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Unravelling the mix - towards effective simulation, implementation and operation of mixed mode buildings

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Abstract

Notwithstanding the immense potential to minimise a building's carbon footprint, there is a very low uptake of mixed mode systems. This paper addresses issues concerning mixed mode buildings in Australian climates that vary from mild to warm/hot climates. The paper documents issues and barriers to the proper functioning of mixed mode buildings based on projects that the authors have reviewed, surveyed or consulted upon. The impact of rating tools and guidelines, limitations in performance prediction, operational issues in practice and insights from post occupancy feedback are discussed from the perspective of mixed mode buildings. Delivering mixed mode buildings via the current commercial processes increases the risk of the design intent not being carried through to completion. The paper identifies a need for comfort guidelines explicitly developed for mixed mode building in contrast to prevailing frameworks for air-conditioned buildings and offers strategies for rethinking comfort, simulation, implementation and operation of mixed mode buildings.

Keywords: mixed-mode, comfort, guidelines, barriers, integrated design

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Introduction

Post occupancy studies of free running buildings and research into adaptive comfort indicates that occupants can tolerate significantly wider bands of temperature (and humidity) than conventionally defined as "comfortable" under a number of standards for comfort such as ISO 7730 and older versions of ASHRAE 55-R that continue to be applied to air-conditioned buildings across the globe. Previous research (Thomas, L. and Ballinger, 1997) has shown that there is the potential to design and comfortably operate office buildings in a naturally ventilated or "free running" mode for up to 80% of its operation in temperate climates such as Sydney. The research further concluded that the success of such buildings hinges on how the residual discomfort is managed for the occupants and suggested that these buildings could adopt a mixed mode or hybrid ventilation approach where by energy based heating and cooling is only provided at the times when conditions swing outside the nominated comfort range.

Many studies have shown that mixed mode building offer energy savings over conventional air-conditioned buildings, for example, in the US (Brager 2000), the UK (CIBSE, 2000) and Australia (Rowe, 2003) amongst other countries. Well designed and operated mixed mode buildings have also been documented to show improved comfort, productivity and air quality (Leaman and Bordass, 2001; Brager 2006 and Rowe 2003) over air-conditioned buildings. Recent European work on mixed mode buildings (Kalz, 2009) using Thermo-Active Building Systems (TABS) show good application in cool, dry climates, but may be less suited to the warmer, often humid climates that characterise many of Australia's population centres.

Lomas *et al* (2009) discuss the importance of undertaking simple, qualitative, pre-occupancy commissioning trials, the critical role of high quality, automated, window systems in maintaining thermal comfort and energy efficiency in advanced, naturally ventilated buildings, and the need to isolate mechanically vented areas from passively ventilated zones.

Notwithstanding the immense potential to minimise a building's carbon footprint, there is a very low uptake of mixed mode systems. This paper will review implemented projects, simulated results and monitored outcomes, and insights from mixed mode buildings in operation in an attempt to examine the successes, challenges and strategies for integrating a mixed mode approach for environmental control.

This paper addresses issues and barriers to the proper functioning of mixed mode buildings in mild and warm/hot Australian climates, based on a number of projects that the authors have reviewed, surveyed or consulted upon. Insights from four mixed mode projects are presented in the paper, three of which have been reported upon previously. They will be referred to as Buildings A through C. The fourth project, Building D, will be reported in detail in the public domain in the near future, although a number of commercial-in-confidence reports have already been developed.

While the paper discusses the issues and barriers that affect the uptake of mixed mode buildings in Australia, the authors are passionate about reducing greenhouse gas emissions from buildings and believe that the mixed mode approach offers a great deal towards achieving this goal.

Factors affecting the uptake of mixed mode systems

Building guidelines and environmental rating tools

In the commercial reality that governs the Australian property market, decisions for inclusion of options such as mixed mode of operation are influenced largely by the cost effective manner in which prescribed standards, energy targets and desired environmental rating can be achieved. While this discussion is predominantly about the Australian market, experience in this country provides useful insights.

At the top end of the market, developers consider the grading of their property based on the Property Council of Australia (PCA)'s quality ratings (PCA, 2005) for Premium, Grade A, Grade B and Grade C buildings. Although air conditioning is no longer stipulated as a condition for the Grade Matrix, many attributes listed are based on air-conditioned buildings. The guide does not include space temperature, humidity or comfort guidelines or provide explicit guidance or reference to how mixed mode or naturally ventilated buildings may be considered for inclusion in the matrix.

