Title

Summary Report: Control Strategies for Mixed-Mode Buildings

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Control Strategies for Mixed-Mode Buildings

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1. BACKGROUND

1.1 OBJECTIVE

The objective of this project was to study the operational control strategies for mixed-mode buildings, with a focus on: 1) developing a framework for understanding issues that guide the decision-making process that informs mixed-mode buildings, and 2) identifying and documenting example control algorithms used in existing buildings. We examined buildings that use a combination of manual and automatic control of windows and mechanical system components and the indoor and/or outdoor environmental conditions used as inputs into their control algorithms.

1.2 JUSTIFICATION

In current commercial buildings in the U.S., cooling & mechanical ventilation account for over 30% of total energy use, approximately 20% of electricity use, and approximately 40% of peak demand. However, prior to the 1950s, air conditioning and mechanical ventilation were not commercially viable. Commercial buildings had little choice but to utilize natural ventilation for cooling. Buildings typically had extended perimeter zones so that every office could have access to windows that would open to the outdoors, and provide the primary source of light and fresh air. But the availability in the 1950s of large-scale mechanical ventilation and cooling, along with other technologies such as curtain walls and fluorescent lighting, led to the more common commercial building forms of today that are typically all-glass, flush-skin buildings with large floor plates and no operable windows. These buildings miss out on the large number of documented benefits of operable windows – thermal comfort over a wider range of temperatures based on the adaptive comfort zone, reduced energy consumption compared to conventional air-conditioned buildings, and fewer Sick Building Syndrome symptoms.

But even with all these potential benefits, there are a variety of concerns and design challenges associated with operable windows. The ability to rely solely on natural ventilative cooling is limited by loads and climate. And given our modern day expectations, engineers are often uneasy about the lack of predictability and control over indoor thermal conditions in naturally ventilated buildings. As a result, many innovative engineers are exploring “mixed-mode” buildings – a way to combine the best features of naturally ventilated and air-conditioned buildings, and essentially extend the range of climates in which operable windows are feasible even when they can’t provide acceptable comfort year round.

Designers of mixed-mode buildings are faced with challenges, however. There are no standard protocols for the operations and control strategies for mixed-mode buildings, nor is there consensus about the relative degree of personal vs. automated controls that they should provide. There is also a lack of accessible information for designers and engineers about the range of control options, and the various building and climate conditions they can be used to address. Case studies alone do not necessarily help the design team see the relevance of such precedents for their unique situation. We have also identified a need for a detailed classification scheme, or taxonomy, for mixed-mode buildings to help place individual building projects into context and better inform mixed-mode designs moving forward.

This project was aimed at meeting those needs. Our intent was to go beyond existing classifications that label a building once it has been built, and to focus on the issues that drive decisions about both its design and operation. By providing a conceptual model for the mixed-mode design decisions, case study examples of buildings and control algorithms in use, and how they fit into this model, designers and engineers can familiarize themselves with the varied palette of design and control opportunities so they can select the one that best fits the needs of their building, client, occupants, climate, and budget.

1.3 WHAT IS MIXED-MODE?

"Mixed-mode" refers to a hybrid approach to space conditioning that uses a combination of natural ventilation from operable windows (either manually or automatically controlled), and mechanical systems that provide air distribution and some form of cooling. A well-designed mixed-mode building allows spaces to be naturally ventilated during periods of the day or year when it is feasible or desirable, and uses mechanical cooling only as necessary for supplemental cooling when natural ventilation is not sufficient. The goal is to maximize comfort while minimizing the significant energy use and operating costs of air conditioning.

Natural ventilation or mixed-mode strategies may not be suitable for all situations, perhaps least so for climates with very high humidity, or sites with excessive levels of outside noise or pollution. However, there is a wide range of climates and sites for which it is feasible and worthy of consideration. Even in the more extreme climates, an examination of the number of swing season days may conclude that operable windows will provide a net benefit.

Mixed-mode buildings are typically classified in terms of their operation strategies, which describe whether the natural ventilation and mechanical cooling are operating in the same or different spaces, or at the same or different times. Some of the most common categories are "concurrent" (where mechanical cooling and natural ventilation can operate in the same space at the same time), "change-over" (where the building switches between mechanical cooling and natural ventilation on a seasonal or daily basis), or "zoned" (where mechanical cooling and natural ventilation operate in different areas of the building). One of the objectives of this study was to develop a more detailed classification system based on the design decision-making process and the reality that many well designed systems draw upon every one of these categories. The new system is described in detail in section 3.

The decision to design a fully air-conditioned, naturally-ventilated, or mixed-mode building has implications for the building form and envelope design, daylighting and lighting options, comfort, ventilation, and energy use. In practice, there is a continuum of control options, ranging from simple and manual, to a more sophisticated, automated integration of systems, sensors and actuators. A successful control strategy needs to consider how to balance the best of both approaches to optimize both comfort and energy consumption. Naturally, this balance is affected by local climatic conditions, programmatic needs, project budgets, and a host of other contributing factors.

Table 1 summarizes some of the typical characteristics of natural ventilation, air-conditioning, and mixed-mode conditioning strategies. Tables 2 and 3 summarize some of the wide range of options for mechanical system and window system strategies. (all from Ring, 2000 with minor modifications).

Table 1: Characteristics of Typical NV, AC and MM Buildings

	Natural Ventilation	Air-conditioning	Mixed-mode
Building Form	Narrow floorplates, which allow for cross-ventilation and generous ceiling heights are typical.	Large floorplates with relatively low ceiling heights are often preferred.	A plan depth of no more than 15 m (45 ft) is recommended to take full advantage of natural ventilation.
Building Envelope	The mass of the building fabric and structure helps to dampen diurnal temperature swings. External shading is used for solar control.	Envelope is relatively light weight and designed to be tightly sealed. Tinted or spectrally selective glazing is used in lieu of external shading to control solar heat gain.	Thermal mass in the building envelope and structure should be used to dampen daily temperature swings. External shading is preferred.
Windows and Lighting	Windows are relatively small and are operable. Daylighting is preferred to avoid internal heat gains associated with artificial lighting.	Glazing is sealed and often deeply tinted. High glass-to-wall ratios are typical. Fluorescent lighting is standard.	Windows are operable and may include both automatic and occupant control. Window design and controls are more complex than NV or AC.
System Controls	Control of indoor conditions is dependent on occupant behavior. Occupants must both respond to and predict outdoor conditions in determining how much to ventilate the building.	HVAC controls may be complex and are generally handled by automated systems, using feedback control. System operators play a key role in maintaining the system.	Control may be a synthesis of occupant and automatic control systems. Both feedback (responsive) and feed-forward (predictive) strategies should be employed.
Occupant Comfort	Occupant comfort is largely dependent on external conditions, which may vary significantly seasonally and daily.	HVAC system strives to maintain uniform thermal conditions. Occupant comfort is closely linked to HVAC system performance.	Occupants have control with AC system providing "background" cooling and ventilation. AC provides relief if NV system fails (or vice-versa).
Ventilation Rate and IAQ	Ventilation rates are very high during temperate and warm outdoor conditions. IAQ is rarely a problem.	Ventilation rate is often fixed in a minimal position. HVAC system may cause IAQ problems if not maintained properly.	On average, ventilation rate will be somewhat higher than AC bldgs. NV can provide quick relief if IAQ problems emerge.
HVAC Energy	Relatively little HVAC energy is consumed.	HVAC energy use varies depending on system design and operation. Often systems operate inefficiently for extended periods with little or no correction.	HVAC energy use should be less than AC buildings. Energy may be wasted, however, if NV and AC systems are not carefully coordinated.

Source: Ring, 2000

Table 2: Mechanical System Options for Mixed-mode Office Buildings

	System	Comments
Increasing cost, complexity, and/or energy intensity →	Minimal "Background" Ventilation	Background ventilation systems include trickle ventilators and other low-energy devices that induce a minimal amount of ventilation in otherwise naturally ventilated buildings. This approach is uncommon in the US but quite common in Europe where many buildings are naturally ventilated in the summer cooling season, and radiantly heated in the winter. Background ventilation allows for minimal heat loss during the heating season.
	Mechanical Ventilation	Mechanical ventilation (without refrigeration) systems provide ventilation air to deeper and more complex buildings than can be practically served by natural ventilation. Heat-vent systems that provide fresh air in all seasons and heated supply air in the winter are common in temperate climates, for commercial buildings of all sizes.
	Static Cooling	Static cooling includes systems such as radiant cooling panels and chilled beams that remove heat without forced air movement. There is currently a rising tide of interest in these systems, although their cooling capacity is generally somewhat limited. Often these systems are used in conjunction with mechanical or background ventilation systems. In humid climates, static cooling systems can develop condensation problems if not carefully controlled.
	Personal Terminal Air Conditioning (PTAC) and Packaged Units	PTAC systems include individual zone air conditioning systems, usually installed through an exterior wall or window. Rooftop packaged units and split systems, while somewhat larger than PTAC units, are operated in a fundamentally similar way with one AC unit serving one zone. These systems are inexpensive and easy to control, but also noisy, energy inefficient, and maintenance intensive.
	Distributed Air Conditioning	Distributed air conditioning systems include fan coil units (FCUs) and water-source heat pump units (WSHPs). Air circulation and cooling are handled by zonal units that reject heat to a central water-loop. Often ventilation air is served to the FCU or WSHP units by a separate ducted ventilation air system.
	Central Air Conditioning	For central air conditioning systems, one or more central air handling units (AHUs), each serving multiple zones, provide both ventilation and cooling. Individual zone controllers control, mix, and/or reheat supply air at the zone. Constant volume, VAV, dual-duct, and multi-zone are all common types of central air conditioning in commercial buildings.

Source: Ring, 2000

Table 3: Natural Ventilation (Window) System Options for Mixed-mode Office Buildings

	System	Comments
Increasing cost and/or complexity →	Simple Manual Operable Window	Manual operable windows are the most basic way to allow for natural ventilation in an office space. Research has demonstrated that occupants open windows in two distinct modes. In the first mode occupants open windows slightly to provide ventilation, with little regard for indoor or ambient thermal conditions. In the second mode, occupants open the window somewhat wider to induce air movement and comfort cooling when indoor conditions become too warm.
	Multi-element operable window	Although more expensive, windows with more than one opening element are often preferred over more simple windows for mixed-mode buildings. With a two-element window, the high element can be left open on temperate days to allow for general ventilation, while the lower element remains under control of the occupant nearest the window (who will be most bothered by drafts if the lower element is always open). In general providing multiple window elements, (particularly high and low), allows more control over how opening the windows will naturally ventilate the space.
	Automated operable window	A further level of sophistication in operable window design is to provide automatically controlled actuators on some or all elements of the windows. For example, the upper element of the windows might be automatically controlled for nighttime ventilation whenever conditions are appropriate, while control of the lower window element is at the discretion of occupants. In general, windows that are completely automated with no opportunity for manual override are highly irritating to occupants who expect to have some control over when and how much the windows that affect their workspace are open.
	Advanced Natural Ventilation	Advanced Natural Ventilation (AVN) is a term used by the authors of the PROBE series to describe buildings in which sophisticated natural ventilation systems are automatically controlled. These systems attempt to passively cool and ventilate buildings somewhat larger and more spatially complex than what can traditionally be handled by natural ventilation. ANV buildings tend to be complicated and experimental building designs, heavily analyzed during design development and requiring significant post-occupancy tuning, management, and maintenance to operate effectively.

Source: Ring, 2000

1.4 BENEFITS OF MIXED-MODE

Naturally ventilated or mixed-mode buildings will be most successful if they have been properly designed to incorporate other climate-responsive strategies as well. Particular attention should be paid to shading and daylighting to reduce cooling loads, as well as thermal mass so that direct ventilative cooling during the day might be combined with nighttime cooling. A well designed and properly operated mixed-mode building can scale back or eliminate the use of mechanical cooling and ventilation systems throughout much of the year, with associated reductions in energy use, greenhouse gas emissions, and operating costs. Mixed-mode buildings also offer potential benefits in occupant impacts including thermal comfort, health and productivity

Energy savings. The most common goal of well-designed mixed-mode buildings is to reduce or eliminate the fan and cooling plant energy consumption whenever conditions are moderate enough for natural ventilation to maintain comfort. When the outside weather is appropriate, operable windows are essentially acting like a distributed economizer cycle, allowing for reduced chiller use. There is also the potential for reduced fan energy consumption during the day. However, mechanical night ventilation might offset the energy savings albeit at off-peak utility rates. If the need for mechanical ventilation is eliminated entirely, such as in a radiant cooling system, one can also reduce the first costs associated with the fans and ducts that are no longer needed. A radiant mixed-mode system also offers the potential for reducing peak demand in addition to overall energy use.

Energy savings of mixed-mode buildings can be assessed either through simulation or physical monitoring, but neither approach has been exhaustive and more research is certainly needed in this area. Some useful preliminary simulations of mixed-mode buildings demonstrated the potential for reduced energy consumption compared to conventional air-conditioned buildings (Daly 2002, Emmerich and Crum 2005), but they were based on simplified single-zone models where assumptions about window operation and HVAC control strategies were not necessarily realistic. More recently, simulations using EnergyPlus demonstrated that energy savings associated with various forms of mixed-mode operation ranged from 13% (medium-sized office building with a VAV system in Miami) to 29% (small office building with a CAV system in Atlanta) to 79% (similar building in Los Angeles).

The best physical monitoring of the energy savings in mixed-mode buildings has been conducted in the High Performance Buildings Research program at the National Renewable Energy Laboratory. They have done extensive research on high performance commercial buildings, including naturally ventilated and mixed-mode buildings, focusing primarily on energy consumption. The informative case studies are nicely organized on their website: (http://www.eere.energy.gov/buildings/highperformance/).

In a series of six case studies using both physical monitoring and computer simulation, the research group studied overall energy performance as well as analyzing the integration of specific energy-efficient features, and comparing measured performance to design expectations. Overall, energy performance in the six buildings was worse than predicted, but much better than standard practice yields. Net source energy savings ranged from 22% to 77% compared to a minimally code-compliant building (Torcellini et al. 2004). Savings calculations were based on measured consumption data compared to a calibrated code minimum simulation. Those savings included all end uses, including heating, cooling, and fan energy, and, as is often the case, it is difficult to determine exactly what percentage of those savings can be attributed simply to the natural ventilation alone.

Thermal comfort. In addition to the energy benefits of using natural ventilation in place of mechanical cooling, mixed-mode buildings have the potential to offer occupants higher degrees of control over their local thermal and ventilation conditions, which should lead to increased occupant satisfaction. Adaptive comfort theory demonstrates that greater degrees of personal control allow occupants to fine-tune their thermal environment to match their own personal preferences, while also resulting in a wider acceptable range of indoor temperatures (de Dear and Brager, 1998). In an analysis of the CBE Survey database, 13 of 302 buildings were identified as naturally ventilated or mixed mode. Of those, 10 ranked in the top quartile in terms of thermal satisfaction, with two more in the upper third.

Health and productivity. Mixed-mode buildings have also been shown to reduce problems associated with indoor air quality. One of the most extensive studies 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). Relative to naturally ventilated buildings, the air-conditioned buildings (with or without humidification) showed 30-200% higher incidences of sick building syndrome symptoms. Carnegie Mellon's BIDS, Building Investment Decision Support, is a case-based decision-making tool that calculates the economic value added of investing in high performance building systems based on the findings of building owners and researchers around the world. In their latest report on Guidelines for High Performance Buildings (2004), CMU's BIDS demonstrate the productivity benefits of natural ventilation and mixed-mode system from eight case studies. For example, it states that replacement of supplemental mechanical ventilation with natural ventilation or mixed-mode conditioning achieves 0.8-1.3% health cost savings, and 3-18% productivity gain, for an average ROI of at least 120%. Apart from issues of occupant comfort, these quantitative values help to compare the performance of mixed-mode systems to those that employ other strategies. Such data helps to place our research in the context of the greater dialogue on sustainable building practices.

2. METHODS

Sources of information for this project have included literature review, study of existing case studies available for mixed-mode buildings, building documentation such as design and operations specifications, and interviews with architects, design engineers, building operations engineers, and facility managers. Specific control sequences and algorithms for existing buildings are not typically found in existing publications, and often can only be obtained directly from the building engineer – a task that was much more difficult than we originally anticipated.

One source of information was the CBE database of approximately 150 mixed-mode buildings (http://cbesurvey.org/mixedmode/database.asp). A second approach was to start with people – contacting professionals in the industry and academia who we believed has worked on these kinds of buildings, and asked them for anything and everything they could send us about the control sequences. Our acknowledgements thank many of them by name, and we appreciate their valuable contributions to this report.

A third approach was to look at other building databases that try to categorize 'green buildings' or 'energy efficient buildings'. For example, the New Buildings Institute offers a comprehensive buildings database for high-performance buildings (www.advancedbuildings.net) that have typically met or exceeded a 50% beyond code requirement for the energy use. Amongst the 117 buildings, we narrowed down 12 that utilize mixed-mode as primary HVAC strategies. Other useful resources for finding mixed-mode buildings included:

1. US DOE Buildings Database (www.eere.energy.gov/buildings/database)
2. USGBC LEED Project Lists (www.usgbc.org/DisplayPage.aspx?CMSPageID=1452&)
3. NRDC Case Studies (http://www.nrdc.org/buildinggreen/casestudies/default.asp)

4. NREL Building Research (http://www.nrel.gov/buildings/projects.html)
5. AIA/COTE Top Green Projects (http://www.aiatopten.org/hpb/)
6. Betterbricks Success Stories (http://www.betterbricks.com/default.aspx?pid=successstories)

The combined rate of success with these approaches has unfortunately been less than hoped for in terms of number of fruitful responses. Too often the people working on the project had left the firm and couldn't be found, or people considered this information proprietary, or for some buildings the sequences are written directly on the drawings and are not easy to extract and send to us. Furthermore, it is quite common for the design documents to fall out of date as a building is commissioned and occupied. The as-designed control algorithms are typically what is available, but the actual algorithms in use are what we have been looking for. Otherwise, attributing measured performance to the controls makes less sense.

In the end, we drew upon all of our sources to identify typical and exemplary mixed-mode buildings to use as case studies. In the process, we identified several additional mixed-mode buildings that have been completed since the CBE database went online or originally escaped our attention. Our intention was to obtain detailed documentation on the control algorithms in use for all case studies. However, in addition to the difficulties in obtaining the control algorithms in the first place, the ones we did get were documented with varying degrees of clarity and detail and often quite site specific. It has been difficult to do any meaningful side-by-side comparisons or draw general conclusions from the algorithms available. We decided to produce a set of control algorithm case studies with the information that we had, and to complement them with a greater number of higher-level mixed mode case studies that include the essential characteristics of each strategy. The result is that we have both detailed information on controls for a handful of buildings, and documentation of the mixed-mode strategies and systems for a geographically and programmatically diverse set of buildings. We are pleased to report that the two types of case studies compliment each other nicely.

