and green lights.


### Operating Conditions and Occupant Response

Relative to other buildings in the study, it was common for occupants in Savery Hall to report instances in which




RED LIGHT/ GREEN LIGHT SEQUENCE OF OPERATION

1. THE RED LIGHT/GREEN LIGHT SYSTEM CONSISTS OF A PAIR OF LIGHTS MOUNTED IN EACH EXTERIOR SPACE. THE LIGHTS INDICATE TO THE OCCUPANT WHETHER OR NOT THE WINDOW IN THE SPACE SHOULD BE OPENED OR CLOSED. IF THE RED LIGHT IS ENERGIZED, THE WINDOW SHOULD BE CLOSED. IF THE GREEN LIGHT IS ENERGIZED, THE WINDOW SHOULD BE OPENED. THE DDC SYSTEM DETERMINES WHICH LIGHT SHOULD BE ENERGIZED BASED ON OUTDOOR AND INDOOR TEMPERATURE. DDC ALSO CONFIGURES THE INDOOR VRF UNITS FOR BOTH EXTERIOR AND INTERIOR SPACES IN CONJUNCTION WITH THE ABOVE TEMPERATURE READINGS.
2. VRF UNITS SERVING EXTERIOR SPACES: IF THE OUTDOOR AIR TEMPERATURE IS BETWEEN 60 DEG F AND 75 DEG F, AND THE INDOOR SPACE TEMPERATURE IS BETWEEN 68 DEG F AND 82 DEG F, COMMAND THE CORRESPONDING INDOOR VRF UNIT'S ON/OFF POINT TO OFF, AND ENERGIZE THE GREEN LIGHT. IF THE OUTDOOR AIR TEMPERATURE OR INDOOR SPACE TEMPERATURE MOVES OUTSIDE OF THE SPECIFIED RANGE BY 2 DEG F, COMMAND THE CORRESPONDING INDOOR VRF UNIT'S ON/OFF POINT TO ON, COMMAND ITS OPERATION MODE POINT TO AUTO, AND ENERGIZE THE RED LIGHT.
3. VRF UNITS SERVING INTERIOR SPACES: IF THE OUTDOOR AIR TEMPERATURE IS BETWEEN 60 DEG F AND 75 DEG F, AND THE INDOOR SPACE TEMPERATURE IS BETWEEN 68 DEG F AND 82 DEG F, COMMAND THE CORRESPONDING INDOOR VRF UNIT'S OPERATION MODE POINT TO FAN. IF THE OUTDOOR AIR TEMPERATURE OR INDOOR SPACE TEMPERATURE MOVES OUTSIDE OF THE SPECIFIED RANGE BY 2 DEG F, COMMAND THE CORRESPONDING INDOOR VRF UNIT'S OPERATION MODE POINT TO AUTO.

the red light was on when conditions outside seemed preferable to those inside (both cooler and warmer). This may be a function of factors such as cool surface temperatures or internal gains that cause variable thermal conditions not accounted for by the mechanical system, or it could be related to the control strategy for the lights.

To address the expected variation in loads among different spaces in the building, the control sequence for the green light includes indoor as well as outdoor temperature criteria, and each zone operates independently, which is unusual. Because indoor temperatures must be within the comfort range for the green light to be on, the mechanical system essentially assumes the responsibility for maintaining comfort. In Savery Hall, the cooling set-point is adjustable between 78° and 82°F, which is high, and thermal mass likely does a good job dampening gains during the summer, allowing the building to coast if people don't respond to the green signal. However, if internal gains are sufficient to raise the indoor temperature on a temperate day, it is possible for the red light and VRF to come on during hours that are theoretically still suitable for natural ventilation.  One would have to monitor the operating hours in each mode to understand whether VRF units are operating for more hours than intended.

The fact that the building is large and occupants work in private offices on their own schedules is also an important factor. For the first year, general awareness of the system was low and communication about the meaning of the green and red lights was inconsistent. Since our study was conducted, a manual explaining the meaning of the signals was distributed to occupants. It tells them to regard the green light as an "option to satisfy temperature needs" within the wide comfort range defined by the building. The message for the red signal is stronger, that "it is important to close windows completely." Based on our findings regarding why people naturally use windows, we expect that a minority (~15 %) of occupants will still act on the green signal unless there's a stronger imperative; the majority will wait until they are uncomfortable; again, whether this matters to energy use isn't clear. It's also important to note that a bigger concern for management is how to ensure windows are not left open over night, particularly in classrooms. This is most likely the biggest energy question related to the operable windows, and it is unrelated to the signaling system.