In its "environmental" section, the PCA Grade Matrix document cross references two schemes in Australia that have become influential in shaping the commercial property market, namely NABERS and Green Star. The National Australian Building Environmental Rating Scheme or NABERS OFFICE is a post occupancy environmental rating system for office premises that currently encompasses Energy, Water, Indoor Environmental Quality and Waste. The Green Star rating tool developed by the Green Building Council of Australia uses information from the building design and delivery process to rate the environmental potential (design intent) of buildings.

Energy considerations

While the Building Code of Australia (BCA) stipulates minimum mandatory energy efficiency provisions for non-residential buildings (ABCB, 2009), the actual operational performance of office buildings is benchmarked under the NABERS Energy scheme by calculating a $kg{\cdot}CO_2/m^2/yr$ result based on one year's utility bills. Although a voluntary system, it is now quasi-mandatory, since many state governments and the commonwealth government have mandated a minimum NABERS Energy rating for buildings that are leased or owned by these agencies. (Resource Management Systems and Team Catalyst, 2008).

Given the potential for rating tools to influence market behaviour, the levels of performance that can be achieved under the NABERS scheme is of interest. Some air-conditioned buildings achieve the top rating of 5 star for energy certification through supplementary purchase of green power. Top ratings (without purchase of green power) is evident where careful attention is paid to an integrated approach to design, deliver and operation (and in instances where efforts are made to go beyond basic envelope and plant efficiency to incorporate innovative strategies including a mixed mode of operation. (Thomas, P.C., and Rao, 2009; Thomas, L., and Vandenberg 2007)

The Green Star scheme aims to push buildings towards a carbon neutral position by allocating maximum of 20 "energy improvement" points at carbon neutral emission level levels for "base building[1]" based on computer simulations of predicted energy performance, (GBCA, 2008). Whereas the conditional requirement for being eligible to be considered for a Green Star rating is 110 $kg{\cdot}CO_2/m^2/yr$, typical energy efficient air-conditioned "base" buildings in Australia aim for 6 points (70 $kg{\cdot}CO_2/m^2/yr$). Our experience has shown that developers look for ways in which they can achieve additional points by improving the predicted performance of projects. The recent success of some mixed mode building in achieving top ratings (6 Star) has raised interest in mixed mode designs. However, mixed mode buildings are currently only of interest to the market if their predicted performance can be shown to be better than that of air-conditioned

[1] Base building energy refers to energy use for most building uses. It includes energy used by HVAC for the whole building for typical office occupancy levels and excludes tenant lighting and power

buildings, and they are estimated to cost substantially less than alternate options such as tri-generation which has recently gained attention

Thermal comfort and Indoor Environmental Quality

Although there is no separate guideline for mixed mode buildings in Australia, some criteria can be inferred from guidelines for air conditioned and naturally ventilated buildings.

In the absence of a definite thermal comfort standard for Australia, the general practice is to design air conditioned buildings to conform to ISO 7730 and ASHRAE 55-R which predicates a narrow range of operational temperatures. In practice, a number of commercial lease agreements are even more stringent and reflect the NSW Government Workplace guidelines which suggest that air conditioned systems should generally be designed to provide 22.5 ± 1°C. The NSW guideline also raises the option of natural ventilation and the integration of hybrid ventilation systems where natural ventilation is harnessed as the “free-cooling” mode.

The BCA does not prescribe thermal comfort conditions for the actual building operation. However, the authors’ experience in practice is that the 20-24 °C range that is stipulated under the code’s computer simulation protocol for achieving compliance has often become the surrogate temperature guideline that continues into building operation. Interestingly, there are also known instances when projects have used the HVAC based temperature criteria to assess performance of naturally ventilated building.

In 2009, NABERS introduced an Indoor Environmental Quality (IEQ) tool whereby office tenancies are rated using approved questionnaire protocols to assess occupant satisfaction of thermal comfort. Whole buildings and/or base building ratings require assessment of physical environmental parameters (temperature, relative humidity and air speed) known to influence thermal comfort. When assessing the physical measurements, the NABERS IEQ tool treats mixed mode buildings in the same way as mechanical buildings based on their ability to control conditions beyond the natural ambient conditions. Top points achievable for mixed mode and AC buildings are allocated in situations where temperature drift of 0°C [from agreed comfort temperature conditions] is observed in weekly measurements at 12 locations, and relative humidity remains within 30-70% and air speed lies in the 0.1-0.2 m/s range. The temperature conditions can be interpreted as a tendency to reward stringent narrow conditions. On the other hand, through its reference to agreed comfort temperature conditions in lease agreements between owner and tenant, the tool provides flexibility as to what the stipulated temperature range might be. The potential for a wider band of agreed temperature comfort conditions in lease agreements has not yet been exploited in practice to further the uptake of mixed mode designs.