As a direct consequence of broadening our search and focusing on providing just essential data on more mixed-mode buildings, we began to recognize that the existing mixed-mode classification system itself cannot capture the range of real world solutions in sufficient detail to support clear comparisons between buildings, and provide meaningful design guidance or rules of thumb. Based on the desire to understand the thought process and needs behind the strategies employed by our case study buildings, we have compiled a suggested taxonomy of drivers for mixed mode buildings that incorporates programmatic, climatic, and practical concerns. It should help designers and engineers find case study buildings and insights that mirror the characteristics of their own projects.

Table 4 below is a complete list of our two types of case study buildings (high level and control algorithms). Two buildings, the Aldo Leopold Legacy Center, and the San Francisco Federal Building, have both types of information, and are documented through detailed case studies.

Table 4: Mixed-Mode Case Studies

Name	City	State (or Country)	Built
Detailed Case Studies			
Aldo Leopold Legacy Center	Baraboo	WI	2007
Federal Building San Francisco	San Francisco	CA	2006
William and Flora Hewlett Foundation	Menlo Park	CA	2002
High-Level Case Studies			
Ash Creek Intermediate School	Monmouth	OR	2002
Bighorn Home Improvement Center	Silverthorne	CO	2000
Bren School of Environmental Management	Santa Barbara	CA	2002
Carnegie Institute Center for Global Ecology	Palo Alto	CA	2004
CBF Merrill Environmental Center	Annapolis	MD	2000
Chicago Center for Green Technology	Chicago	IL	2002
Clackamas High School	Clackamas	OR	2002
Gap 901 Cherry St. Building	San Bruno	CA	1997
Gilman Ordway Building at Woods Hole	Falmouth	MA	2003
Jean Vollum Natural Capital Center	Portland	OR	2001
Lewis Center for Environmental Studies	Oberlin	OH	2000
Natural Resources Defense Council	Santa Monica	CA	2003
OHSU Center for Health and Healing	Portland	OR	2006
Pennsylvania DEP Cambria Office	Ebensburg	PA	2002
San Mateo County Forensics Lab	San Mateo	CA	2003
Schlitz Audubon Center	Milwaukee	WI	2003
Seminar II Building	Olympia	WA	2004
Simmons Hall, MIT	Cambridge	MA	2002
SMUD Customer Service Center	Sacramento	CA	1996
UCLA Kinsey Hall AKA Humanities Bldg.	Los Angeles	CA	2007
Zion National Park Visitor's Center	Zion Natl. Park	UT	2000
Control Algorithm Case Studies			
University of Nottingham	Nottingham	UK	2002
Waterland School	The Hague	Netherlands	2001
Scottish Parliamentary Building	Edinburgh	UK	2004
Zoomazium Woodland Park Zoo	Seattle	WA	2006

3. MIXED-MODE CLASSIFICATION FRAMEWORK

3.1 WHY THE NEED TO UPDATE?

We mentioned earlier that mixed-mode buildings are often classified in terms such as “zoned”, “concurrent”, “change-over”, etc. This commonly-referenced mixed-mode classification scheme is a taxonomy originally proposed by Max Fordham and Partners, revised and further explored by Bill Bordass, Adrian Leaman, Erik Ring and others, and most thoroughly described in CIBSE (2000) and Ring (2000). It is useful for classifying buildings and their operational control strategies as they have been built, but does not directly address the dynamics of the process that drives designs and adoption of various ventilation strategies. As such, there remains a growing need for practical design guidance on the operating and control strategies for mixed-mode buildings.

In an effort to better guide designers and engineers towards systems that are most appropriate to their specific needs, we set out to develop a framework that integrates the existing classifications with a view of the building design decision process itself. We hope to develop a finer grain system for categorizing buildings to help design team quickly identify and better understand precedents, and address informational barriers of entry into mixed-mode design.

As a starting point, we recognize there are a set of spatial and temporal constraints on the design of naturally ventilated and mixed-mode buildings that are partially pre-determined by site, climate, and building characteristics:

- Existing codes, programmatic requirements, and site conditions can determine which parts of a building can be naturally ventilated (e.g. whole building, just offices, etc.)
- Regional and site-local climate patterns determine which mixed-mode strategies have the greatest potential to efficiently meet occupant needs and over what timeframe they must be controlled (e.g. real-time, daily, seasonal)

These fundamental drivers apply equally to new and existing buildings, though new buildings often have some flexibility around siting, orientation, programmatic priorities, massing, fenestration, etc. When the process is viewed in this way, it emerges that building engineers are constrained in their system choices by factors they do not directly control. As a result, their decisions can partially be supported by pre-calculated recommendations and design guidelines. Our hope for the next phase of this research is to use simulation to make standard program- and climate-based best practice design recommendations that will provide a firm foundation for designers and engineers as they make decisions about the envelope and mechanical systems of mixed-mode buildings and optimize their control algorithms. The new classification framework and examples of control algorithms developed in this current project will be an important contribution to that work.

3.2 EXISTING FRAMEWORK & THE DESIGN PROCESS

To get a better handle on the potential structure and benefits of a more detailed classification framework, let’s revisit the standard mixed-mode classification scheme and begin the discussion about what design decisions are implied by its categories. In the simplest terms, these classifications are based on whether natural ventilation and air-conditioning are operating in the same or different spaces in a building, and at the same or different times.

Zoned

This category generally refers to the physical distribution of different conditioning strategies (i.e., different spaces, but same time). The benefits of natural ventilation only penetrate a limited distance into a building from openings to the outside environment. Central stacks or air shafts can expand its spatial extent, but it is often used only as a perimeter conditioning strategy. Zoned mixed-mode is a good choice for buildings where deep floor plates create large interior zones (e.g. many existing sealed large office buildings), or there are ventilation requirements in parts of the space that cannot be met by natural ventilation (e.g. labs), or there are other programmatic differences that dictate the use of different strategies (e.g. office space vs. meeting space, low offices with noise or security concerns associated with having operable windows, directionally biased sources of scooped ventilation or non-optimal stack location).

A zoned mixed-mode building might have spaces that are either exclusively naturally ventilated, or exclusively mechanically cooled. But they might also have spaces that combine both operable windows and mechanical cooling in the same space – and those spaces within the building may then fall into one of the following categories below (i.e., "concurrent" or 'changeover" - same space, and either same or different time).

Given the diversity of spatial options, it seems clear that spaces, and not whole buildings, should be the logical units of mixed-mode classification. Buildings have the potential to employ many different specific strategies over time and space and the best performing buildings will surely do so. However, the dominant role played by climatic constraints on mixed-mode system performance should result in the emergence of common best practice designs in various climate zones.

Complimentary

This can be any system with physically overlapping systems of natural ventilation and mechanical cooling (i.e., same space, and either same or different times). Most interesting mixed-mode systems fall into this category. They come in many varieties, but one typical way to break them out is:

Concurrent

This category describes systems that operate in the same space at the same time. For example, an appropriately scaled HVAC system might supplement a natural ventilation system to extend energy savings and occupant comfort into shoulder seasons or to meet code minimum ventilation requirements in winter. In open plan offices, there can be a blurry line between zoned and concurrent spaces, as zones in these spaces are not physically separated. Concurrent systems raise a common fear that operable windows will result in higher energy demands as building operators pay to condition outside air coming in through open windows. But just because the operable windows and mechanical cooling are present in the same space and have the potential to operate at the same time, it doesn't mean that they always do. For example, you can move your setpoints higher such that the building is primarily in passive mode most of the time, and the mechanical cooling only kicks in to control the peaks. Even though you could potentially lose energy if windows are open when the mechanical cooling is on, you may have much longer periods of time when the mechanical cooling isn't running, and those savings overshadow the waste.

Changeover

This category is based on classifying the temporal distribution of conditioning strategies in the same space. These buildings can change their strategies over short time periods (as a system that reacts more or less to outside or inside conditions, like humidity, CO_2, etc.), and/or medium time periods (e.g. night ventilation with MV/AC during the day) and/or long time periods (e.g. buildings with operable windows that are sealed all winter). The type of operating parameters that dictate which timescale(s) of control are appropriate include climate (from seasonal changes to current conditions), building characteristics (e.g. massing and orientation), and site-local climate conditions. The different time scales of changeover systems hint at the idea that they might be broken out into additional sub categories based on the driving conditions of each changeover strategy and the type of control strategies used.

However, the time scales of mixed-mode can be varied and often coexist. A night ventilation system that only operates during summer has seasonal and daily adjustments that it can make. A system that always does the theoretically optimal thing (e.g. achieves the theoretically optimal energy savings or occupant satisfaction, or cost savings) would clearly be changing all the time in response to and in anticipation of indoor and outdoor conditions. Consequently, the controls of good systems are likely to span multiple temporal classifications, whether they are entirely manual, or completely automated.

Alternate

This category describes systems that run indefinitely in one mode or the other and are switched manually between modes. The switch is often tied to seasonal climatic variation, though it doesn't have to be. The manual nature of their operation and not the trigger of the change is the primary characteristic of such buildings. At one extreme of non-operation, these building begin to blur into contingency. At the other, they may look and behave a lot like changeover buildings, except that their changes will be manually controlled. Though it is important to recognize the difference between manual operation and automated control, this category seems to be based on a very specific set of control conditions that have been picked out of a continuum. Consequently, alternate buildings could productively be fit into an expanded definition of changeover that recognizes a smoothly varying range of control strategies.

Contingency

These are buildings built entirely with either mechanical ventilation or natural ventilation, but "provisions" for changes in the future. There are definitely structural/layout considerations that should shape buildings that might change operation one way or another, so there is an element of planning ahead, but past a certain point (floor plate depth, room for ducts, etc.) there isn't much one can do to be ready for the change. The characteristics of these forward looking buildings may represent good planning, but it is doubtful that they represent a significant number of existing buildings and uncertain what proportion are ever converted. Rather than designating a category whose criteria include design intention, it may be more generally useful to assign buildings that (intentionally or not) have good retrofit potential to the same category. By removing the requirement of intention, we can re-classify these buildings as **Retrofitable** (with moderate capital investment) or even **Adaptable** (with relatively little additional investment) to mixed-mode operation. This notion fits nicely into the trend of growing interest in adaptive reuse of buildings, and the practice of designing buildings to change over their lifetimes. Relevant questions to ask about such buildings include: What needs and trends will drive changes to the building? Is the program of the building likely to change over time?

In the study of potential global energetic impact of mixed-mode conditioning, Retrofitable buildings should be of great interest. Some retrofits are undertaken to conserve energy and reduce conditioning loads, but many are undertaken to add or expand air conditioning capacity. Depending on which of these motivations is driving a retrofit, very different decisions criteria could be used to assess the merits of mixed-mode systems. For example the addition of operable windows to a conditioned space is likely to reflect a desire for increased natural ventilation and perhaps an awareness of the health, comfort, and energetic consequences of operable windows. The addition of mechanical ventilation and/or conditioning, on the other hand, is likely to be driven by comfort or possibly code compliance criteria.

3.3 ISSUES FOR SHAPING A NEW FRAMEWORK

Informed by all the good work that has gone into defining and updating the “classic” mixed-mode taxonomy, and some new insights into the motivations that shape design and engineering decisions on mixed-mode projects, we are ready to further define the classification criteria that will best serve an updated framework. Sine we are interested in defining a framework that works at a practical level, we have taken care to ensure it reflects the real world diversity of systems within and between buildings.

Hypothetical Example

In practice, buildings are often broken out onto many zones that each have different conditioning needs, and thus may utilize many strategies. In this section we’ll work through a simple example to develop criteria for evaluating our new framework. Consider the following simplified diagram of a three-zone building:

Table 6: Three-zone mixed-mode building

Zone 1 **Natural Ventilation**	**Zone 2** **Mixed Mode** (e.g., night ventilation during Summer, trickle vent in winter)	**Zone 3** **Mechanical Ventilation and Conditioning**

The Problem

With just three zones, this building demonstrates the difficulties of using a whole-building classification system. It is clearly a **zoned** mixed-mode building because of zones 1 and 3 (or 2 and 3). It is just as clearly a **changeover** building because of the change from summer to winter operation in zone 2, unless that change is manual, in which case it is an **alternate** building. It is also a **changeover** building because of the change from daytime to nighttime operation implied by night ventilation. Finally, it is a **concurrent** building because of the trickle vent strategy employed during winter. So we have one building that defies classification as whole building, and a single zone (zone 2), which qualifies as changeover on a couple different timescales, possibly as alternate, and also as concurrent.

The Physical Layout and its Motivations

How might this building be better understood by a more detailed classification system? First, instead of allowing for the building to simultaneously embody all of the above strategies, a more detailed system should break out conditioning classifications by zone. It should also consider the motivations behind the decision to zone the building in the first place, since the same motivations are likely to better inform decisions about conditioning strategies.

In the example above, why might Zone 3 be fully conditioned? It might have large anticipated conditioning or ventilation loads that should logically be separated from the rest of the building to reduce overall energy usage. On the other hand, maybe it is a private office for an unforgiving occupant. The naturally ventilated Zone 1 might be an open-plan area with a narrow floorplate that can easily be cross-ventilated, a semi-outdoor space like an atrium, or it might experience only transitory or seasonal use and would not be worth the expense of conditioning. Mixed-mode Zone 2 could be an open office space recently retrofit to introduce summer cooling only during peak conditions, or could be minimizing cooling loads by taking advantage of the stack effect of the atrium next to it.

Whatever these zones are, the reasons for their breakout and the strategies used in each are likely to be similar to the program and associated strategies of many other existing and future buildings. Developing an understanding the drivers for differentiation and viable solutions for each specific situation should help enhance the utility of these case studies, and will ideally simplify the decision process for future buildings and lead to more predictable and repeatable results.

The Climate and Site Conditions

The climatic setting and site specific conditions of a building (along with internal loads, which here can be thought of as programmatic) are likely to be primary drivers of the effectiveness of various ventilation and conditioning strategies, and are also likely to have similarities across many existing and future buildings. The climatic drivers for various control strategies should therefore be broken out as specifically as possible.

Buildings in four-season climates almost by definition will require different strategies in different seasons. For example, mixed-mode strategies might be used to extend energy savings and other benefits from natural ventilation into the shoulder seasons. In such cases, we'd expect to see seasonal changes in the control strategies employed.

In moderate climates, natural ventilation strategies are likely to be viable over a greater portion of the year, with controls primarily or exclusively operating in daily cycles and/or responding to real time conditions.

Finally, because of natural synergies between specific control strategies and the systems used to actively condition the space, we might expect to see logical pairings arise. For example, when night ventilation is a viable strategy, it is typically supported by strategic use of thermal massing. If that thermal mass could also be activated through slab conditioning strategies (typically hydronic/radiant), the system is likely to operate much more efficiently throughout the year. However, if the ventilation system takes advantage of real-time conditions – wind blowing off a lake for example – the control system employed may need to respond too quickly for slab conditioning to keep up.

Other Very Real Constraints

In the end (or perhaps at the very beginning!), budgetary constraints and other practical concerns are very likely to shape the outcome of building system decision-making. They are consequently critical to include in any real world classification system. While they can be deal breakers, we are assuming from the outset an active interest in utilizing mixed-mode strategies. As such, we expect that the programmatic and climatic (spatial and temporal) constraints will be examined first and then the overall expense, complexity, and detailed operating characteristics of the system will be tuned using practical concerns. While these concerns may have the last say on the shape and function of a system, they should not rule anything out from the beginning.

3.4 A PROPOSED FRAMEWORK

As the above example demonstrates, decisions about mixed mode systems can be thought of as being driven by independent criteria acting in parallel. We are proposing a framework that integrates several mutually independent taxonomies (one for each driver) into one structure that allows designers and engineers to look at each separately or all of them together in determining their approach.

The criteria that stand out as primary drivers for the typical decision process are:

1. **Programmatic/Spatial** influences will primarily determine the overall layout of a building and the planned use and occupancy of its spaces. Zoned systems should be developed to meet the needs of each while taking advantage of the variations whenever possible.
2. **Climatic/Temporal** influences will largely shape the heating and cooling loads in a building, and will certainly shape the properties of outside air brought into a building through natural ventilation. Since outside conditions will change seasonally, daily, and minute-by-minute, climatic conditions will often drive the appropriate time scale of controls.
3. **Moderating Practical Concerns**, like budgets, desired levels of occupant control, and personal taste will often determine what is done in practice and how it deviates from any known ideals. They will also be used to differentiate between options that aren't obviously resolved by objective criteria.

Consequently, we've developed a system that looks at the decision processes for these 3 categories separately. Building design decisions are assumed to be a superposition of all these processes acting in parallel, but it is a judgment left to designers to determine the relative importance of each on a project. This allows for the Climatic/Temporal Criteria to shape diverse zones differently, and for the lessons learned from a case study of a whole building system to perhaps be used to inform the design of just a single zone in a similar climate on another project. It also allows for the reality of equipment prices, occupant behavior, energy performance goals, and other factors to be taken seriously in the system without allowing them to preclude awareness of optimal system configurations.

All that being said, there is not yet consensus on whether or when simpler manual control systems are preferable to more sophisticated advanced control systems. The advanced controls have the advantage of being more predictable and potentially closer to the theoretical best operating strategy for a given zone, but the manual controls are typically cheaper, easier to install and operate, often more adaptable, and more likely to support variation in individual comfort criteria. Since these tradeoffs require a judgment call, we expect the degree of complexity in controls and systems to vary independent of the classification system's criteria in ways that it can suggest but is only partially capable of representing.

Tables 7-10 below represent our proposed system for identifying and classifying the key drivers of mixed-mode system design and performance. We have attempted to balance the need to cover the diverse range of real world design drivers with a desire to provide as concise a hierarchy as possible. In some cases the specifics options may merit further adjustment, but we hope that the general framework illuminates the issues that mixed-mode building designers face. Wherever possible, we have provided a brief description of the design consequences of each driver and have provided examples of case study buildings that have responded to similar circumstances.

Table 7: Programmatic/Spatial Drivers

Main criteria	Sub-Criteria	Tangible Impact/Examples
Single Zone Conditioning		Not very common in commercial space. Most likely in an open floor plan for a small office, possibly a retrofit of industrial space. See Kubala Washatko Architecture office retrofit.
Zoned Conditioning		Most mixed-mode commercial space is zoned in one way or another. Optimal energy use often depends on containing high loads to isolated parts of the building. Further, natural ventilation can usually only condition perimeter spaces.
	Perimeter vs. interior	• Bren School (naturally ventilated perimeter offices vs. mechanically cooled interior labs)
	Open office vs. meeting spaces	• SF Federal Building (floor plans) • Evergreen College's Seminar II (division of space)
	Performance/Gghly variable internal loads)	• Adam Joseph Lewis Center (see NREL study's lessons learned about energy use associated with unexpectedly frequent and popular gatherings.) • Seminar II building • Aldo Leopold Center • Global Ecology Center (meeting rooms get special attention with separate condition/ventilation strategies.)
	Unusual requirements for ventilation (e.g. labs, kitchens) or Unusual conditioning loads (e.g. server rooms)	These situations are often dealt with by physically isolating the high load space, and conditioning it separately.
		For lab ventilation strategies, see: • Bren Center (naturally ventilated perimeter offices vs. mechanically cooled interior labs) • Global Ecology Center • Ordway Building at Woods Hole • San Mateo Forensics Lab. Similarly, server rooms are often isolated due to their high cooling demands, even in sealed mechanical buildings.
	Seasonal spaces	It is possible to use natural ventilation in spaces that would otherwise tend to have mechanical cooling but are unoccupied during the summer. This is most common in high performance schools • Clackamas High School • Simmons Hall at MIT.