# 14. Orinda City Hall, Orinda, CA

Group 4 Discontinued air supply, outdoor temperature control

| | |
|---|---|
| **Project Scope** | Small, 2-story public building |
| **Architect** | Siegel and Strain |
| **Mechanical Engineer** | Taylor Engineering |
| **Year Completed** | 2007 |
| **Perimeter Program** | Combination of small open office space, shared workstation clusters and private offices |
| **Occupants** | 40 |

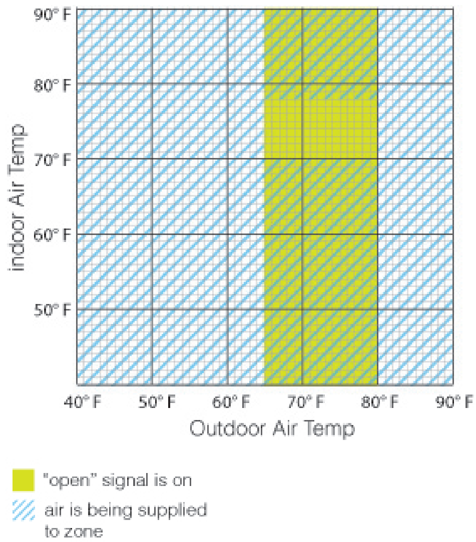
| **Intent of Signals** |
|---|
| Operable windows and signaling system intended to provide cost-effective natural ventilation. The “open” signal is controlled by outdoor temperature, and is on between 65° and 78°F. Air supply is shut off at the zone if temperature is within the acceptable comfort range (70 – 78°F). |

## System Description

The starting point for the design of Orinda City Hall was to eliminate compressor cooling by reducing internal lighting loads, using aggressive exterior solar control and high performance glass, and by providing occupants operable windows and ceiling fans to justify a wider range of acceptable indoor temperatures. The lower floor is partially earth-bermed to enhance passive nighttime cooling. When additional cooling is required, the building relies on an indirect evaporative cooling system.

The design team weighed several options for providing meaningful natural ventilation at low cost. A true change-over system would have been ideal but was prohibitively expensive because it would have required each office space to be thermally compartmentalized. Instead, “open windows” signs were installed in corridors, visible from open workstations and hard to miss when leaving private offices. The “open” signal corresponds to outdoor air temperature, similar to the cases in group 1; however, even though the system is technically “concurrent,” allowing the simultaneous use of central air supply and windows, ventilation energy is minimized by shutting off air supply at the VAV box when the zone temperature is within heating and cooling setpoints.

*Glazed interior corridors with operable transom windows are intended to enhance daylight and ventilation when the signs are on.*




Sequence of Operation, April 2005

3.02.C.6 Isolation Area operating modes
b. Natural ventilation mode:
1) An Isolation Area is in the Natural Ventilation Mode when all of the following are true:
a) The zone is in occupied mode
b) The outside air temperature is greater than 65°F (adjustable)
c) The outside air temperature is less than 78°F (adjustable)
d) The signal from the "manual close upper window & skylight" (disables natural ventilation) switch is not enabled
e) The isolation zone is above the heating setpoint
f) The isolation zone is below the cooling setpoint plus 2°F (adjustable)
2) An Isolation Area is in the Natural Ventilation Mode when the associated window is proven open.

3.02.D.2. Setpoints
a. Each zone shall have separate unoccupied, window open and occupied setpoints,and separate heating and cooling setpoint.
1) As a default, the occupied heating setpoint shall be 70°F and the occupied cooling setpoint shall be 78°F.

3.02.E Dual-Duct VAV boxes (non-CO2 zones)
3.b. If the VAV box is tied to the natural ventilation mode, Vcool-max, Vheat-max and Vmin shall be zero when the room is in natural ventilation mode.

3.02.F Dual-Duct VAV boxes (CO2 zones)
3.c. During natural ventilation mode boxes serving zones that are served by operable windows shall operate with Vmin at zero unless the Natural Ventilation has been overridden. CO2 reset shall operate to reset Vmin*, see 3.02F.3.e and 3.02F.3.fC. All zones will have Vmin at zero during Natural Ventilation mode except zones 1-3, 1-4, and 2-8.

## Operating Conditions

During its first year of operation, the building experienced overheating and humidity issues due to a series of heat waves combined with an undersized evaporative cooler that was mistakenly installed. Even after the problem was fixed, the building received very low thermal comfort and thermal control satisfaction scores in our survey, and it is unclear whether these responses have to do with the legacy of the first summer, ongoing issues, occupant attitudes, or a combination. Currently, the building operates with tighter set-points than in the initial design. Almost all areas are operated to a heating setpoint of 68-70F heating during the winter, and 72-74F cooling setpoint during the summer.