Under Green Star, mixed mode buildings are required to comply with the natural ventilation criteria when operating in the natural ventilation mode and separately achieve the stringent criteria for air-conditioned buildings when operating in the air conditioned mode. Thermal comfort in naturally ventilated buildings is assessed in relation to Fig 5.3 of ASHRAE 55 under both NABERS and GreenStar. With top points awarded when actual measurements (for NABERS) and predicted temperatures for Green Star are within the 90% acceptability limit. Air conditioned buildings under Green Star are expected to comply with the more stringent ISO 7730 guidelines, where maximum points require predicted achievement of PMV ±0.5

While some of the rating tools discussed above recognise the potential for mixed mode type of systems, much of the guidance is framed from a traditional HVAC perspective. The implications of these standards in the context of climate change are discussed in subsequent section. Clearly there is pressing need for a coherent set of guidelines for mixed mode buildings

The nature of design and development

The majority of office building projects in Australia tend to be "speculative developments" in Australia, where the final mix of tenants is not known at the start of the project. Many of these projects are also procured by the "design and construct" tender system, where a lead contractor wins the job, generally on price. There is an agreement on "gross maximum price" or GMP to deliver the building. The lead contractor's profit is based on how much can be saved from this GMP. The profit motive can lead to a minimum specifications approach, to just meet the required specifications.

When such building projects are developed to use mixed mode environmental control with the view of garnering additional points to score higher Green Star ratings, there is the potential to lose sight of the basics for successful implementation of natural ventilation systems such as narrow floor plates for airflow control, passive design principles to reduce loads and thermal mass to moderate temperatures (DETR, 1999).

Value engineering at this stage can result in the specifications being forced to be as close as possible to standard HVAC buildings. For example, a commonly encountered problem relates to openable façade elements which are significantly more expensive that fixed glazing. In scenarios where insect screens are introduced, an active pressure to reduce incurred costs often mean that the additional openable façade area required to combat increased pressure differential screens bring to bear on the system is not provided. Such decisions can adversely affect the final performance of the system.

Another example of short-sighted value engineering occurs where the quality of the HVAC systems specified for mixed mode buildings may be downgraded on the argument that these systems need to run for much less time. Often the downgraded systems are unable to explicitly control/maintain relative humidity in the space, and are forced to revert to lowering the dry bulb temperature to a conventional 22.5 ± 1 °C in order to compensate for high humidity levels within conditioned areas at warmer temperatures.

Since mixed mode systems are not the norm in Australia, apportioning the responsibility (and therefore the risk) for the delivery of mixed mode systems can be difficult. While it is well documented (Thomas, L. and Hall, 2004, Leaman *et al*, 2007) that "Green Building" projects perform best when delivered in an integrated fashion, existing legal frameworks can sometimes make this a difficult proposition. It can be quite difficult to deliver the integrated approach demanded by mixed mode buildings when a design team is not able to work together with some level of trust or in situations where perceived risk causes consultants or contractors to curtail their responsibilities.

As discussed elsewhere the juxtaposition of knowledge, power and risk is not uncommon in any design development process (Thomas L. and Hall 2004). In order to ensure design intent is carried through, it is necessary to extend the integrated approach to achieve collaboration and shared understanding and aspirations amongst all the project stakeholders.

Simulation barriers/errors:

Carrying out a reliable and accurate building energy simulation on a proposed building design is a painstaking and time consuming exercise. Building energy simulation is best used assess to compare and assess a range alternative design iterations under identical operational conditions. However, in a climate where is there is a greater emphasis on energy performance reporting, there is an increased reliance on building energy simulation to predict operational performance.