Table continued on next page ….

Table 7: Programmatic/Spatial Drivers, *continued* …..

Main criteria	**Sub-Criteria**	**Tangible Impact/Examples**
Zoned Conditioning *continued ….*	Circulation spaces	Due to their programmatic role, lobbies, stairwells and other circulations spaces may be naturally ventilated while the rest of the building is mechanically conditioned. This strategy is often coupled with displacement ventilation or radiant heating/cooling. • OHSU Center for Health and Healing (lobby and stair wells) • Oberlin's Adam Joseph Lewis Center (automated windows in the lobby) • Global Ecology Center (indoor/outdoor lobby.)
	Retrofits that add natural ventilation to full mechanical building OR Add or alter mechanical ventilation and cooling	In many cases, retrofits will be undertaken to add AC to existing naturally ventilated buildings. Despite potentially large paybacks in occupant satisfaction and lower energy bills, retrofits to add natural ventilation to an existing sealed mechanically ventilated building are less common.
		For adding AC, see: • Jean Vollum Natural Capital Center • Chicago Center for Green Technology. For changes to an existing mechanical system see: • UCLA's Kinsey Hall AKA Humanities Building)
	Prevailing wind or other site local constraint	• SF Federal Building (site specific wind driven ventilation) • Chesapeake Bay Foundation Headquarters. (NREL evaluation of the ventilation orientation)

Table 8: Climatic/Temporal Drivers

Main Criteria	Sub-Criteria	Tangible Impact/Examples
Conditions support Changeover strategies		Changeover strategies represent the best energy savings potential in mixed-mode buildings because they involve periods of non-operation of the HVAC equipment. However, since they are designed to opportunistically take advantage of favorable outside conditions their actual performance is sensitively dependent on control strategies and climate.
	Seasonal climatic variations	• Aldo Leopold building (manual seasonal changeover (Alternate) in a four season climate) • Seminar II building (moderate climate, 80% NV using stack effect, but with a trickle vent heating strategy for winter.
	Daily temperature swings	Night cooling of thermal mass is a classic changeover control strategy. This might include variations on air-to-slab cooling: • Gap 901 Cherry Building • SF Federal Building Or a night sky hydronic cooling system • Global Ecology Center
	Changing real time conditions	For active window controls, see: • SF Federal Building (active window controls) Or simpler red/green light systems that notify occupants when it is “OK” to open the windows • Chesapeake Bay Foundation • Hewlett Foundation
Conditions support Concurrent strategies		Concurrent systems have the potential to blow conditioned air straight out the window and many people are worried about poor concurrent performance when they think about mixed mode buildings. Still, good design strategies and low air volumes often make concurrent strategies energetic and comfort winners.
	Responsible occupants	On the assumption that a building’s occupants can be expected to take responsibility for their decisions, some designers choose to allow all manual concurrent operation of their systems. This offers occupants the greatest flexibility of use and can be less expensive to install and operate. • Gap Office at 901 Cherry • Pennsylvania DEP Cambria Office Building • Global Ecology Center
	Code minimum ventilation requirements	Trickle vent heating/ventilation in a well-sealed and insulated building: • Evergreen College’s Seminar II building

Table 9: Practical Concerns / Control Specifics

Main Criteria	Sub Criteria	Tangible Impact/Examples
Budget constraints		Budgets are often a concern with mixed-mode buildings. While good strategies should substantially simplify mechanical systems and lower their cost, typically both natural ventilation and mechanical systems must be purchased, installed, and configured in mixed-mode buildings.
	Not a primary driver	Two buildings that focused primarily on minimizing their footprint and spent more than what was "cost effective": • Aldo Leopold Center • Global Ecology Center
	Lowest first cost	Natural ventilation strategies may work so well that they allow for a substantial downsizing of mechanical systems. These changes sometimes pay for the rest of the ventilation system. • Clackamas High School (built with little or no premium over a typical school in the same area.)
	Lowest operating cost	Buildings with simple controls such as window interlock systems that disable mechanical systems when the windows are open are guaranteed to save energy over mechanical systems and are fairly inexpensive to install. Systems primarily based on natural ventilation with night cooling and ground source heat pumps feeding a slab cooling systems or displacement ventilation are likely to cost less to operate that similar buildings in the area (but may have high first costs for setup and installation).
Degree of occupant responsibility	Aware and highly trained occupants where manual control is culturally acceptable	Often notification lights only with concurrent operation possible • Global Ecology Center • Ordway Building at Woods Hole
	Occupants not expected to operate system effectively	Fully automated systems can make theoretically optimal control decisions, which may be counter intuitive for buildings with high thermal mass, complex ventilation plans, or sensitive systems that require close to real time adjustment. • SF Federal Building (challenge was to design a system that would accommodate user operable windows even through the whole system is too complex for individual users to make all the operating decisions.)
Other factors	Security or noise considerations	• SF Federal Building (see lower floors which are sealed for security)
	Historic façade preservation	• Kubala Washatko Architecture office (historic but leaky windows.)

Finally, there may be cases where buildings are intended to be flexible and have either made allocations for future retrofit work that enables mixed-mode operation, or that have gone a step further and have installed the necessary systems but do not actually use both mechanical and natural ventilation systems strategically on a regular basis. This category includes the traditional classifications of "Alternate" and "Contingency" strategies. These buildings would not be considered actively mixed-mode, but they can be classified according to the programmatic and climatic criteria that they would theoretically use if their retrofit were to occur. Here we might also look at a classification of the likely drivers for an eventual switch to mixed-mode operation in these buildings.

Table 10: Retrofit Drivers

Main Criteria	Tangible Impact/Examples
Programmatic change	Buildings that are being retrofit due to programmatic change, might include renovations of old warehouse or industrial space. These will almost invariably be adding A/C but preserving natural ventilation options. See • Jean Vollum Natural Capital Center • Chicago Center for Green Technology
Occupant change	When occupancy changes at the end of a lease, for example, the new tenant will often make improvements on their new space. These improvements may include the addition of A/C, or, in the case of increasingly popular "green" retrofits, might include the addition of operable windows and mixed mode controls to a previously sealed space.
Occupant satisfaction improvement/expansion	If occupants are actually uncomfortable, unhappy, or merely outgrowing their space, they will sometimes invest in a renovation to improve the conditions of their space. In these cases, the changes they make will likely be geared toward occupant comfort and satisfaction. Some well informed people in this position are likely to make the connection between mixed-mode and these other benefits.
Energy retrofit	With rising energy costs, growing awareness of the consequences of climate change, the advent of performance contracting, and energy service companies, there are an ever increasing number of people undertaking energy retrofits of their buildings. In these cases, people are still working toward cost effective solutions, but energy performance is their goal. Retrofits undertaken for this reason are very likely to benefit from mixed-mode systems.

4. CONTROL ALGORITHMS

4.1 MANUAL VS. AUTOMATED: A CONTINUUM OF CONTROL STRATEGIES

As described previously, mixed-mode buildings have traditionally been classified in terms of their operational control strategy (concurrent, change-over, or zoned). But this classification makes the most sense if it refers to spaces, not necessarily to an entire building. In many buildings, these control strategies occur in combinations in different spaces. The relevance for this project is that there are control implications for each of these operating strategies, related to whether the windows and vents are automated, or to where one establishes the thermostat setpoints to determine when the mechanical heating or cooling will turn on, or whether there are override controls for the HVAC system. These options range across timescales measured in minutes, days, and months.

Ventilation controls don't stop with operable windows. We've found control strategies in our case studies that take advantage of trickle vents, or other non-glazed vents located at the top of stacks, in the roof, mounted on the floor, or in underfloor plenums. The range of control algorithms and the mechanical systems they control are truly diverse. Our challenge has been to make sense of all these varying systems and offer an overarching organizing framework that supports the real world diversity of systems that are out there.

Our initial focus was on automated control of operable windows, and these could include occupant-level windows as well as clerestory and atrium windows. But we also found that control strategies in our case studies were sometimes aimed at other air flow openings in the envelope, including trickle vents, or other non-glazed vents located at the top of stacks, in the roof, or mounted on the floor or in underfloor plenums. Based on the case studies and interviews we've conducted, we can offer general guidelines about where automated vs. manual windows work best, and for what functions. Some of the case studies will then present specific control algorithms that have been used for automated windows.

- Automated windows are best used in high spaces, where they are difficult for occupants to reach (e.g., stack, atrium, or clerestory windows, or roof vents), or in public spaces, where they would not be "owned" by anyone and therefore might not be operated manually. They are also most commonly used to meet minimum ventilation requirements, to provide nighttime ventilation, to control overall ambient conditions in the buildings, or to provide controlled ventilation during periods of high winds or rain.
- Manually operated windows are best placed lower in the occupied zone, where they can easily be accessed by the occupants. While there may be a need for some automated windows for the reasons noted above, one should give occupants as much direct control as possible over at least some of the windows in order to garner the benefits of adaptive comfort.
- In addition to providing occupants with direct control over their thermal environment, manually operated windows are also important for their "psychological benefits", and for providing occupants with a sense of connection to the outdoor environment. For manually operated windows, it's essential that the user controls be visible and readily accessible, placed more closely to the point of need, intuitively obvious and easy to understand, and easy to operate by both occupants and management.

It is important to note that there is not consensus in the industry on the relative degree of personal vs. automated controls that they should provide. This condition is in part due to different priorities when assessing the tradeoffs involved in optimizing both comfort and energy consumption. Adaptive comfort theory demonstrates that greater personal control allows occupants to fine-tune their thermal environment to match their own personal preferences and creates a wider acceptable range of temperatures in the building. A typical approach to adaptive comfort is to use simpler and more manual controls that depend on educating occupants to operate the building efficiently and in response to their comfort needs. This approach is unlikely to achieve optimal energy performance, but can do pretty well and it is likely to achieve higher than average satisfaction ratings. At the other end of the spectrum, sophisticated integration of the HVAC and building fenestration systems, utilizing window sensors, actuators, and control algorithms that respond to indoor and outdoor climate conditions, often in real time, can be employed to optimize both energy and comfort. These highly engineered solutions make building behavior more predictable and are well suited to energy optimization. However, as one moves more towards a fully automated central control system, there is the risk of losing the adaptive opportunity afforded by personal controls while committing to higher first cost and maintenance. With real world examples of the range of strategies and control algorithms currently in use, this work is intended to help support designers and engineers as they navigate these tradeoffs.

4.2 CONTROL VARIABLES

Input Signals

Systems use a variety of input signals in their control sequences. In normal mode, the most typical control variables used as the input signal are indoor temperature and CO2 concentration. These are typically monitored continuously, perhaps using the average of distributed sensors across a zone, and then when their levels or concentrations deviate from their respective setpoints, they generate a "ventilation demand" signal. Indoor temperature is often the most common input signal, and is considered relatively cheap, accurate, and effective. CO2 sensors serve as a surrogate for occupant sensors, and provide the potential for more energy-efficient, demand-controlled ventilation. In contrast to temperature sensors, however, they are relatively expensive and might need regular calibration. Moisture is also sometimes used as an input signal, but in the cases we've seen so far it's not to control indoor humidity for comfort. Instead, the moisture sensors might be used in conjunction with surface temperatures of a radiant cooling system to prevent condensation.

Modifiers

To ensure that outside weather does not adversely affect the inside comfort condition, the ventilation demand signal can also be modified in several ways to take into account outside air temperature, wind speed & direction, rain, or as mentioned the surface temperature of radiant cooling surfaces. For example, if the outdoor temperature is below a given threshold, the system will revert to minimum ventilation, perhaps with heat recovery through mechanical ventilation or trickle vents. Or if the outdoor temperature is too hot, the actuators will close the envelope and the system will revert to mechanical cooling. Wind speed can also act as a modifier. For example, it can be used to optimize the performance of stack ventilation, where high windward openings would be closed to maximize the negative pressure for the exhaust openings on the leeward side. Or wind might be used to modify the openings for lower windows if winds are too high. Rain, or the surface temperature of a radiantly cooled surface, can also be used as modifiers.

Control Actions

In response to the input signals or modifiers, a number of different control actions can take place we found a range of examples where either the windows are modified (by number of windows open/closed, or degree of opening), or elements of the mechanical ventilation or cooling system are controlled in response to window position and indoor environmental conditions.

Control Functions

There are a variety of criteria, or environmental conditioning functions, that drive the control sequences for operable windows. In this sense, the term "natural ventilation" is viewed by some as a bit of a misnomer, in that it can provide a range of functions:

1) Ventilation control. The term "ventilation" refers specifically to the exchange of outside air to provide required oxygen, and dilute pollution (in contrast, the term "natural ventilation has traditionally be used to refer to a wider range of functions). For ventilation control, CO2 sensors might be used to trigger the degree of window openings, or when mechanical ventilation kicks in.

2) Thermal comfort control. Here, the exchange of outside air is being used to cool people, by bringing in higher levels of air movement past the skin. The combination of temperature and air velocity in the occupied zone are the important parameters here (even though air velocity is not always monitored or controlled for directly). In its primary mode for this function, the control sequence typically looks at whether temperature setpoints vary from a preset deadband. This can either be the traditional narrow deadbands typical of buildings with centralized control, or could be set to a wider deadband representing an adaptive comfort zone, allowing for a wider range of

floating temperatures. There could also be an alternative mode for comfort control, designed specifically to control peak demand, where the mechanical cooling is switched on only when an extended upper setpoint is exceeded.

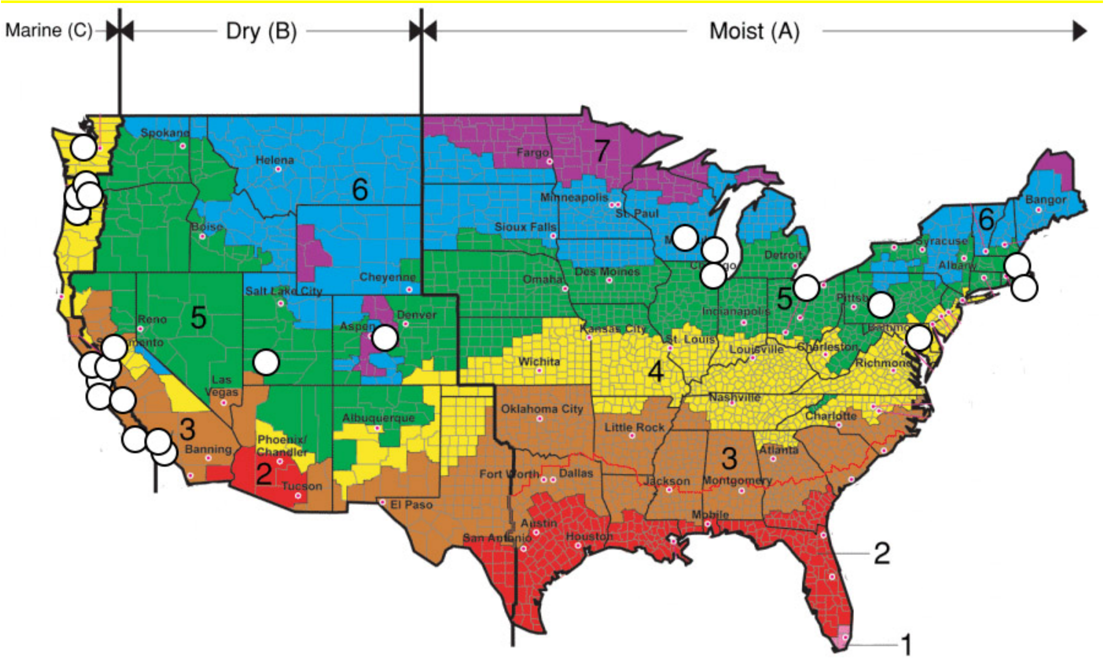
3) Space cooling. The focus is to maintain the ambient temperatures within the temperature deadband, similar to the notes above but without any concern for air velocity per se. Outside air will only cool the space if it is cooler than the inside air temperature at that moment, so a control strategy might need to monitor both inside and outside air temperatures.

4) Structural cooling. This strategy utilizes nighttime ventilation in combination with thermal mass to precool the structure. It may also incorporate early morning mechanical cooling if there are large east or southeast-facing windows, and/or if there is a predicted heat wave coming.

The distinction between these different control functions is important, because: 1) you can sometimes use different types of openings to provide those different functions, each with different control implications, and 2) the airflow requirements for these different functions can vary significantly.

5. CASE STUDIES OVERVIEW

In this section and in *Appendix A: High Level Case Studies*, we include details on many of the mixed-mode buildings we've looked at as a part of this study. Figure 1 below illustrated the location of the buildings studied. They are intended to provide more in depth information on the control strategies in use in existing buildings as well as a starting point for further research into mixed-mode strategies. Every example given in the taxonomy section of this final report has a corresponding entry in the list of case studies and the information provided is intended to help designers consider how the various strategies fit into the framework we've developed. To keep the main body of this text a reasonable length, we've placed the majority of the case studies in Appendix A at the end of the document. The information found in those studies is based on our source material and remains of central importance in this study, so please be sure to read the Appendix if you are interested in the buildings we've studied to draw the conclusions found in this report.



All of Alaska in Zone 7 except for the following Boroughs in Zone 8: Bethel, Dellingham, Fairbanks, N. Star, Nome North Slope, Northwest Arctic, Southeast Fairbanks, Wade Hampton, and Yukon-Koyukuk

Zone 1 includes: Hawaii, Guam, Puerto Rico, and the Virgin Islands

Figure 1: Location of case study building on national climate map (see climate discussion below and in *Appendix B: Notes on Climate Zones*)

5.1 TERMS AND KEY TO THE CASE STUDIES

The case studies in this document are not really comprehensive case studies in the traditional sense. They are focused on providing a high level overview of each building's conditioning strategy, equipment, and controls as they relate to mixed-mode. In this sense, they could be considered studies of the strategies, rather than studies of the buildings.

Each case study begins with the name, basic information, and three or more pictures of the building described. In the basic information there are a few terms that may require further explanation.

Program is a rough measure of the building's primary purpose, but has not been standardized.

Control complexity gives a qualitative sense of how complex the buildings control systems are.

Climate zone is the climate zone of the building as defined by the 8 zone DOE climate breakdown used in most current building codes (e.g. the numbering and names have specific meanings). See *Appendix B: Notes on Climate Zones* for more detailed discussion of climate zones, the origin of the DOE zone configurations, and the particular importance of climate zones to mixed-mode buildings.

Next, each case study contains a table structured summary of the mixed mode strategies ("Mixed-mode strategies at a glance") used in the buildings. They are described in detail below. It is important to keep in mind that they are part of a best fit system and sometimes which should be fill in has been ambiguous. For example, many buildings attempt some form of stack ventilation, but one a few actually rely on it. In the case where it seems to be a non-functional gesture, it will not be checked. If it seems to have been a first order design criteria, it will be checked. When we've deemed it necessary, we added brief notes to ambiguous fields.