## Occupant Response

Survey results for Orinda City Hall showed the highest percentage of survey respondents reporting "never" responding to the signals as well as being "very likely" to open the window if they want to, regardless of the sign. There are a number of circumstances that probably compound to produce these results. First, the green film used in the sign is fairly luminescent, and it can be hard to tell if the signs are on or off. Secondly, transom-level windows rarely get used and doors are often closed, which removes the notion that the windows benefit the building generally. Finally, there is very little social reinforcement of the type observed in other buildings in this study, which can be a function of interest level (architects, environmental researchers), office layout (big spaces shared by many people), and/or a coordinated education effort. There was an initial orientation and information card prepared for occupants and ongoing sporadic efforts by the building manager, but comfort issues early on may have produced a general apathy. During a site visit I perceived an attitude that the "open windows" signs are a nice idea, but more of a "green" gesture than something that is informative or otherwise of benefit to one's daily routine.

# 15. Boora Architects Offices, Portland, OR

Group 5 Decoupled cooling and ventilation

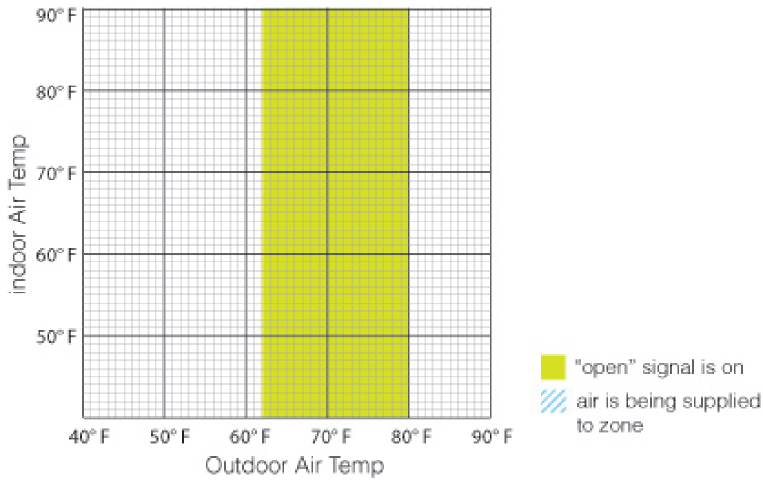
| | |
|---|---|
| **Project Scope** | Major LEED renovation of top floor in historically significant building, designed by tenants |
| **Architect** | Boora Architects |
| **Mechanical Engineer** | Arup |
| **Year Completed** | 2008 |
| **Perimeter Program** | Small open office, 2 workstations deep |
| **Occupants** | 50 |

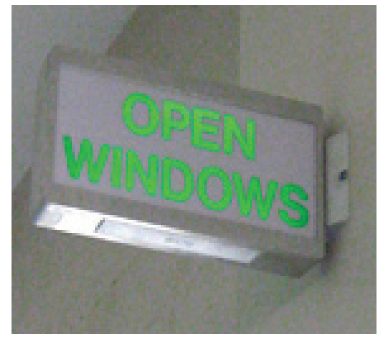
| **Intent of Signals** |
|---|
| To lend visibility to the building's original design, so that comfort is maintained without ducted air supply and cooling energy is minimized. "Open Windows" signs illuminate when outdoor temperatures are within 62° and 80°. |

## System Description

When Boora was looking to expand and modernize their offices, they decided to remain on the top floor of a historic multi-story building, and undergo a renovation that would return the building to its original design and provide an example to other tenants. A reconfiguration of the office space into perimeter open workstations accompanied the downsizing of mechanical equipment and the installation of daylighting controls and ceiling fans. The building is heated and cooled by a three-pipe hydronic system with perimeter fan-coil units. Occupants can manually change the temperature and fan settings of their units, and a central building management system turns off the fans at 6 pm every day to save energy. Because the tenants could not remove the cooling system altogether, they had to find a way to remind staff to take advantage of their windows and discourage using windows and cooling units simultaneously. One "open windows" sign is installed in the center of each office wing, and it is individually wired to an outdoor temperature sensor and indoor thermostat, making the controls the simplest and most legible among buildings in the study.

*Original double-hung windows line the perimeter offices, which are now open-plan.*




## Occupant Response

Indoor environmental quality satisfaction is very high according to our survey. Similar to ZGF Architects (Group 1) and NBBJ Architects (Group 4), this project benefits from an occupant group that is very well-informed and positive about their space. The biggest issue noted by occupants is the tendency for the signs to go un-noticed because of their location (half the people on each wing face away from the sign), and their similarity to the exit signs. The next most common comments refer to unique personal temperature preferences, reports that the signs go on when conditions are either warmer or cooler than certain individuals would choose. A few people also commented that fresh air and air movement should be taken into account.

Based on these comments and interviews with the design team, there are two aspects of the system that could be refined. First, given their location on the 8th floor in a downtown area, the acceptability of the temperature set-points depends a great deal on wind, which isn't taken into account. Secondly, because the mechanical systems have already been downsized, further energy reduction opportunities may require staff education regarding the control of their fan-coil units and ceiling fans, rather than a focus on the windows alone. Overall, because the project is such a simple and successful application of signaling systems, it provides a unique opportunity to study how different educational strategies or adjustments to the control algorithms can maximize participation or reduce cooling energy.