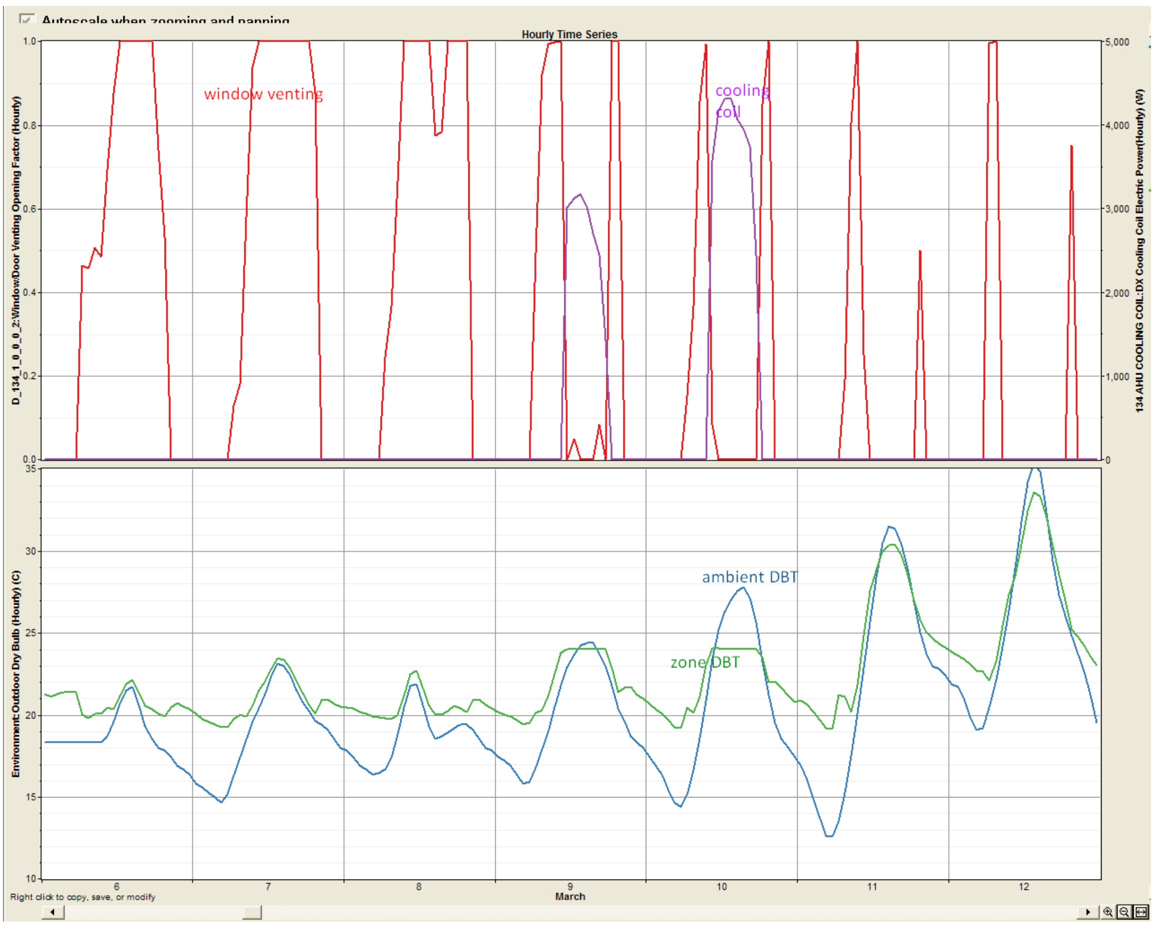
Reviews of design documentation, including building energy simulation reports, for over twenty conventionally air-conditioned building projects have been carried out in the past two years. This experience indicates that a number of similar “errors” seem to be repeated by simulators, resulting in optimistic energy predictions (Thomas PC, 2010).

Energy simulation of mixed mode systems introduce an extra level of complexity by requiring accurate and simultaneous prediction of heat AND mass transfer effects to account for the movement of moisture and heat due to varying rates of air flow encountered in most natural ventilation problems. Cooling building thermal mass with ambient night air extends the envelope for mixed mode operation. Adequately analysis this process requires the simulation engine to explicitly couple a nominated thermal mass with a changing air mass flow rate.

Simulation engines based on the early CIBSE admittance calculation procedures did not account for thermal mass correctly. Some of the older energy simulation programs like DOE-2 were developed to compute the energy used by HVAC systems (and other energy sub-systems, of course), and concentrated on the issue of heat transfer. These program was originally coded over 30 years ago, and a saving in computing power was achieved by calculating the space heat load from one fixed load calculation temperature. This compromise provides fast calculation times, but can result in load, temperature and energy calculation errors when loads for mixed mode conditions need to be estimated from separate heating and cooling set points. These effects can lead to over sizing of equipment and erroneous results for energy saving that make the tool incompatible for mixed mode systems.