HVAC				
GSHP	Panel	Slab	UFAD	Forced Air
Ground source heat pump. Hydronic geothermal loop.	Panel-based radiant heating and/or cooling	Slab heating and/or cooling	Under Floor Air Distribution	Forced Air System, typically VAV A/C

Classification		
Changeover	Concurrent	Zoned
Changeover strategy employed in at least one zone in the building	Concurrent strategies employed in at least one zone in the building	Zoned strategies employed in at least one zone in the building

Controls			
Red/Green notification	Window HVAC interlock	Mechanical window operation	Manual window operation
Lights that notify occupants when natural ventilation is OK	Switches integrated into the windows that shut off conditioning when the window is open	Some of the windows in the building are mechanically controlled	Some of the windows in the building are manually controlled

Ventilation			
Windows	Vents	Stack	Cross Vent
System employs window openings for ventilation	System employs vents to the outdoors for ventilation	Ventilation is driven by the stack effect	Ventilation is driven by wind pressure across the building

After the “at a glance” section is a brief “System summary” that contains a terse overview of the specifics of the mixed mode strategy. This section highlights any unusual characteristics of the system, its basic control strategy, and the equipment involved.

In the more detailed case studies, the next sections describe the building design process and control strategy in more depth and provide actual control sequences.

Finally, each case study ends with annotated links and paper citations so you can learn more about the building. The web being as dynamic as it is, some of the links may become dated pretty quickly. However, it is our judgment that the convenience they afford interested readers outweighs the risk of putting them down on paper (or PDF).

In the control algorithm studies we’ve provided, the format is a little more free form to accommodate the range of information we’re providing. We provide building images and background information at the beginning, a discussion of the control algorithm in the middle and a “Learn more” section at the end.

6 DETAILED CASE STUDIES

6.1 ALDO LEOPOLD LEGACY CENTER


Image: Aldo Leopold Foundation


Image: Kevin Matthews / Artifice Images


Image: Kevin Matthews / Artifice Images

Location: Baraboo, WI

Architect: Kubala Washatko Architecture

Engineer: Utzinger

Year built: 2007

Program: Nature Center

Climate: 6A(Cold – Humid)

Control complexity: Complex system with manual controls

Mixed-mode strategies at a glance

Classification		
Changeover	Concurrent	Zoned
X	X	X

HVAC				
GSHP	Panel	Slab	UFAD	Forced Air
X		X		X

Controls			
Red/Green notification	Window HVAC interlock	Mechanical window operation	Manual window operation
X (virtual)	X		X

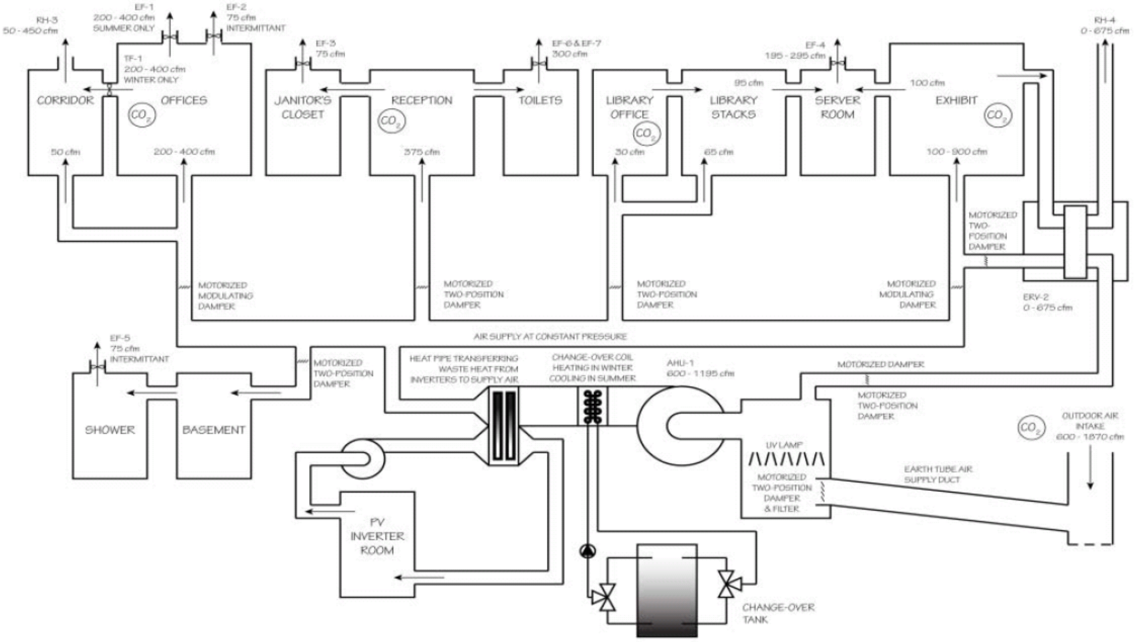
Ventilation			
Windows	Vents	Stack	Cross Vent
X		X	X

System summary

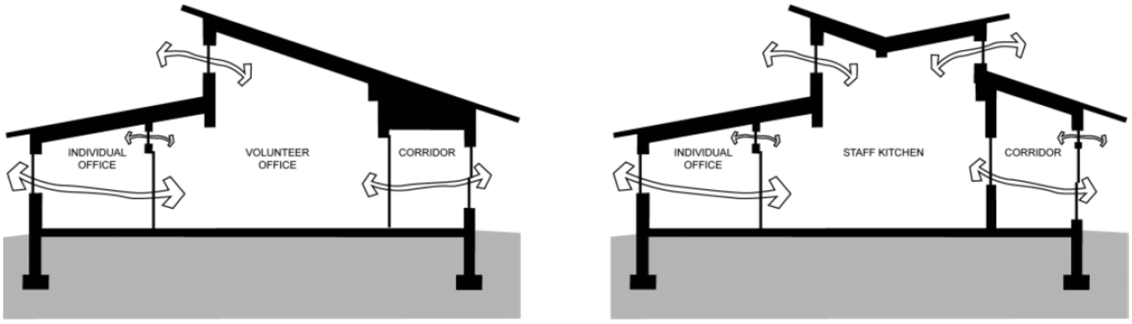
Ground Source Heat Pump; radiant slab heating and cooling; low flow A/C dehumidifies air; occupant choice when to use it vs. pure Natural Ventilation; VAV displacement ventilation to control IAQ only. LEED Platinum building with a goal of net zero carbon.

Control details

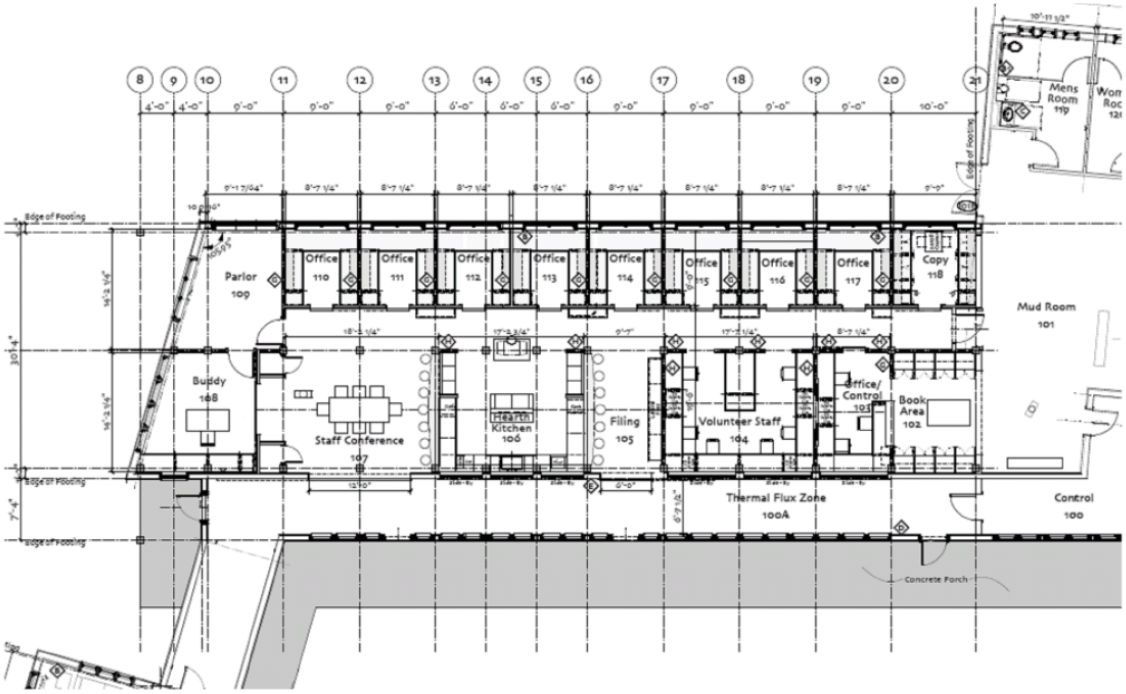
This control information in this case study is from a combination of interview notes with Mike Utzinger, an architect, practicing design engineer, and building researcher at UW-Madison, and a close reading of his paper with David Bradley on the design and simulation of the systems in the Leopold Center. The schematic of the building's mechanical systems below and the building sections and plan that follow are drawn from their work and are for reference throughout this case study.



Schematic of the mechanical system (Source: Bradley and Utzinger 2007)



Office core sections (Source: Bradley and Utzinger 2007)



Office core plan view (Source: Bradley and Utzinger 2007)

The building is really two different building types. One wing (meeting room) has a well insulated wood floor and has no thermal contact with ground. Everything else is slab on grade. The basement was pared down to keep it only mechanical so it isn't programmed (or conditioned). There are no interior zones in the building.

The portion of the building that is slab on grade has sufficient heat capacity to support radiant heating and cooling using geothermal loop flowing through a cooling coil with a 60° supply temperature (slab actually at 62-24°) for cooling and 85° supply for heating. In the conference wing there is a displacement ventilation forced air system.

The designers estimate that the mechanical displacement ventilation system is 1/5 the size of a typical system in a comparable space. It supplies air at 65° in winter and 68° in the summer, when it is dehumidified and re-heated. The original design called for waste heat from the PV inverters to do the reheat, but in practice they didn't provide enough heat so they pulled out a heat pipe and added re-heat coil (after the ASHRAE paper was submitted). A transfer fan system is used to circulate warm air from the control room to the main level of the building. They also have an enthalpy heat exchanger and draw outside air into the system through earth ducts to pre-cool it.

They used Contam to determine the greatest number of operable windows and clerestories and knew that it would be incorporated into the model supporting their LEED application. Many additional hours went into their work because of the LEED requirements. They wanted to minimize the operable area that would still provide NV and minimize the infiltration in the winter.

There is a system humidity cutoff based on occupant comfort and approaching dew point temperatures. When the conditions are close to condensation or reaching beyond the comfort range, the system can tell you, but the call is ultimately up to the occupants whether or not to enable the humidity lockout. Below is a visualization of data from the building operating with and without humidity controls (the y-axis is humidity in the building and the x-axis is temperature). The boxes are ASHRAE 55 2004 comfort boxes for winter and summer clo values. We can see here that some form of humidity control is required to maintain acceptable comfort. Naturally, dehumidification and reheat represent substantial energy demands.

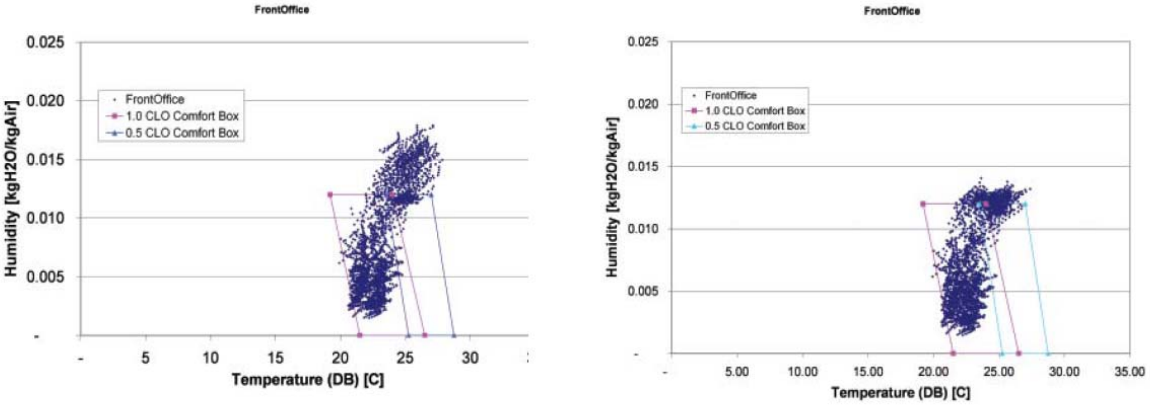


Illustration of humidity control (Source: Bradley and Utzinger 2007)

There are web based controls that the staff can access is used to control operation in NV mode or mechanical mode. When they are in NV mode, all of the heat pumps and other mechanical systems are off. The details of necessary start up and shutoff routines are hidden for the users by the building automation system. They didn't want to do a formal red/green light system, but the computer interface has this functionality (a virtual red/green system). They met with the clients several times over the control strategy and client is largely in control and knows how the system works.

The date they switch over from heating to cooling and back again during the course of the year (they have a single switchover coil) is up to the users. Ideally this happens during the change over seasons when neither the heating nor the cooling in being used much during the day. Energy use is increased by switching to cooling too soon due to extra re-heat load, particularly in the cool mornings.

The building was occupied in June 2007. They have minimized internal loads. Standard operating conditions have none of the lights on. June 24th they turned the cooling on (made it a long time) and they've been bemused by the slab (cool on their feet). Their conversation about the chilled floor was a conversation about basements in Wisconsin. People go to their basement for cooling and the floor is the source of that cooling, so people understand the analogy.

For cooling, the temperature of the slab is kept between 62-64 degrees. Ideally radiant cooling is from above, but because they don't go to air conditioning mode until there are high temperatures, it is ok for the space. When the air is in the mid to upper 70s, slab in mid 60s is comfortable. The ventilation air has the humidity pulled out, but you can't expect the system to take the humidity out of the air under all conditions. It is not sized to do so.

Occupants see themselves as embarking on an experiment. Time will tell if it works under all conditions. For example, they are not sure that the system can handle a large gathering on a hot day for example (though they expect that it should be able to).

Learn more

See http://www.aldoleopold.org/LandEthicCampaign/construction.html

And this brochure on the radiant floor

http://www.aldoleopold.org/LandEthicCampaign/radiant%20floor.pdf

http://www.architectureweek.com/2007/1003/design_1-1.html

Bradley, D., Utzinger, D. M. (2007 (Accepted)). "The Enhancement and Use of Combined Simulation Tools in the Assessment of Hybrid Natural / Mechanical Ventilation Systems." ASHRAE Transactions.

6.2 FEDERAL BUILDING SAN FRANCISCO

Location:	San Francisco, CA		
Architect:	Morphosis and SmithGroup, Inc.	**Engineer:**	Ove Arup and Partners (Los Angeles),NaturalWorks (NV modeling)
Year built:	2006	**Program:**	Public/Office
Climate:	3C(Warm – Marine)	**Control complexity:**	complex computer control adapts to user operable windows

Mixed-mode strategies at a glance

Classification		
Changeover	Concurrent	Zoned
X		X

HVAC				
GSHP	Panel	Slab	UFAD	Forced Air
		X (passive)	X (low floors)	X (lower floors)

Controls			
Red/Green notification	Window HVAC interlock	Mechanical window operation	Manual window operation
		X	X

Ventilation			
Windows	Vents	Stack	Cross Vent
X	X	X (weak)	X

System summary

AC zoned to lower floors so windows remain closed for security and programatic reasons; 70% of floor space is cross ventilated NV; complex controls manage clerestory windows; users control view windows; the system uses automated controls to facilitate night ventilation that passively cools ceiling slabs.

Control Details

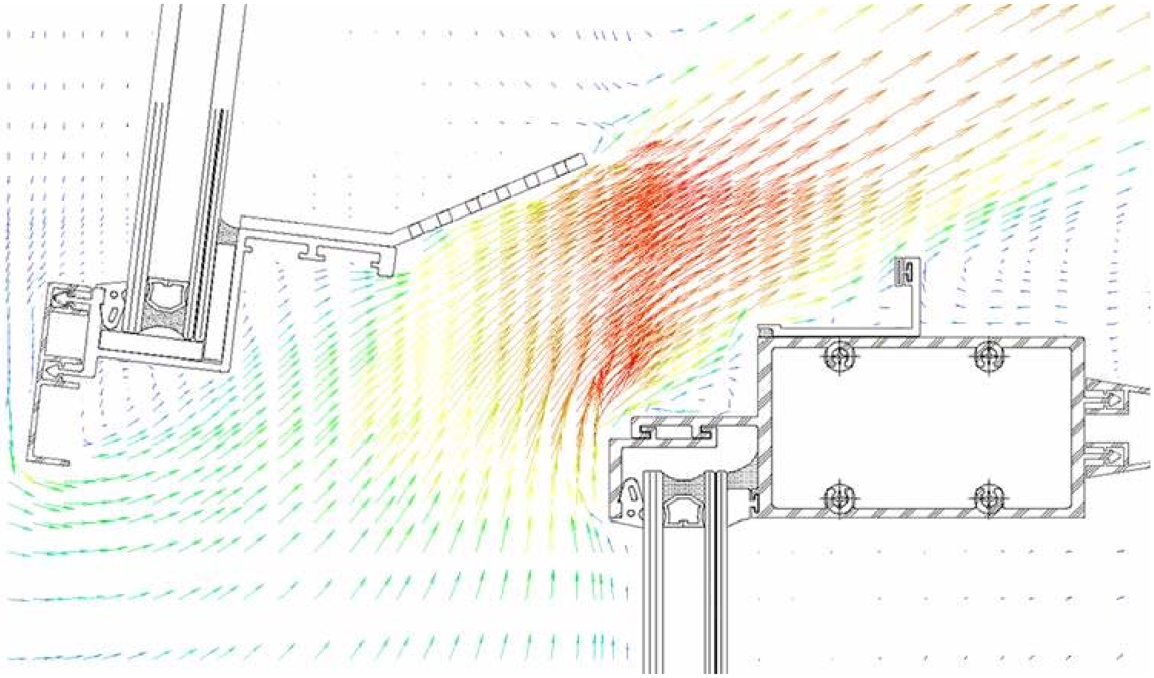
The San Francisco Federal Building was designed by Morphosis with Arup as the mechanical engineer. Phil Haves from LBNL, and Paul Linden from UCSD, were extensively involved in the analysis of the natural ventilation schemes. Several academic papers, specifically those cited at the end of this case study, document the design process and control algorithm development in detail.

Despite its striking appearance, the key features supporting natural ventilation in the building are fairly basic. They include its narrow floor plate (55' or so), favorable location and orientation with respect to prevailing winds (no other high buildings around, reliable San Francisco ocean breezes), its exposed thermal mass, particularly in the ceiling, and a mix of operable and manual windows, and a sophisticated automated control system. The aggressive ventilation strategy is possible because of San Francisco's mild year round climate and consistently cool nighttime temperatures and the building's unique physical location with no other buildings of comparable size upwind to degrade its wind resource.