## 16. Compton Union Building, Washington State University, Pullman, Eastern WA

Group 5 Decoupled cooling and ventilation

| | |
|---|---|
| **Project Scope** | Major renovation and modernization of 1950s 250,000 s.f. student union building with original operable windows |
| **Architect** | Pfeiffer Partners, Integrus Architecture |
| **Mechanical Engineer** | WSP Flack and Kurtz |
| **Year Completed** | 2008 |
| **Perimeter Program** | Private and shared enclosed offices |
| **Occupants** | 24 |

| **Intent of Signals** |
|---|
| To remind people to use their windows for ventilation and to keep them closed above 76 F for maximum cooling benefit. |

*photo courtesy: Tim Griffith photogrpher*

### System Description

The original 1950s building was designed to depend on a large central air-handling system. The goal during the renovation was to open up the building by reducing ductwork and relying on radiant heating and cooling where possible. Once it was determined that staff liked having operable windows, they were retained in office spaces and combined with radiant panels for the perimeter offices, reducing fan energy from 100 to 20 cfm/person. A set of green and amber lights are placed in common/circulation areas near the offices. Both the lights and the cooling system operate based on outdoor air temperature. Above 76, the cooling system does a better job at keeping people comfortable, so it goes on and people are told to keep their windows closed for maximum benefit.

### Operating Conditions

The green mode range, originally designed to be 60-77 F, was adjusted by campus controls staff to 71-77 F, which is closer to the indoor temperature setpoint range. The building manager wasn't sure why this was done, probably because 60 F seemed too cold an outdoor temperature to let in. A potential consequence is that indoor air temperatures might reach the 76 F sooner than they would otherwise, depending on the balance point of the building.

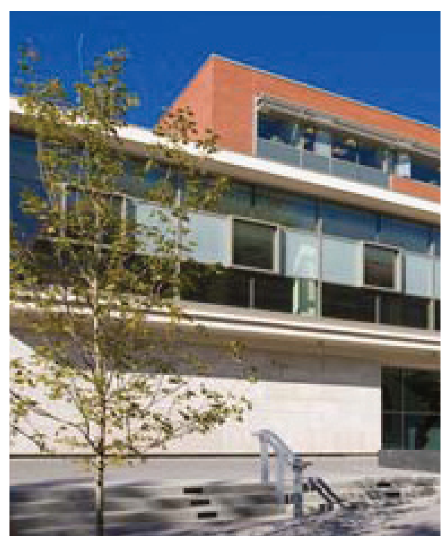
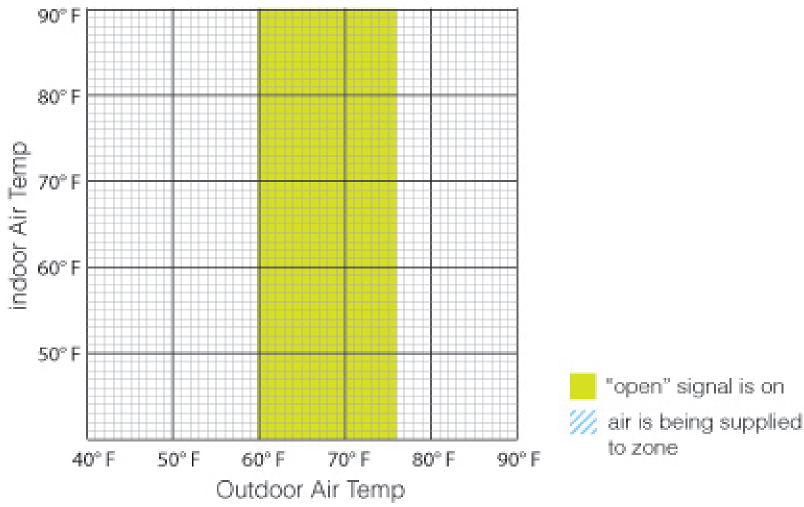


*photo courtesy: Integrus Architecture*

*Casement-type operable windows are available to the small office space on the 4th floor.*




*We were unable to collect images of the offices or the lights. This is a similar indicator used in a different project by the engineer.*

## Occupant Response

Without having visited the building, there are not enough survey comments to get a clear picture of what conflicts are most common, but it seems that the signs are more likely to go unnoticed in this building than others both because of their placement and a lack of internal policy/reinforcement. This building has the largest percentage of “dismissive” comments, including the “I dont’ pay attention” as well as “i do what I want.” Three out of ten total comments noted fresh air as a main reason they open the window regardless of the lights. One respondent said that the light was counter-intuitive; that the light has been red when it could be green.