Most energy simulation programs calculate *zone average values* using a one hour weather data file. The performance of natural ventilation systems would probably be better predicted using more refined grids within each zone, particularly for tall, narrow zones. For example, the ESP-r program carries out a quasi CFD simulation (Beausoleil-Morrison, 2002) at each time step to improve predicted performance for naturally ventilated buildings. However the program has some limitations on large system HVAC components, which can make it difficult to develop models within commercial timeframes for predicting mixed mode outcomes in warm climates.

While it has been possible to model mixed mode operation at a high level for research type projects, advances in development of integrated energy simulation engines are just beginning to bring these advanced capabilities addressing some of the above issues into programs and graphic interfaces that allow analysis to be completed within the constraints of a commercial cost/timeline. Figure 1 provides a seven day excerpt (last two days are weekend, no HVAC allowed) of a mixed mode building in Sydney, simulated using EnergyPlus. The integrated simulation model is able to predict window venting, ambient and zone temperatures, and operation of the cooling coil when venting (natural ventilation) is insufficient to maintain the zone at a 24°C cooling setpoint that was stipulated for this project. This example is only designed to illustrate that the new generation of building energy simulation program are becoming capable of generating and reviewing the multiplicity of data in a commercially viable timeframe for mixed mode building projects.



------------fraction of window venting
------------cooling coil power (W)
-------------ambient Dry Bulb Temperature °C
------------zone Dry Bulb Temperature °C

Figure 1: Mixed mode prediction using EnergyPlus

It is important to note that the hourly weather data file in a simulation cannot account for climate events such as external wind gusts or localised dust events that affect the practical operation of mixed mode systems. The omission of such considerations in computer simulations can lead to optimistic energy saving predictions, that affect life cycle cost predictions, which when not achieved, lead to perceptions amongst the client community that these systems don't work.

Legacy software code can have subtleties in the implementation of calculation algorithms that can lead to errors when used for predicting the performance of mixed mode systems. Simulation of mixed mode systems within commercial time requires the design team to develop and ask the right questions. Many consultants would generally have invested time and money in one computer simulation package. In such cases, they need to be aware of the limitations of the simulation program being used, and develop appropriate simulation with conservative assumptions. It is also critical to run differential risk scenarios to test if small changes in critical values result in unreasonably large changes in outcomes. If the latter occurs, the anomalies should be carefully investigated to ensure they are not an artefact of the simulation.

Operational issues

It is necessary for the design team to be cognisant of operational issues that could negate the design intent when designing the system and control strategy. In addition, it is necessary for checks and balances right through the design and development process to ensure that the design intent of the system is not compromised. A few examples from our experience in practice are noted below:

Speculative developments do not always have advance information on tenancy requirements. Natural ventilation systems require free flowing spaces for effective ventilation control to maintain thermal conditions. Even with good coordination between the tenancy fitout architectural team, there can be changes in the design that get built and effectively block the free flow of air between inlets and outlets in the natural ventilation design; significantly compromising the effectiveness of the design.

Mainstream BMS programs are not generally designed for natural ventilation operation, and do not always have standard logic sequences for mixed mode operation. The control logic has to be proprietarily programmed. This leads to a high chance of errors (compared to pre-written and pre-tested logic for standard HVAC component operation, for example an AHU damper operation logic sequence).

Concerns with security maybe difficult to manage, and can result in the louvers controlling airflow in natural ventilation mode being closed up completely after hours and until just before it is occupied next morning. This practise is particularly detrimental in Australia where the authors have reviewed metering data from conventional air-conditioned buildings showing peak air-conditioning demand for the week is the first hour of operation on a Monday morning after a warm/hot weekend.

In mixed mode buildings that do not deal with this issue at design stage and/or follow it through to construction:

- the building loses the opportunity to keep temperatures in control overnight, and
- loses the opportunity to cool the building early in the morning before the ambient temperature begins to rise to levels that initiate changeover to air-conditioned mode, and
- increases annual energy used by the air-conditioning system for cooling

Post occupancy feedback from four buildings

In this section, insights from four buildings located in Sydney and Melbourne are discussed. All buildings were surveyed using the Building Use Studies (BUS) methodology. The mixed mode system and feedback from each of these buildings is discussed below.