Due to security concerns and the relatively poor wind resource nearer to the ground, the first five floors of the federal building and its annex building are sealed and mechanically cooled using under floor air distribution. This qualifies the federal building as zoned mixed-mode. However, the innovations in real time control, low energy ventilation, and night cooling that make this building worthy of a detailed mixed-mode case study all exist in the purely naturally ventilated portion of the building.

During the day, the natural ventilation is used to provide for occupant comfort and indoor air quality requirements. At night, the system uses cooler air to cool the thermal mass of the building. These seemingly simple features require sophisticated controls to ensure that the building is responding properly in real time to a whole range of climatic conditions, and that the cross ventilation strategy is ventilating the leeward side of the building adequately.

On both the windward and leeward sides of the building, the automated system controls clerestory windows high on each floor and trickle vents low to the ground. Occupants are free to control the midlevel view windows as they please, but opening apertures are limited by safety and control concerns. Proper cross ventilation requires that the incoming air be directed up towards the ceiling in a manner that allows it to flow smoothly across the space against the ceiling to the leeward side of the building without creating windy conditions at desks right near the operable windows. This requirement led to the design of custom metal tabs that attach to the bottom of each window that helps direct air flow properly. An architectural detail drawing depicting the tab in a CFD simulation is included below.

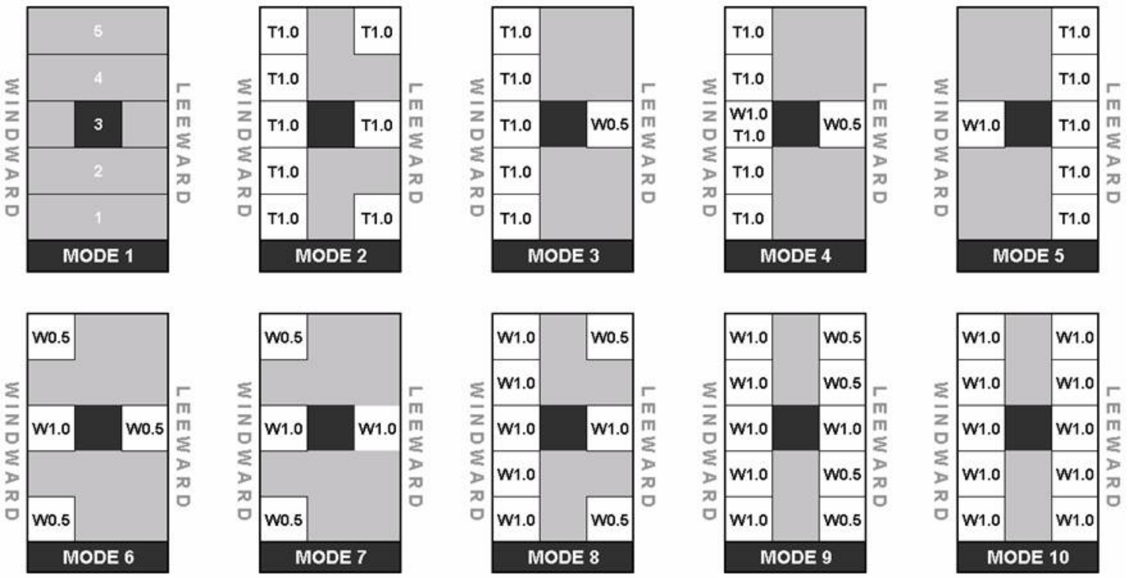


(Source: Phil Haves)

The automated window control system knows the pressure drop across the building, and the state of each operable window. In response to these conditions and changing weather patterns, it attempts to control airflow with by adjusting the clerestory windows and vents. For example, on windy days, the system only opens its apertures a little bit to get the desired airflow. On still days, the path from the vent to the clerestory windows is used as a form of weak stack ventilation.

The figure below is a schematic representation of 10 different operating modes of the windows and trickle vents, where openings are changed based on temperatures, velocities and pressure differentials, and a host of other rules. These modes were developed using extensive computer simulation and represent a gradient of building openness from fully closed to fully open. Note how windward and leeward opening are treated differently, and that there is usually more open area on the windward side. Note also how the various modes are responsive in some way to the circulation core in the center of each floor plate (dark square in the middle of each floor plate).

(T=trickle vent; W=window)



(Source: Phil Haves)

The various modes can be classified in terms of the ratio of windward and leeward opening area (A_W/A_L), the incoming air velocity (V_{IN}), the occupied zone air velocity (V_{OZ}), and the percentage of all windows open. The table below summarizes this data.

Mode	A_W/A_L	V_{IN}(m/s)	V_{OZ}(m/s)	Open(%)
1	-	-	-	0
2	2.0	2.7	0.89	3.4
3	0.5	-	-	6.7
4	1.3	3.8	-	22.2
5	3.7	1.6	0.53	7.3
6	4.0	1.5	0.50	13.7

7	2.0	2.7	0.89	25.3
8	2.5	2.3	0.76	52.5
9	1.7	3.1	1.02	72.8
10	1.0	4.3	1.42	100

Each mode is assigned to a particular situation for which it has been design to be useful. Predictably, the most closed modes are allocated to storm conditions, the next to providing for IAQ with the building is in heating mode, and the most open for mild or cooling conditions. The table below summarizes these relationships.

Situations	MODES
Storm	1, 2
Heating/Rain	3, 4
Mild/Cooling	5, 6, 7, 8, 9, 10

The building management system uses weather data, and indoor conditions to pick the mode that the windows should be in. However, there are also conditions of wind speed and pressure differentials that require limiting behavior to prevent the system from exceeding the tolerances of occupant comfort (or in extreme cases, the physical integrity of the system). The wind and pressure limitations are as follows:

1. If $\Delta P > 60$ or $V_{wind} > 20$m/s then the mode number cannot go above 8
2. If $\Delta P > 130$ or $V_{wind} > 25$m/s then the mode number cannot go above 6
3. If $\Delta P > 300$ or $V_{wind} > 30$m/s then the mode number cannot go above 2
4. If heating is on in both bays, or it is raining then the mode number cannot go above 4
5. If both sides are in cooling mode then the mode number cannot go below 5

Occupant behavior can also affect the system. Every time a window is opened or closed, the total area on the windward or leeward side is altered. Whenever possible, the building management system attempts to keep the ratio that delivers the mode it is trying to achieve. However, like concurrent mixed-mode systems, it is possible for overzealous or careless manual window control to upset the balance.

It should be noted here that the Federal Building has received mixed, but unscientific, reviews on thermal and visual comfort. One consequence is that it looks like the carefully planned air paths from the operable windows will be somewhat disrupted by new sets of blinds or screens addressing glare issues. Further, the ventilation strategy and control algorithms are still being tuned to provide the performance predicted by computer modeling. For any system as sophisticated as the on used by the federal building, designers, occupants, and owners should expect and plan for a period of tuning the building after it is occupied and work to include the impacts of occupant behavior in their carefully tuned models.

In addition to documenting the control sequence specifications, we have been participating in what promises to be an extensive post-occupancy evaluation of this building, in collaboration with this long list of other universities, research lab's and consultants. Before they moved in, we completed pre-move surveys with future occupants, and will eventually be collecting POE survey data and physical measurements in the building. However, this latter step is on hold while people get settled into the building and the kinks are worked out of the control system.

Learn more

Media Coverage of the building can be found all over the place, including:

http://www.treehugger.com/files/2007/03/san_francisco_f_1.php

http://www.natural-works.com/projects/sffed.php

http://www.lbl.gov/tt/success_stories/articles/energy_plus.html

McConahey, E., P. Haves, et al. (2002). "The integration of engineering and architecture: A perspective on natural ventilation for the new San Francisco Federal Building." 2002 ACEEE Summer Study on Energy Efficiency in Buildings, Pacific Grove, CA (US), 08/18/2002--08/23/2002.

http://buildings.lbl.gov/hpcbs/pubs/E4P21T1a3_LBNL-51134.pdf

Christ, T. "AN ARCHITECTURAL PERSPECTIVE ON NATURAL VENTILATION A New San Francisco Federal Office Building."

http://www.design.asu.edu/msenergy/Neeraj/Christ.pdf

Carrilho da Graça, G., P. F. Linden, et al. (2003). "Design and testing of a control strategy for a large, naturally ventilated office building." Augenbroe and Hensen, ed. Building Simulation 3: 11-14.

http://www.ibpsa.org/proceedings/BS2003/BS03_0399_406.pdf

Haves, P., P. F. Linden, et al. "Use of simulation in the design of a large naturally ventilated commercial office building." Proceedings of Building Simuation ‘03, IBPSA, Eindhoven, Netherlands.

http://www.ibpsa.org/proceedings/BS2003/BS03_0451_458.pdf

6.3 WILLIAM AND FLORA HEWLETT FOUNDATION


Image: © B.H. Bocook, AIA, Architects


Image: © B.H. Bocook, AIA, Architects


Image: © B.H. Bocook, AIA, Architects

Location:	Menlo Park, CA		
Architect:	B.H. Bocook Architects, Inc.	**Engineer:**	Critchfield Mechanical, Inc.
Year built:	2002	**Program:**	Commercial
Climate:	3C(Warm – Marine)	**Control complexity:**	Moderately complex

Mixed-mode strategies at a glance

Classification		
Changeover	Concurrent	Zoned
X	X	

HVAC				
GSHP	Panel	Slab	UFAD	Forced Air
			X	X

Controls			
Red/Green notification	Window HVAC interlock	Mechanical window operation	Manual window operation
X		X	X

Ventilation			
Windows	Vents	Stack	Cross Vent
X		X	

System summary

Operable windows, UFAD with localized manual floor diffusers; red and green light system alerts staff when air conditioning or heating systems are active.

Control details

The Hewlett Foundation building takes advantage of many low energy conditioning strategies, but these strategies have not been altered much by the presence of operable windows. Window operation is concurrent to other conditioning strategies, but there is a red and green light system in place to notify occupants when they can open their windows. Given that there is no window interlock or other strategy for turning back the heating and cool when windows are in use, the light system is most likely preserving energy performance.

When return air is warmer than the outside air and the outside air is between 50° and 78°, the cooling system shuts down, mechanical awning windows open in the upper clerestory bays utilizing the stack effect to exhaust air from the building and manual ventilation lights change from red to green indicating to the occupants that it is acceptable to open windows.

The rest of the time, the system uses under floor air distribution to keep air flow and fan energy low. The system utilizes manual floor diffusers and stale return air and exhaust fans in the ceiling. When possible, this system runs on outside air. When necessary, air is conditioned through heat exchange with chilled and hot water loops. Hot water is provided to the system at 180° from a boiler system and hot air is provided mostly to the exterior zones. Cold water is supplied by an evaporative cooling chiller. During peak demand periods, chilled water is provided by ice made overnight. The setpoint temperature is achieved by mixing chilled air with outside air (via control of the outside air damper). The outside air damper is also modulated to control CO_2 levels in the space.

Learn more

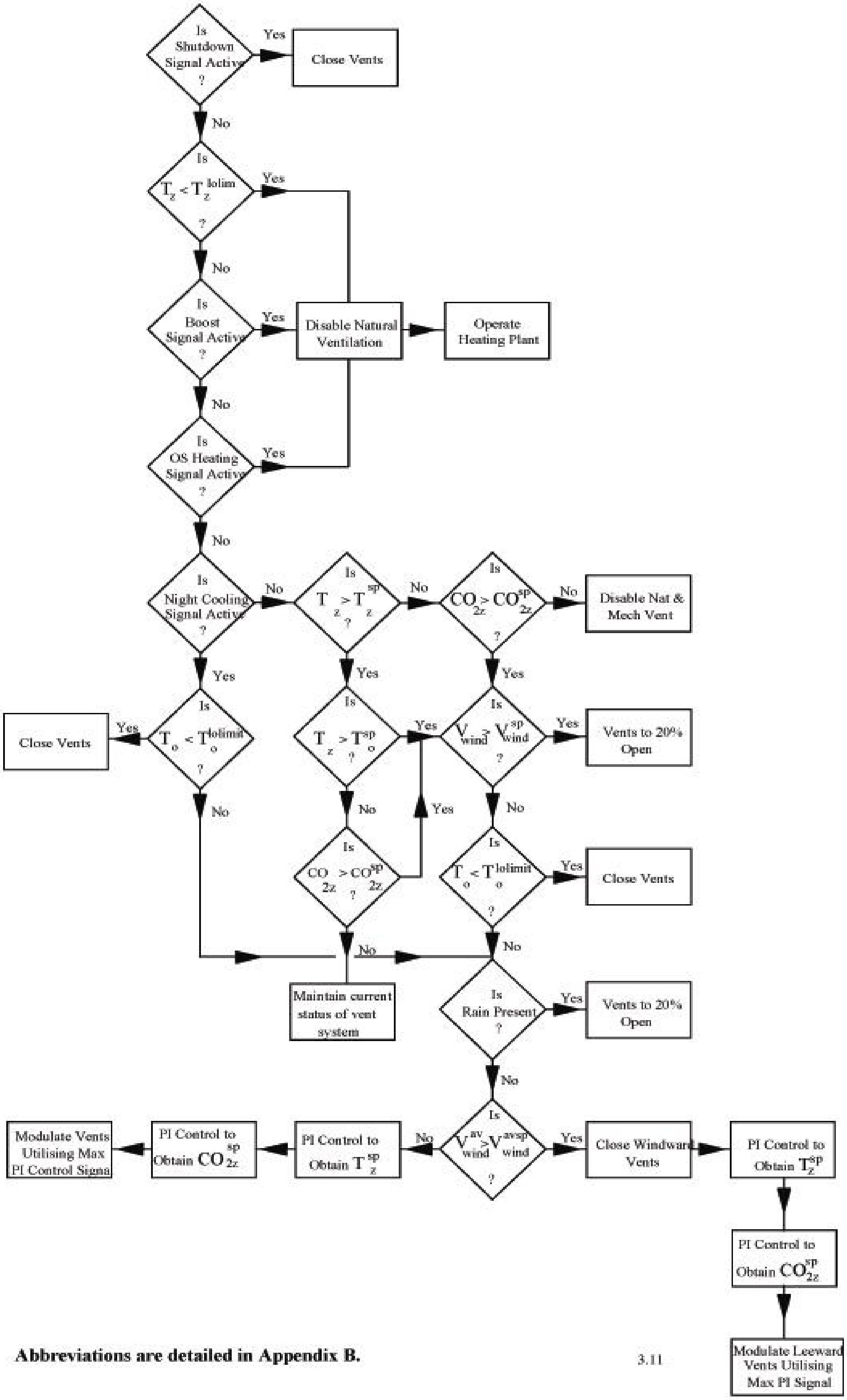
http://www.cbe.berkeley.edu/mixedmode/wfhewlett.html CBE mixed-mode case study.

http://www.hewlett.org/More/Foundation+Headquarters/ Hewlett foundation overview.

7. CONTROL ALGORITHM STUDIES

The format of the control sequence information we collected varied considerably, ranging from narrative descriptions, bulleted text, equations, and diagrams. The figure on the next page presents a generic control sequence flowchart representing the kinds of input and modifier signals that might be used to control the building in response to heating needs, daytime comfort control, or nighttime cooling (Martin 1998). The real world examples that follow come from our correspondence with building researchers, architects and engineers. They represent the diversity of control complexity, mechanical systems, and documentation style we've seen involved in mixed-mode ventilation. However, the algorithms as collected were not ideally suited to our task of distilling down the conceptual essence of control strategies and control complexity. They proved difficult to obtain for our desired set of case study buildings and their applicability to their site conditions remains subject to interpretation.

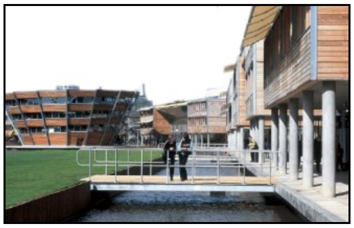
All that being said, these real world algorithms provide a valuable glimpse at the control strategies being deployed by leading edge mixed-mode buildings and begin to hint that we may be able to develop a library of standard mixed-mode control algorithms.



Abbreviations are detailed in Appendix B.

Example Control Sequence for a Mixed-Mode Building
(Source: Martin 1998)

7.1 UNIVERSITY OF NOTTINGHAM JUBILEE CAMPUS, UK



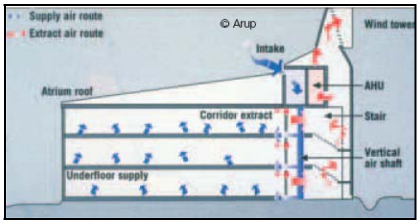


Image: McConahey, Arup

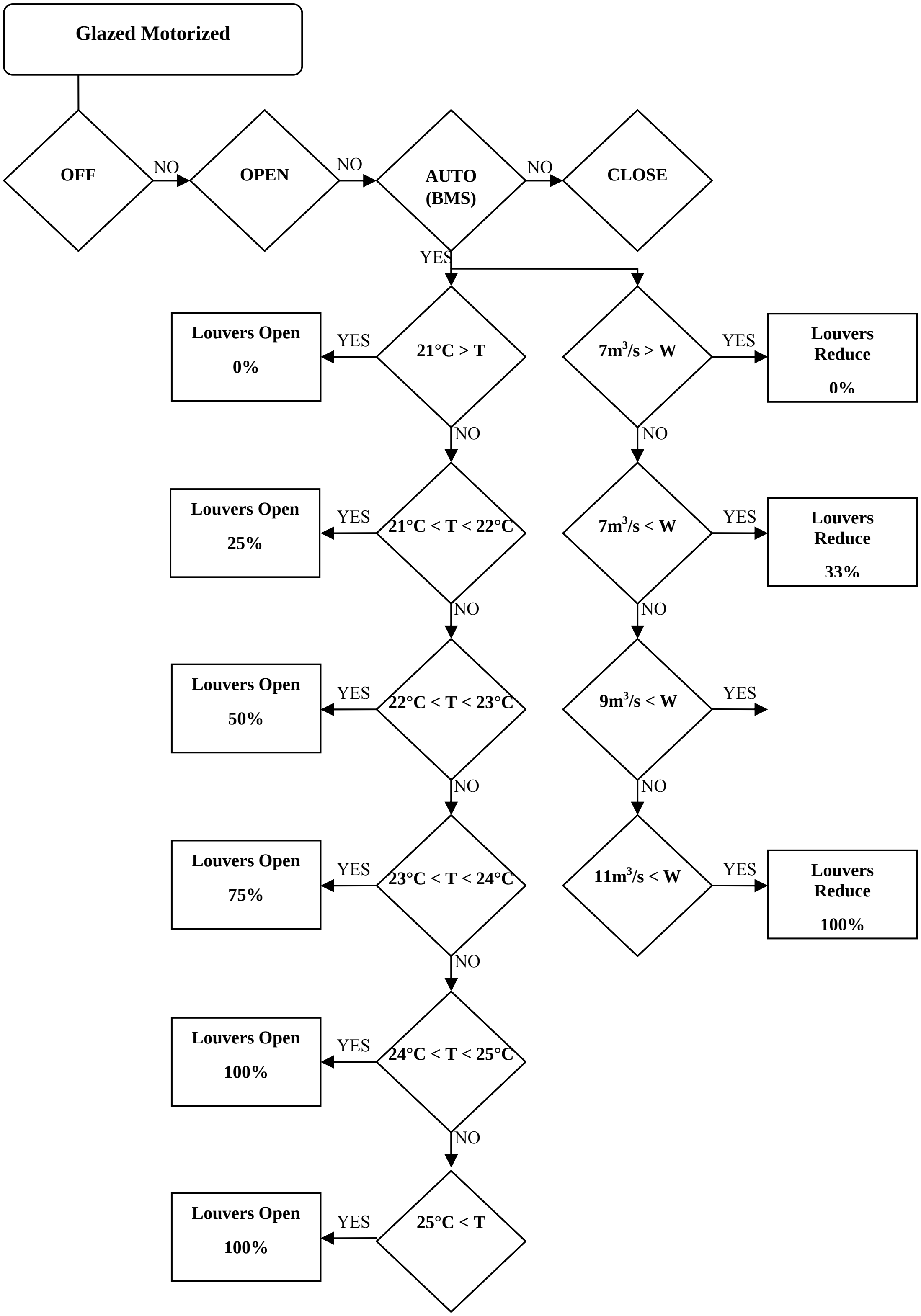
This school in the UK was designed by architect Michael Hopkins, with Arup as the engineer. It was completed in 2002, and can best be characterized as a changeover strategy. It relies heavily on stack ventilation through a tall atrium and wind tower. For this building, air flow is controlled by increasing the size of the openings at the top of the atrium in response to rising temperatures. Wind speed then serves as a modifier variable, where the openings might be reduced in increments as the wind speeds get too high for a certain duration.

(Control algorithm next page)

Learn more

Detailed pdf describing the campus.

http://www.caa.uidaho.edu/arch504ukgreenarch/CaseStudies/JubileeCampus2.pdf


Glazed Motorized
OFF
NO
OPEN
NO
AUTO (BMS)
NO
CLOSE
YES
Louvers Open 0%
YES
21°C > T
NO
$7m^3/s > W$
YES
Louvers Reduce 0%
NO
Louvers Open 25%
YES
21°C < T < 22°C
NO
$7m^3/s < W$
YES
Louvers Reduce 33%
NO
Louvers Open 50%
YES
22°C < T < 23°C
NO
$9m^3/s < W$
YES
NO
Louvers Open 75%
YES
23°C < T < 24°C
NO
$11m^3/s < W$
YES
Louvers Reduce 100%
Louvers Open 100%
YES
24°C < T < 25°C
NO
Louvers Open 100%
YES
25°C < T

7.2 WATERLAND SCHOOL, NETHERLANDS

(Source: Van der Aa, 2002)

The building is located at a new housing estate near The Hague. The school building consists of 6 separate school buildings, a day nursery, a gymnasium and a central meeting place. The design task was to develop a low energy concept with a reduction of 20% compared to the Dutch building regulations, a good indoor air quality and thermal comfort. This building is an example of hybrid ventilation (operable windows with mechanical ventilation, but no mechanical cooling). The ventilation set point is based on measurements of CO_2 and temperature. The central control system uses the algorithms shown on the next page to control air inlets and fans, based on separate winter and summer conditions. The inlet grills on the façade are electronically controlled, while the windows are entirely manually controlled by the users.

Winter

During day control on IAQ, local control per classroom:

7. If $CO_2 > 700$ ppm: Inlet grill 1 is opened

8. If $CO_2 > 1000$ ppm: Inlet grill 2 is opened

9. If $CO_2 > 1300$ ppm: Fan is switched on

During night inlet grills are close (CO_2 concentration < 650ppm)

Summer

During day control on IAQ, local control per classroom:

1. If > 700 ppm: Inlet grill 1 and 2 are opened

2. If > 1300 ppm: Fan is switched on

During night grills open, based on central controlled night cooling as long as:

1. $T_{internal} \geq T_{external} + 2°C$

2. $T_{external} > 15°C$

3. $T_{internal} > 20°C$

Learn more

http://www.hybridventilation.dk/pdf/CS13%20Waterland.pdf

http://www.hybridventilation.dk/buildings.asp?cat=4&cn=Schools&id=62

http://www.hybridventilation.dk/pdf/TP124.PDF HybVent technical paper on ventilation strategy.

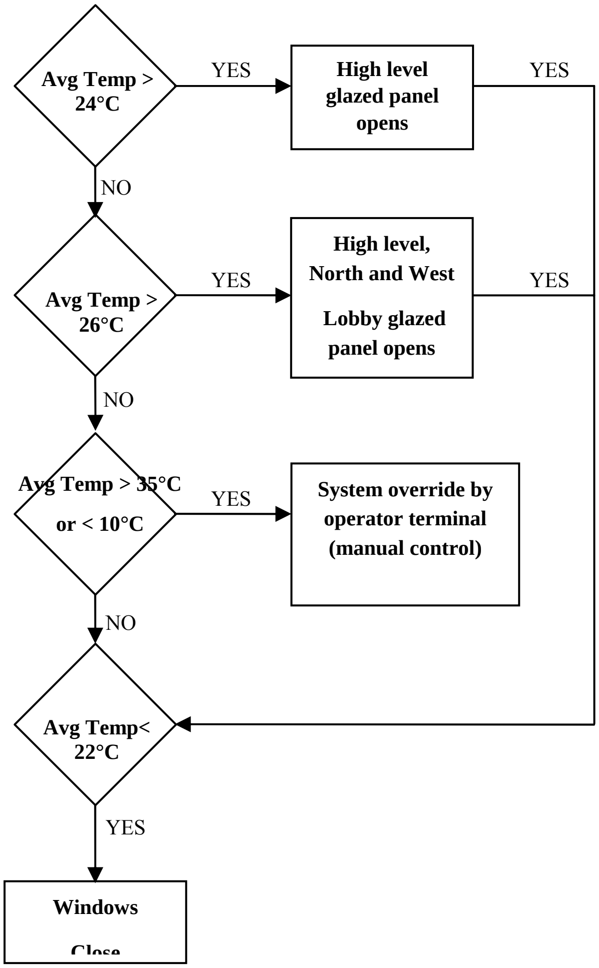
7.3 SCOTTISH PARLIAMENTARY BUILDING, UK

Image: GNU Licensed (From Wikipedia)

Image: Public Domain (Wikipedia)

Image: Andrew Gainer via Wikipedia

The building is located in Edinburgh, UK and was designed by a collaboration of two architectural firms, EMBT and RMJM – the lead architect was Enric Miralles. Other members of the design team are Ove Arup and Partners and RMJM Scotland Limited, and are responsible for structural, mechanical, and electrical engineering services. The building employs changeover ventilation in the atrium spaces.



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7.4 ZOOMAZIUM, WOODLAND PARK ZOO, SEATTLE

(Source: Allan Montpellier, Flack + Kurtz)

Situated in Seattle, the Zoomazium is the first of its kind: a purpose-built indoor/outdoor nature play space in the heart of a naturalistic zoo. Taking full advantage of its surroundings, it incorporates "green" design throughout. Zoomazium utilizes energy-efficient lighting and natural heating/cooling systems; a vegetated roof system; sustainable materials, green solar screens, and recycled content materials. The building is designed by Mithun architect, with Flack+ Kurtz as mechanical/plumbing/fire projection engineering services.

The system features a night flush mode between 1 and 4am that flushes the building if the outdoor temperature is below 72° and the indoor temperature is over 70°.

Indicator lights provide visual cues for the operation of the windows. When the OAT is between 60° and 76°, the system turns on the green light. Otherwise, the amber light is on.

Ventilation is controlled by CO_2 level. Internal levels maintained at 700 PPM or less above outside air. The ACU is disabled between 66° and 76°. When the building is in occupied mode and the ACU is disabled, motorized operable windows are automatically opened. ACU set point is 78° for cooling. When the temperature drops below 70°, heat pumps are operated to maintain a 72° set point. For both heating and cooling, conditioned air is delivered through an under floor plenum.

Learn more

Official website: http://www.zoo.org/zoomazium/inside.html

8. NEXT STEPS

There still remain unanswered questions about how to optimize the design of a mixed-mode building. There is a critical need for easy-to-use design tools and regionally-based guidelines to help designers decide when and where unassisted natural ventilation can be used, the applicability of different types of mechanical cooling systems and control strategies, and the effect of building/system design and control on energy use and comfort.

The Center for the Built Environment, in collaboration with Lawrence Berkeley National Laboratory, was just awarded funding from the California Energy Commission's PIER-BERG[1] program to address this need. Using the EnergyPlus simulation program (whose capabilities will also be enhanced through this research), the project will quantify the energy savings potential of different natural ventilation and mixed mode operational strategies across California's 16 climate zones (note that we are actively pursuing additional funding at the national level to extend this analysis to various U.S. climates). We will present the findings in easily-interpreted graphical formats that can be used directly by designers, building owners, utility program planners, and CEC policy-makers and consultants revising Title 24. The analysis will be based on both new construction and renovated buildings, and special attention will be paid to radiant slab cooling, which is particularly advantageous for concurrent mixed-mode systems.

The classification system and case study control algorithms developed in this project will directly support this new effort. Simulations will utilize "reality-based" best practice building prototypes and control algorithms, identified from this current project, as the basis for modeling operational control sequences. By starting with buildings that have already demonstrated superior performance in their own climate context, we will then move those buildings to different climates, making modifications as needed, to determine optimized design characteristics and climatic limits of applicability. This 18-month project should be complete by April 2009.

In addition to this new project we are about to embark on, to evaluate the energy savings potential for mixed-mode buildings in different climate zones, there is a need for more widespread research and education before we can fully realize the energy-efficiency and comfort benefits from this promising design strategy. In particular, we believe the following activities are needed:

- Further development of multi-zone, coupled energy and airflow simulation tools.
- Theoretical and experimental studies of airflow patterns and ventilation rates in buildings with operable windows (with and without mechanical ventilation or cooling).
- Theoretical and experimental studies of building control algorithms to optimize both comfort and energy.
- Detailed field studies that combine subjective surveys with field measurements of thermal conditions, IAQ, and ventilation levels in mixed-mode buildings.
- Field studies to investigate the influence of personal control and natural ventilation on worker performance and associated financial implications.
- Widespread publication of case studies of existing mixed-mode buildings in both the architecture and engineering press
- Revisions of ASHRAE Standards 55, 62, and 90.1 to enable more alternative environmental control strategies

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[1] PIER = Public Interest Energy Research; BERG = Building Energy Research Grant

9. SUMMARY

It would be a mistake to think of a mixed-mode building as simply a conventional air-conditioned building where the windows open. A well designed naturally ventilated or mixed-mode building must incorporate other climate-responsive strategies that reduce cooling loads (which should be a primary energy-conserving strategy for all buildings). Shading will reduce solar heat gain, daylighting and associated dimming controls will reduce the internal heat gains associated with electric lighting, and thermal mass with nighttime ventilation can reduce both energy use and peak demand. Even in an extreme climate, an integrated design solution will likely extend the times of the year when mechanical cooling can be avoided.

Close collaboration between the building owner and various members of the design team, early and throughout the design and construction process, is essential. All members need to be in agreement about the underlying environmental and performance-based goals of the project, and be willing to challenge conventional design assumptions in order to realize those goals. Integrated design requires an integrated design process – again something that should ideally happen in all buildings, but is essential in high-performance buildings.

There are implications for mixed-mode design and controls at the earliest programming stages of a building, and that is where the discussion must begin. The spatial organization of mixed-mode strategies tends to follow the spatial programmatic requirements of a building, so this needs to be part of the early conversations. Although engineers of mechanical cooling systems are used to looking at temperature and humidity data early in their design, the design team needs to add wind resource availability to the list, since that can influence spatial organization of the mixed-mode zones as well. Design temperatures are often considered sufficient for sizing mechanical systems, but more detailed, dynamic climate patterns will need to be evaluated for mixed-mode design.

Also on the table for early discussion should be an understanding of occupants' expectations and desired level of engagement with the building. The operation of a mixed-mode building is complex, and requires somewhat of a paradigm shift from the "centralized control" way of thinking. Ideally, operation should allow for natural ventilation as much as possible, and encourage maximum occupant control of the windows to realize the benefits of adaptive comfort opportunities. When there is shared control of the windows, such as in open plan offices, workers need to develop a "good neighbor policy" so that they are sensitive to the effect of the open window on others, recognizing that people's personal preferences may differ. This is not unlike several people in a zone having to share a thermostat.

When the air-conditioning is used, it should be the supplemental, not primary, form of control to keep thermal conditions from rising above the adaptive comfort zone. To ensure that a building is being operated as designed, it is essential that all occupants of the buildings –the facility manager, maintenance staff, and workers – be educated about how the building is designed to interact with the climate, and what the occupants can to do optimize their own comfort while being sensitive to other people's desires and larger concerns such as energy efficiency. The adage "passive buildings require active occupants" is especially true for mixed-mode buildings.

We recognize that mixed-mode design is complex and not necessarily a universal solution to society's critical need to reduce energy use and associated greenhouse gas emissions. We acknowledge that there remain several limitations or challenges to overcome before this approach can realize its full potential. These include site-specific limits of applicability (climate, load capacity, poor air quality), lack of predictability (thermal conditions and ventilation rates), environmental tradeoffs (noise, security, cleanliness), building codes (energy, ventilation, thermal comfort, fire & smoke control), unfamiliarity (lack of design tools), and potentially higher first costs (redundant systems).

But we also believe that the potential benefits of mixed mode buildings – designed properly when and where it makes sense – are significant enough that the challenges above are worth overcoming. The benefits will include reduced energy consumption, reduced CO_2 emissions, improved occupant comfort, improved indoor air quality and occupant health, greater degrees of personal control, connection to the natural environment, and lower operating costs.

It is our hope that this project will provide building owners, designers, and engineers with an improved understanding of the range of ways that mixed-mode buildings work in practice, so they can more easily realize mixed-mode strategies appropriate to their program, site conditions, and design goals.

APPENDIX A: HIGH LEVEL CASE STUDIES

A.1 ASH CREEK INTERMEDIATE SCHOOL

Image: Better Bricks Profile

Image: Better Bricks Profile

Image: Better Bricks Profile

Location: Monmouth, OR

Architect: BOORA Architects, Inc.

Engineer: EESI,Systems West Engineers, Eugene (commissioning)

Year built: 2002

Program: K-12

Climate: 4C(Mixed – Marine)

Control complexity: Manual

Mixed-mode strategies at a glance

Classification		
Changeover	Concurrent	Zoned
	X	X

HVAC				
GSHP	Panel	Slab	UFAD	Forced Air
	X			X

Controls			
Red/Green notification	Window HVAC interlock	Mechanical window operation	Manual window operation
			X

Ventilation			
Windows	Vents	Stack	Cross Vent
X	X	X	

System summary

Operable windows with ceiling roof vents; radiant panel re-heat; some zoned AC.

Learn more

http://www.betterbricks.com/default.aspx?pid=casestudy&casestudyid=6&sectionname=overview

http://www.oregon.gov/ENERGY/CONS/school/docs/ashcreek.PDF

A.2 BIGHORN HOME IMPROVEMENT CENTER


Image: Jim Yost

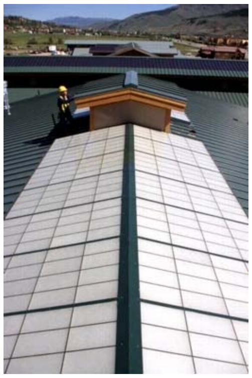


Image: NREL HPBD


Image: NREL HPBD

Location:	Silverthorne, CO		
Architect:	Marketplace Architects	**Engineer:**	M-E Engineers, Inc.
Year built:	2000	**Program:**	Retail
Climate:	7(Very Cold)	**Control complexity:**	Simple automated

Mixed-mode strategies at a glance

Classification		
Changeover	Concurrent	Zoned
	X	X

HVAC				
GSHP	Panel	Slab	UFAD	Forced Air
		X		X (warehous only)

Controls			
Red/Green notification	Window HVAC interlock	Mechanical window operation	Manual window operation
		X	X

Ventilation			
Windows	Vents	Stack	Cross Vent
X		X	

System summary

Gas-fired boilers for hydronic in-floor slab radiant heat; Clerestory windows, triggered by CO2 levels and/or cooling setpoint, open to vent stale air. A stack ventilation effect when lower windows and doors are opened. Ceiling fans to mix stratified air.

Learn more

http://www.eere.energy.gov/buildings/database/overview.cfm?ProjectID=54 NREL High Performance Buildings Database entry.

Performance overview: http://www.eere.energy.gov/buildings/info/documents/pdfs/28545.pdf

Detailed energy case study: http://www.nrel.gov/docs/fy06osti/39533.pdf

A.3 BREN SCHOOL OF ENVIRONMENTAL MANAGEMENT

Image: © Timothy Hursley, courtesy of ZGF

Location:	Santa Barbara, CA		
Architect:	Zimmer Gunsul Frasca Partnership	**Engineer:**	Flack+Kurtz,
Year built:	2002	**Program:**	Academic
Climate:	3C(Warm – Marine)	**Control complexity:**	Manual offices; automated labs

Mixed-mode strategies at a glance

Classification		
Changeover	Concurrent	Zoned
		X

HVAC				
GSHP	Panel	Slab	UFAD	Forced Air
				X (lab space)

Controls			
Red/Green notification	Window HVAC interlock	Mechanical window operation	Manual window operation
	X		X

Ventilation			
Windows	Vents	Stack	Cross Vent
X	X		

System summary

Zoned for lab space and office space; labs have shared chiller loop with other buildings on campus; entirely NV office space with heating interlock on windows and transomes.

Learn more

http://www.cbe.berkeley.edu/mixedmode/bren_hall.html CBE's mixed-mode case study of the Bren School.

http://www.bren.ucsb.edu/facilities/ UCSB site with basic overview of the Bren School building.

http://www.greatbuildings.com/buildings/UCSB_Bren_School.html excellent images of operable windows and the building in general.

A.4 CARNEGIE INSTITUTE CENTER FOR GLOBAL ECOLOGY

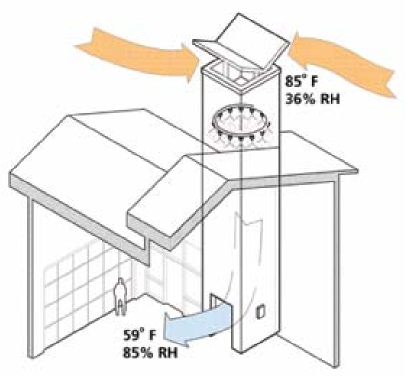


Image: EHDD Architecture

Image: EHDD Architecture

Image: Paul Sterbentz

Location:	Palo Alto, CA		
Architect:	Esherick Homsey Dodge & Davis	**Engineer:**	Rumsey Engineers,
Year built:	2004	**Program:**	Academic
Climate:	3C(Warm – Marine)	**Control complexity:**	Manual controls; complex ventilation system

Mixed-mode strategies at a glance

Classification		
Changeover	Concurrent	Zoned
	X	X

HVAC				
GSHP	Panel	Slab	UFAD	Forced Air
	X	X		X (lab space)

Controls			
Red/Green notification	Window HVAC interlock	Mechanical window operation	Manual window operation
			X

Ventilation			
Windows	Vents	Stack	Cross Vent
X		X	X

System summary

Zoned labs mostly open with only 2 fume hoods; Direct Evaporative Cooling tower with downdraft ventilation; radiant floors; radiant panel in conf room; night evap; lobby open to outside most of the year; building automation system takes information from thermostats, night sky cooling system, and the electric demand to optimize building operations.

Learn more

http://www.cbe.berkeley.edu/mixedmode/carnegie.html CBE mixed-mode case study

http://www.cbe.berkeley.edu/research/pdf_files/Weeks2007-CarnegieCaseStudy.pdf

http://www.aiatopten.org/hpb/overview.cfm?ProjectID=809 AIA COTE Top Ten Green Projects 2007

A.5 CHESAPEAKE BAY FOUNDATION MERRILL ENVIRONMENTAL CENTER


Image: SmithGroup/Prakash Patel


Image: SmithGroup/Prakash Patel


Image: SmithGroup/Prakash Patel

Location:	Annapolis, MD		
Architect:	SmithGroup, Inc.	**Engineer:**	SmithGroup, Inc.,
Year built:	2000	**Program:**	NGO
Climate:	4A(Mixed – Humid)	**Control complexity:**	Automated realtime changeover

Mixed-mode strategies at a glance

Classification		
Changeover	Concurrent	Zoned
X		

HVAC				
GSHP	Panel	Slab	UFAD	Forced Air
X				X

Controls			
Red/Green notification	Window HVAC interlock	Mechanical window operation	Manual window operation
X		X	X

Ventilation			
Windows	Vents	Stack	Cross Vent
X			X

System summary

GSHP for heating and cooling; desicant dehimidificaiton; operable windows with red/green lights; temp and humidity sensors used to turn off HVAC and control clerestory windows;designer's intent was to take advantage of winds that flow from south to north, but winds in the area tend to flow from the northwest when outdoor conditions are good for natural ventilation. See NREL report for detailed energy analysis, including ventilation. First LEED Platinum building.

Learn more

http://www.cbe.berkeley.edu/mixedmode/chesapeake.html CBE mixed-mode case study

http://www.cbf.org/site/PageServer?pagename=about_sub_merrill_main Merrill Center overview from CBF website

http://link5.streamhoster.com/?u=cbfvideo&p=%2Fmerrillvideo.wmv&odaid=1843 "Growing Smart; Building Green"14 minute video on the building

A.6 CHICAGO CENTER FOR GREEN TECHNOLOGY


Image: © Farr Associates


Image: © Farr Associates


Image: © Farr Associates

Location:	Chicago, IL		
Architect:	Farr Associates	**Engineer:**	IBC Engineering
Year built:	2002	**Program:**	Public
Climate:	5A(Cool – Humid)	**Control complexity:**	BMS controls heat pump; windows are manual

Mixed-mode strategies at a glance

Classification		
Changeover	Concurrent	Zoned
	X	

HVAC				
GSHP	Panel	Slab	UFAD	Forced Air
X				X

Controls			
Red/Green notification	Window HVAC interlock	Mechanical window operation	Manual window operation
			X

Ventilation			
Windows	Vents	Stack	Cross Vent
X			X

System summary

Renovation of a 1956 industrial buidling added a mechanical cooling system; ground source heat pump for heating and cooling;

Learn more

http://www.cbe.berkeley.edu/mixedmode/ccgt.html CBE mixed-mode case study

http://leedcasestudies.usgbc.org/overview.cfm?ProjectID=97 LEED Platinum builing case study

http://www.aiatopten.org/hpb/overview.cfm?ProjectID=97 2003 AIA COTE Top Ten

A.7 CLACKAMAS HIGH SCHOOL

Image: Michael Mathers

Image: Better Bricks

Image: Better Bricks

Location:	Clackamas, OR		
Architect:	BOORA Architects, Inc.	**Engineer:**	CBG Consulting Engineers,Interface Engineering, Portland (commissioning)
Year built:	2002	**Program:**	K-12
Climate:	4C(Mixed – Marine)	**Control complexity:**	moderately complex;

Mixed-mode strategies at a glance

Classification		
Changeover	Concurrent	Zoned
	X	X

HVAC				
GSHP	Panel	Slab	UFAD	Forced Air
				X (year round spaces only)

Controls			
Red/Green notification	Window HVAC interlock	Mechanical window operation	Manual window operation
		X	X

Ventilation			
Windows	Vents	Stack	Cross Vent
X	X	X	

System summary

Mechanically tuned NV; AC for year round use areas; seasonal space is NV; controls monitor temperature, CO2, occupancy. LEED Silver.

Learn more

See Betterbricks profile: http://www.betterbricks.com/LiveFiles/12/495/SS__CS_ClackamasSchool_USGBC.pdf

And D.O.E. profile

http://www.eere.energy.gov/buildings/database/overview.cfm?projectid=196

A.8 GAP 901 CHERRY ST. BUILDING

Image: © 2006 David Lehrer

Image: © 2006 David Lehrer

Location:	San Bruno, CA		
Architect:	William McDonough and Partners/Gensler, San Francisco	**Engineer:**	Ove Arup and Partners (San Francisco)
Year built:	1997	**Program:**	Commercial
Climate:	3C(Warm – Marine)	**Control complexity:**	Manual windows; moderately complex controls

Mixed-mode strategies at a glance

Classification		
Changeover	Concurrent	Zoned
	X	

HVAC				
GSHP	Panel	Slab	UFAD	Forced Air
		X(passive)	X	X

Controls			
Red/Green notification	Window HVAC interlock	Mechanical window operation	Manual window operation
			X

Ventilation			
Windows	Vents	Stack	Cross Vent
X			

System summary

Cool nighttime temperatures captured in UFAD system and released during the day; operable windows; high exhause vents minimize conflicts from concurrent operation.

Learn more

http://www.cbe.berkeley.edu/mixedmode/gap.html CBE mixed-mode case study

A.9 GILMAN ORDWAY BUILDING AT WOODS HOLE

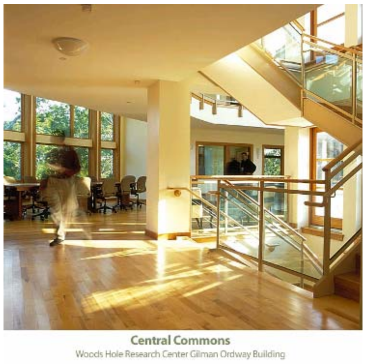


Image: © Judy Watts Wilson

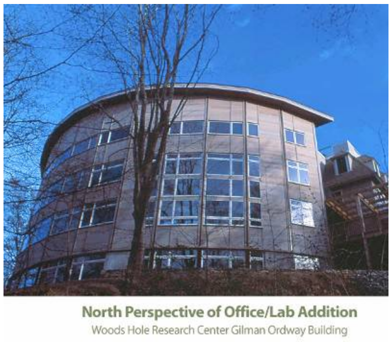


Image: © Alan Orling

Image: © Judy Watts Wilson

Location:	Falmouth, MA		
Architect:	William McDonough and Partners	**Engineer:**	2rw Consulting Engineers
Year built:	2003	**Program:**	Office/Laboratory
Climate:	5A(Cool – Humid)	**Control complexity:**	Complex controls

Mixed-mode strategies at a glance

Classification		
Changeover	Concurrent	Zoned
	X	X

HVAC				
GSHP	Panel	Slab	UFAD	Forced Air
X	X			X

Controls			
Red/Green notification	Window HVAC interlock	Mechanical window operation	Manual window operation
			X

Ventilation			
Windows	Vents	Stack	Cross Vent
X			

System summary

zoned lab space; enthalpy wheels; GSHP with ceiling valence convectors for heating and cooling; operable office windows, code minimum fresh-air ventilation systems, and user-controlled temperature.

Learn more

http://www.aiatopten.org/hpb/overview.cfm?ProjectID=257 AIA COTE Top Ten 2004

A.10 JEAN VOLLUM NATURAL CAPITAL CENTER


Image: Interface

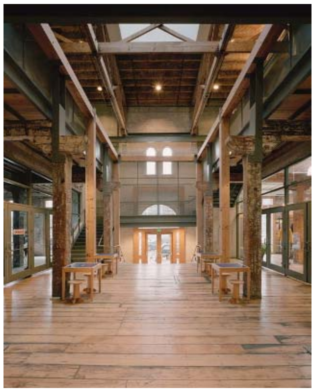


Image: Ecotrust


Image: Ecotrust

Location: Portland, OR

Architect: Holst Architecture

Engineer: Interface Engineering

Year built: 2001

Program: Commercial

Climate: 4C(Mixed – Marine)

Control complexity: Moderately complex

Mixed-mode strategies at a glance

Classification		
Changeover	Concurrent	Zoned

HVAC				
GSHP	Panel	Slab	UFAD	Forced Air
				X

Controls			
Red/Green notification	Window HVAC interlock	Mechanical window operation	Manual window operation
	X		X

Ventilation			
Windows	Vents	Stack	Cross Vent
X			

System summary

Warehouse renovation; Rooftop VAV units; Occupancy sensors reduce HVAC use when vacant; window lockouts on HVAC; CO2 sensors control ventilation rates.

Learn more

http://www.ecotrust.org/ncc/NCC_Fact_Sheet.pdf

https://www.usgbc.org/chapters/cascadia/vollum.pdf LEED Gold USGBC case study

http://casestudies.cascadiagbc.org/overview.cfm?ProjectID=393

A.11 LEWIS CENTER FOR ENVIRONMENTAL STUDIES


Image: Robb Williamson


Image: Robb Williamson


Image: Robb Williamson

Location:	Oberlin, OH		
Architect:	McDonough	**Engineer:**	Lev Zetlin Associates
Year built:	2000	**Program:**	Academic
Climate:	5A(Cool – Humid)	**Control complexity:**	Complex automated controls

Mixed-mode strategies at a glance

Classification		
Changeover	Concurrent	Zoned

HVAC				
GSHP	Panel	Slab	UFAD	Forced Air
X		X		X

Controls			
Red/Green notification	Window HVAC interlock	Mechanical window operation	Manual window operation
		X	

Ventilation			
Windows	Vents	Stack	Cross Vent
X		X	

System summary

GSHP; Radiant floor and passive solar heating; decentralized HVAC; energy recovery ventilators; automatic windows in atrium and living machine room use stack effect; operable windows in classrooms.

Learn more

http://www.oberlin.edu/ajlc/systems_hvac_1.html Lewis Center website has extensive energy monitoring system data.

http://www.eere.energy.gov/buildings/info/documents/pdfs/31516.pdf Brochure highlighting high performance

http://www.eere.energy.gov/buildings/database/energy.cfm?ProjectID=18 High performance building database entry

http://www.nrel.gov/docs/fy05osti/33180.pdf detailed NREL energy performance study

A.12 NATURAL RESOURCES DEFENSE COUNCIL

Image: © Timothy Street-Porter

Image: © Timothy Street-Porter

Image: © Timothy Street-Porter

Location:	Santa Monica, CA		
Architect:	Moule & Polyzoides	**Engineer:**	Syska Hennessy Group
Year built:	2003	**Program:**	Institutional
Climate:	3B(Warm – Dry)	**Control complexity:**	Moderately complex

Mixed-mode strategies at a glance

Classification		
Changeover	Concurrent	Zoned
X		X

HVAC				
GSHP	Panel	Slab	UFAD	Forced Air
			X	X

Controls			
Red/Green notification	Window HVAC interlock	Mechanical window operation	Manual window operation
	X		X

Ventilation			
Windows	Vents	Stack	Cross Vent
X			

System summary

Zoned with NV only in many spaces; operable windows, transomes, and rooftop louvers and fans assist; in spaces that have it, MV is displacement and interlocked to windows. LEED Platinum.

Learn more

http://www.cbe.berkeley.edu/mixedmode/nrdc.html CBE mixed-mode case study.

http://www.nrdc.org/buildinggreen/casestudies/nrdcsm.pdf NRDC's case study.

http://leedcasestudies.usgbc.org/overview.cfm?ProjectID=236 USGBC's case study

A.13 OHSU CENTER FOR HEALTH AND HEALING


Image: Brightworks

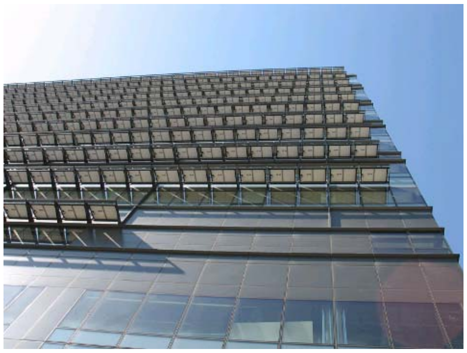


Image: AIA


Image: AIA

Location:	Portland, OR		
Architect:	GBD Architects	**Engineer:**	Interface Engineering, Inc.
Year built:	2006	**Program:**	Medical
Climate:	4C(Mixed – Marine)	**Control complexity:**	Moderately complex

Mixed-mode strategies at a glance

Classification		
Changeover	Concurrent	Zoned
		X

HVAC				
GSHP	Panel	Slab	UFAD	Forced Air
	X (beam)	X		X

Controls			
Red/Green notification	Window HVAC interlock	Mechanical window operation	Manual window operation
			X

Ventilation			
Windows	Vents	Stack	Cross Vent
X			

System summary

The 16-story Center for Health & Healing; 400,000 square feet of physician practices, outpatient surgery, a wellness center, research labs and educational space. On-site micro-turbine plant generates about 35 percent of the building's electricity; Natural ventilation in stairwells and lobby only; displacement ventilation; radiant cooling; and the first use of chilled beams to replace air-conditioning in a large building in the United States. CO2 controlled ventilation rates. The building is LEED Platinum and uses 60% less energy than ASHRAE 90.1. LEED Platinum.

Learn more

http://www.ohsu.edu/ohsuedu/about/transformation/commons/earthfriendly.cfm Brief overview by OHSU.themselves

http://www.nrdc.org/buildinggreen/casestudies/ohsu.pdf NRDC building profile.

http://www.aia.org/aiarchitect/thisweek07/0330/0330d_oreg.cfm AIA article.

http://www.brightworks.net/eventdetail.php?type=news&id=17 Brightworks (green building consultant) documentation.

A.14 PENNSYLVANIA DEP CAMBRIA OFFICE BUILDING

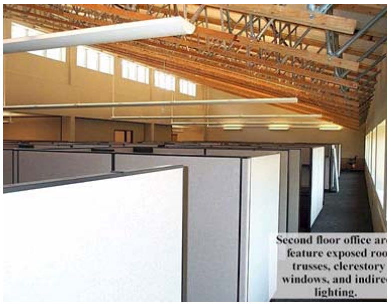


Image: PA Governor's Green Government Council

Image: PA Governor's Green Government Council

Image: PA Governor's Green Government Council

Location:	Ebensburg, PA		
Architect:	Kulp Boecker Architects, P.C.	**Engineer:**	Phoenix Geothermal Services
Year built:	2002	**Program:**	Commercial
Climate:	5A(Cool – Humid)	**Control complexity:**	User

Mixed-mode strategies at a glance

Classification		
Changeover	Concurrent	Zoned
	X	

HVAC				
GSHP	Panel	Slab	UFAD	Forced Air
X			X	X

Controls			
Red/Green notification	Window HVAC interlock	Mechanical window operation	Manual window operation
			X

Ventilation			
Windows	Vents	Stack	Cross Vent
X			

System summary

GSHP to UFAD system; operable windows; enthalpy wheel; individually controlled diffusers. LEED Gold.

Learn more

http://www.eere.energy.gov/buildings/info/documents/pdfs/29941.pdf US DOE highlighting high performance brochure

http://www.gggc.state.pa.us/gggc/lib/gggc/documents/cambriacasestudy.pdf US DOE high performance building write up.

A.15 SAN MATEO COUNTY FORENSICS LAB


Image: Cesar Rubio


Image: Cesar Rubio


Image: Cesar Rubio

Location: San Mateo, CA

Architect: HOK

Engineer: HOK

Year built: 2003

Program: Public

Climate: 3C(Warm – Marine)

Control complexity: Moderately complex; Window interlock system

Mixed-mode strategies at a glance

Classification		
Changeover	Concurrent	Zoned
		X

HVAC				
GSHP	Panel	Slab	UFAD	Forced Air
				X

Controls			
Red/Green notification	Window HVAC interlock	Mechanical window operation	Manual window operation
	X		X

Ventilation			
Windows	Vents	Stack	Cross Vent
X			

System summary

Zoned labs; VAV HVAC in offices interlocked with windows.

Learn more

http://www.aiatopten.org/hpb/overview.cfm?ProjectID=194 AIA COTE Top Ten 2003

A.16 SCHLITZ AUDIBON CENTER

Image: Kubala Washatko Architects, Inc.

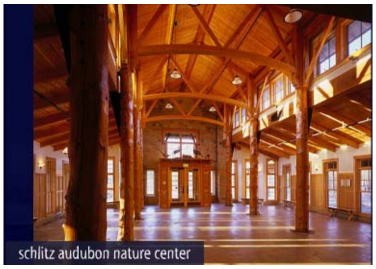


Image: Kubala Washatko Architects, Inc.

Image: Kubala Washatko Architects, Inc.

Location:	Milwaukee, WI		
Architect:	Kubala Washatko Architecture	**Engineer:**	Mike Utzinger
Year built:	2003	**Program:**	Nature Center
Climate:	6A(Cold – Humid)	**Control complexity:**	Moderately complex; window interlock system

Mixed-mode strategies at a glance

Classification		
Changeover	Concurrent	Zoned

HVAC				
GSHP	Panel	Slab	UFAD	Forced Air
X				X

Controls			
Red/Green notification	Window HVAC interlock	Mechanical window operation	Manual window operation
	X		X

Ventilation			
Windows	Vents	Stack	Cross Vent
X		X	

System summary

GSHP - water to air exchange; Operable windows; window interlock. LEED Gold. Was designed using the standard handbook of fundamentals and a spreadsheet. Every independent space has its own mechanical system. Contacts in window turn off local system through central Johnson Controls system. Even if they had not gone to natural ventilation, the system would have been designed with individual controls, so this was not specifically shaped by ventilation strategy.

Would now only do wireless window contacts. The wiring was a huge pain. Staff are happy with Schlitz, have been there 3 years.

Learn more

http://www.sanc.org/ogb.htm Green building biography

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

http://ceae.colorado.edu/ibpsa/ocs/viewpaper.php?id=216&cf=2

A.17 SEMINAR II BUILDING

Image: Lara Swimmer

Image: Lara Swimmer

Image: Lara Swimmer

Image: Lara Swimmer

Location:	Olympia, WA		
Architect:	Mahlum Architects, Seattle	**Engineer:**	Wood/Harbinger, Inc.
Year built:	2004	**Program:**	Academic
Climate:	4C(Mixed – Marine)	**Control complexity:**	Mostly user controls

Mixed-mode strategies at a glance

Classification		
Changeover	Concurrent	Zoned
	X	X

HVAC				
GSHP	Panel	Slab	UFAD	Forced Air
				X (meeting rooms)

Controls			
Red/Green notification	Window HVAC interlock	Mechanical window operation	Manual window operation
			X

Ventilation			
Windows	Vents	Stack	Cross Vent
X		X	

System summary

Zoned approach. 80% NV w/ stack; communal space on lower floor mechanically cooled; user controlled mechanical "trickle vents" to provide minimal ventilation to all space. Night ventilation with high mass walls. LEED Gold.

Learn more

http://www.aiatopten.org/hpb/overview.cfm?ProjectID=464 AIA COTE Top Ten 2005

http://www.betterbricks.com/LiveFiles/28/18/Seminar%20II.pdf Better Bricks profile

A.18 SIMMONS HALL, MIT

Image: ARUP Journal

Image: MIT / The Evolving Campus

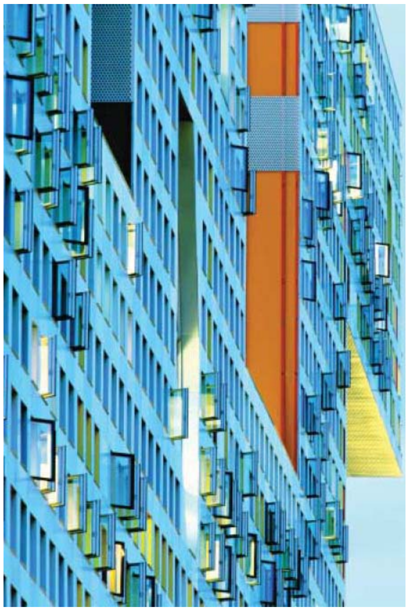


Image: ARUP Journal

Location:	Cambridge, MA		
Architect:	Steven Holl	**Engineer:**	Ove Arup and Partners
Year built:	2002	**Program:**	Housing
Climate:	5A(Cool – Humid)	**Control complexity:**	Moderately complex system

Mixed-mode strategies at a glance

Classification		
Changeover	Concurrent	Zoned
	X	

HVAC				
GSHP	Panel	Slab	UFAD	Forced Air

Controls			
Red/Green notification	Window HVAC interlock	Mechanical window operation	Manual window operation
			X

Ventilation			
Windows	Vents	Stack	Cross Vent
X			X

System summary

3000+ operable windows; less occupied during summer (lowers need for cooling); ARUP design looked at cross vent only, but had to resort to MM; each room has 9 operable windows, low and high for convective ventilation; low-volume ducted A/C system.

Learn more

http://www.arup.com/americas/project.cfm?pageid=596 ARUP overview (low detail)

http://alumni.imsa.edu/~falcon12/arup_simmons.pdf ARUP Journal writeup.

A.19 SMUD CUSTOMER SERVICE CENTER

Location: Sacramento, CA

Architect: Williams + Paddon

Engineer: Hensel Phelps,Robert Bein, William Frost, & Associates

Year built: 1996

Program: Office

Climate: 3B(Warm – Dry)

Control complexity: Moderately complex interlock system

Mixed-mode strategies at a glance

Classification		
Changeover	Concurrent	Zoned
X		

HVAC				
GSHP	Panel	Slab	UFAD	Forced Air
			X	X

Controls			
Red/Green notification	Window HVAC interlock	Mechanical window operation	Manual window operation
	X		X

Ventilation			
Windows	Vents	Stack	Cross Vent
X			

System summary

Underfloor air; chiller; operable windows; designed to maintain slightly positive pressure to ensure exfiltration so that only conditioned air is supplied to the occupied space; operable windows are equipped with micro-switch sensors to reset operation of the adjoining VAV box to night setback mode (increase cooling and decrease heating setpoints) when windows are open.

Learn more

http://www.cbe.berkeley.edu/underfloorair/SMUD.htm#Building%20Design%20Features

A.20 UCLA KINSEY HALL AKA HUMANITIES BUILDING

Image: Wayne Bottomley

Image: Wayne Bottomley

Image: UCLA dept. of Physics

Location:	Los Angeles, CA		
Architect:	Timmons Design Engineers	**Engineer:**	Ove Arup and Partners
Year built:	2007	**Program:**	Academic
Climate:	3B(Warm – Dry)	**Control complexity:**	Moderately complex

Mixed-mode strategies at a glance

Classification		
Changeover	Concurrent	Zoned
	X	

HVAC				
GSHP	Panel	Slab	UFAD	Forced Air
		X	X	X

Controls			
Red/Green notification	Window HVAC interlock	Mechanical window operation	Manual window operation
			X

Ventilation			
Windows	Vents	Stack	Cross Vent
X			

System summary

Retrofit: entire HVAC system replaced with chilled ceiling system with mechanical (displacement) and natural ventilation.

Learn more

http://home.physics.ucla.edu/news/new_humanities_bldg/page1.html

A.21 ZION NATIONAL PARK VITOR'S CENTER

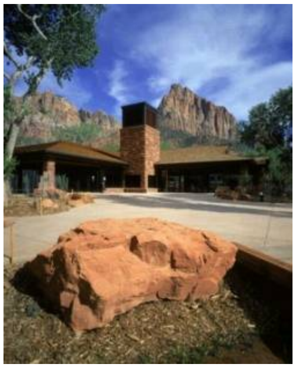


Image: Robb Williamson


Image: Thomas Wood

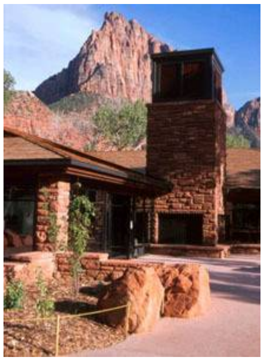


Image: Robb Williamson

Location: Zion National Park, UT

Architect: National Parks Service

Engineer: National Parks Service

Year built: 2000

Program: Nature Center

Climate: 5B(Cool – Dry)

Control complexity: Fairly simple system. Uses DDC.

Mixed-mode strategies at a glance

Classification		
Changeover	Concurrent	Zoned
	X (w/ heat panels)	

HVAC				
GSHP	Panel	Slab	UFAD	Forced Air
	X (heat)			

Controls			
Red/Green notification	Window HVAC interlock	Mechanical window operation	Manual window operation
			X

Ventilation			
Windows	Vents	Stack	Cross Vent
X		X (cool tower)	

System summary

Trombe walls; Electric radiant ceiling panels; Passive solar gains; Direct evaporative cooltowers with downdraft ventilation.

Learn more

See DOE case study

http://www.eere.energy.gov/buildings/database/overview.cfm?ProjectID=16

APPENDIX B: NOTES ON CLIMATE ZONES

Because site weather patterns are important drivers of natural ventilation and seasonal strategies for ventilation, mixed-mode strategies are sensitive to climatic conditions. Whereas most building related climate data is used to determine HDDs and CDDs only, more specific weather data, including temperature extremes, humidity data, and prevailing and seasonal wind patterns, is necessary to properly design and operate mixed-mode buildings. Consequently the climate zones used by building codes and other prescriptive systems, are not likely to be detailed enough to provide conclusive guidance on mixed-mode strategies, but are too prevalent to be ignored.

For example, the best energy consumption data generally available at a national level, the Commercial Building Energy Consumption Survey (CBECS) uses a 5 zone system (derived from NOAA data) as seen below. There are many simulation-based approaches to building energy modeling that use this 5 zone model so that energy simulation data can be calibrated to real world consumption data.

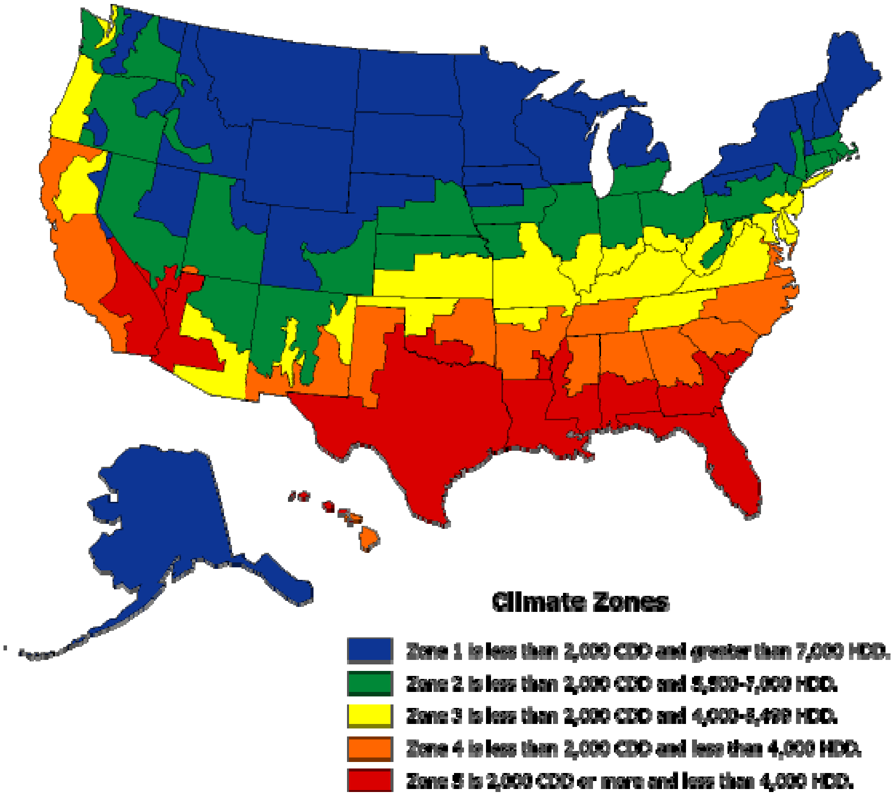


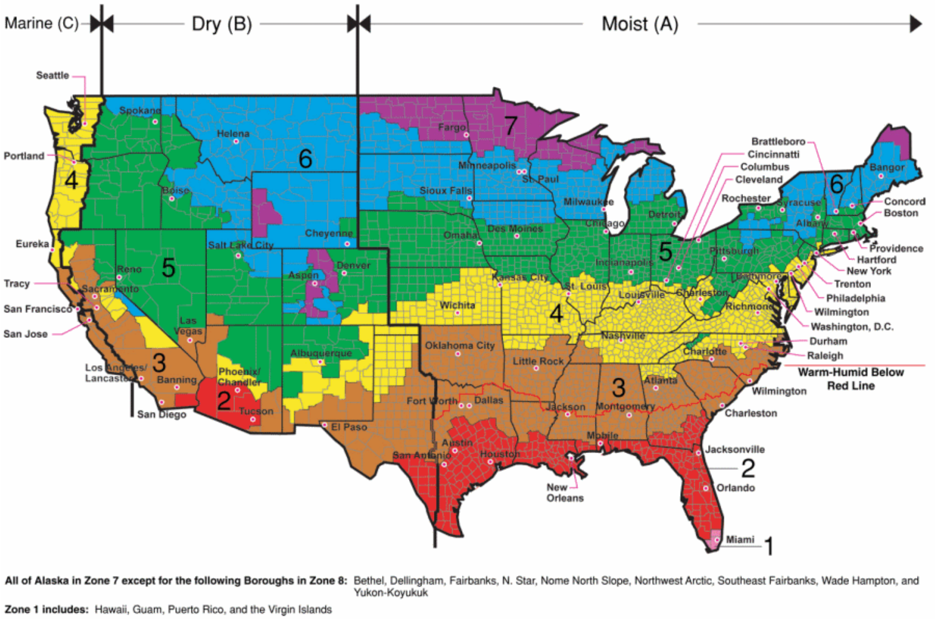
Figure B.1: CBECS 5 climate zones.

As another example, since 2004 the IECC building code and ASHRAE 90 have converged on an 8 zone model developed at PNNL (see http://www.energycodes.gov/implement/pdfs/climate_paper_review_draft_rev.pdf) specifically for building energy codes and standards. The IECC for example made a calculated move away from a more complex 19 zone system to the PNNL model, which is more compatible with political boundaries and the practical concerns of prescriptive building codes. These changes are introduced this way on the DOE website (http://www.energycodes.gov/implement/doe_2004_proposals.stm):

> "The new code defines climate zones geographically rather than climatically, reducing their number to only eight. (The previous code had 19 climate zones defined by degree day ranges.) Compliance and enforcement will be simpler because the new climate zones honor political boundaries, such as state and county lines and

> attempt to keep metropolitan areas together. The redefined climate zones also do a better job of integrating cooling considerations into the code - a key improvement given that air conditioning is a rapidly growing residential load."

The climate zones can be seen below (note that zone 8 is only found in AK, and zone 1 is mostly found in HI and tropical protectorates). See also Building Science Consulting's discussion of Hygro-Thermal regions (http://www.buildingscienceconsulting.com/designsthatwork/hygro-thermal.htm).



All of Alaska in Zone 7 except for the following Boroughs in Zone 8: Bethel, Dellingham, Fairbanks, N. Star, Nome North Slope, Northwest Arctic, Southeast Fairbanks, Wade Hampton, and Yukon-Koyukuk

Zone 1 includes: Hawaii, Guam, Puerto Rico, and the Virgin Islands

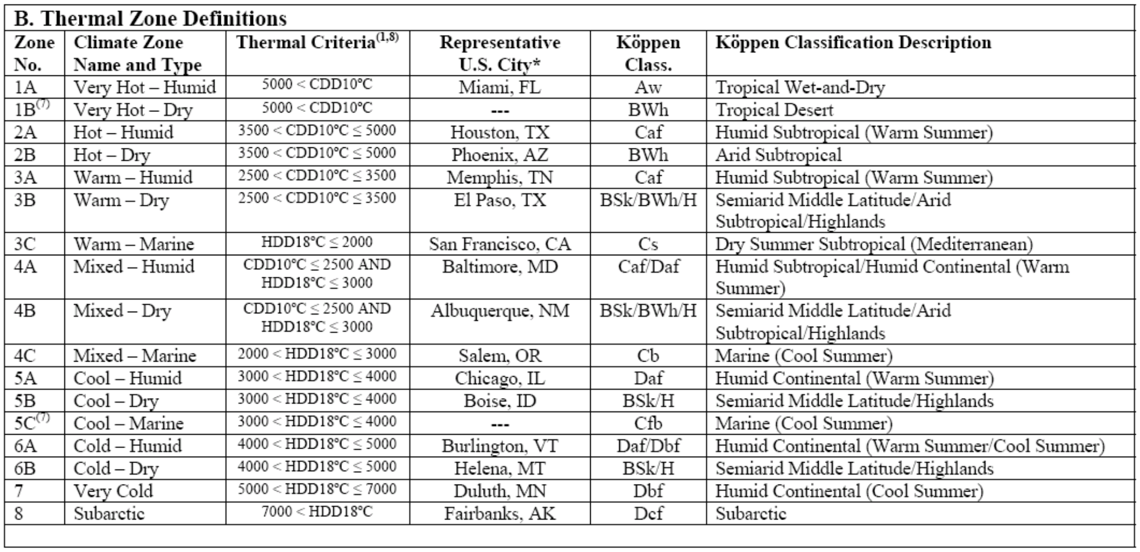
Figure B.2: IECC/90.1/DOE climate zones.

However, for their part, NOAA actually recognizes 359 climate divisions shown below (identified by number within each state).

Figure B.3: NOAA climate divisions (source http://www.cdc.noaa.gov/usclimate/map.html)

It is clear that a more sophisticated climate zoning system than the ones used by CBECS, ASHRAE, or the IECC may be appropriate when undertaking detailed study of mixed-mode buildings. However, there are practical concerns at work in mixed-mode buildings as well. One of the key elements to a successful and robust system will be flexibility. If its design tolerances are too narrow, it is likely to suffer from performance issues when weather inevitably (if occasionally) deviates from the norm. Also, in many areas, site local weather variations are likely to be greater than the averaged climate zone variations. Consequently, an open research question that we hope to address through ongoing funded research (using Energy Plus simulation) is what regional variations in building performance and optimal mixed-mode systems and controls we should expect with variations in climate. For the purposes of this current work, and with full awareness of its potential limitations, we have opted to use the standard DOE climate zones (8 of them).

Drawing on the work from PNNL, we will be using the following climate zone definitions, which are compatible with those used by ASHRAE 90.1 2004 and the IECC:



B. Thermal Zone Definitions

Zone No.	Climate Zone Name and Type	Thermal Criteria(1,8)	Representative U.S. City*	Köppen Class.	Köppen Classification Description
1A	Very Hot – Humid	5000 < CDD10°C	Miami, FL	Aw	Tropical Wet-and-Dry
1B(7)	Very Hot – Dry	5000 < CDD10°C	---	BWh	Tropical Desert
2A	Hot – Humid	3500 < CDD10°C ≤ 5000	Houston, TX	Caf	Humid Subtropical (Warm Summer)
2B	Hot – Dry	3500 < CDD10°C ≤ 5000	Phoenix, AZ	BWh	Arid Subtropical
3A	Warm – Humid	2500 < CDD10°C ≤ 3500	Memphis, TN	Caf	Humid Subtropical (Warm Summer)
3B	Warm – Dry	2500 < CDD10°C ≤ 3500	El Paso, TX	BSk/BWh/H	Semiarid Middle Latitude/Arid Subtropical/Highlands
3C	Warm – Marine	HDD18°C ≤ 2000	San Francisco, CA	Cs	Dry Summer Subtropical (Mediterranean)
4A	Mixed – Humid	CDD10°C ≤ 2500 AND HDD18°C ≤ 3000	Baltimore, MD	Caf/Daf	Humid Subtropical/Humid Continental (Warm Summer)
4B	Mixed – Dry	CDD10°C ≤ 2500 AND HDD18°C ≤ 3000	Albuquerque, NM	BSk/BWh/H	Semiarid Middle Latitude/Arid Subtropical/Highlands
4C	Mixed – Marine	2000 < HDD18°C ≤ 3000	Salem, OR	Cb	Marine (Cool Summer)
5A	Cool – Humid	3000 < HDD18°C ≤ 4000	Chicago, IL	Daf	Humid Continental (Warm Summer)
5B	Cool – Dry	3000 < HDD18°C ≤ 4000	Boise, ID	BSk/H	Semiarid Middle Latitude/Highlands
5C(7)	Cool – Marine	3000 < HDD18°C ≤ 4000	---	Cfb	Marine (Cool Summer)
6A	Cold – Humid	4000 < HDD18°C ≤ 5000	Burlington, VT	Daf/Dbf	Humid Continental (Warm Summer/Cool Summer)
6B	Cold – Dry	4000 < HDD18°C ≤ 5000	Helena, MT	BSk/H	Semiarid Middle Latitude/Highlands
7	Very Cold	5000 < HDD18°C ≤ 7000	Duluth, MN	Dbf	Humid Continental (Cool Summer)
8	Subarctic	7000 < HDD18°C	Fairbanks, AK	Dcf	Subarctic

Figure B.4: zone definitions used in this document developed by PNNL for the DOE and in use by ASHRAE 90.1 and IECC

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