Case study building A (Thomas, L. and Hall, 2004), located in Sydney, incorporated stack ventilation in conjunction with supplementary air-conditioning in the form of ducted variable refrigerant (VRV) system along the perimeter of the open plan ceiling. The switch between the stack ventilation mode and the air-conditioned mode was controlled via a building management system where the original temperature band was set at 19-25°C. The building achieved its performance energy target of 4.5 Star under ABGR (Australian Building Greenhouse Rating: the previous version of NABERS Office Energy) and has been cited for its attention to client commitment, careful briefing and design team selection, and stipulation of tangible environmental criteria at project inception that enabled it to meet its design targets. On the other hand, the building returned disappointing results for occupant feedback for thermal comfort and ventilation with mean scores of survey responses being worse than both scale midpoints and BUS benchmarks. This outcome was attributed to the lack of adequate airflow and erratic temperature controls, and the temperature range had to be narrowed to 20-24°C following occupant complaints for overheating.

In an educational building B (Thomas, L., 2010) located in Sydney the mixed mode system was designed primarily as a naturally ventilated system with operable windows for each class room. The building integrated flexibility for occupants to manually shut windows and initiate air-conditioning when conditions were deemed uncomfortable. Conceptually, such an approach is not very dissimilar to the seasonal modes of operation seen in buildings during the 70's and 80's that relied on air-conditioning only summer, and natural ventilations at all other times. As reported in Thomas 2010, a double wall system along the inner corridor housed the VRV system in alternate sections with the ventilation shaft for stack ventilation. The building achieved positive ratings for temperature and air conditions in summer and winter from students, with mixed ratings from staff. Concerns arose from the inability to open windows as a consequence of traffic noise and lack of control to switch off air-conditioning that was shut down using a timed switch. Nevertheless both groups of users returned strong ratings for overall comfort a and high "forgiveness" factor for minor shortcomings in individual aspects with mean scores survey responses for overall comfort being significantly better than both scale midpoints and BUS benchmarks.

In a major office refurbishment project - building C (Thomas, L. and Vandenberg, 2007) located in Melbourne, the main stairwell was remodelled to serve as a lightwell and thermal stack. The building also integrated exposed thermal mass in the ceiling and a night purge cycle to "pre-cool" the mass and stabilize internal temperatures. The office spaces were designed to operate with a 19-25°C temperature range during occupied hours, with a BMS controlling the switch over to the fan coil units in the ceiling. The building achieved a 6 star (World Leader) rating of Green Star Office Design and a 5 Star NABERS Energy rating. The environmental outcomes were matched by high user satisfaction. Mean scores of survey responses for temperature, air and overall comfort were significantly better than both scale midpoints and BUS benchmarks, and the building rated in the 94th percentile of the 2006 Australian benchmark dataset for overall performance. Our experience in building C suggested that a proactive and user responsive approach to building commissioning and management has ensured that teething problems such as incorrect set-points and a night purge system operating regardless of outside temperature were quickly rectified.

A changeover mixed mode system is implemented at a recently completed Building D located in Sydney. The building has low level mechanical louvers integrated with the façade that act as air inlets for natural ventilation mode, and high level glass louvre windows for air outlets. A large diameter (6m), low speed ceiling fan has been installed to improve air circulation in both the natural ventilation and air-conditioned modes. A simple direct expansion (DX) air conditioning system with a simple duct layout has been design and installed. The building has been constructed and is in operation, but the operation of the mixed mode system is still being optimised. While outcomes will be reported in detail in the public domain in the near future, there are already some valuable insights that are reported here.

The building encountered operational issues not envisaged at the time of design. The building is located in an area prone to short but sudden wind driven rainstorms called "southerly busters". On one such occasion the BMS failed to operate in time to shut the high level glass louvres, resulting in water damage to the fitout. In addition, the building has experienced a lot of issues with dust from adjoining construction sites. These problems have resulted in the natural ventilation system to be temporarily shut down. The author is working with the owner, the BMS controls contractor and HVAC service personnel to simplify the control system, with flexibility for occupant control including manual overrides in case of such storm events.

Feedback from the four building examples discussed above emphasise the importance of post occupancy evaluation to close the loop on performance. Clearly, as seen in Building C, it is possible to design effective mixed mode systems that are capable of meeting energy and environmental targets, while gaining occupant satisfaction. The experience reported here across all four buildings, reinforces observations that while mixed mode buildings incorporate the best of both worlds, they require effective integration in both design and management (see Bordass *et al*, 2001) to ensure positive outcomes for environmental performance and occupant satisfaction.

Adapting to Change – the way forward.

In the present context of global warming, mixed mode buildings can become a vehicle to rethink questions of comfort and adapting to climate change. In returning to passive modes of operation when conditions permit, they offer the opportunity of reducing reliance on carbon intensive modes of cooling and heating.

We propose that while the traditional model of mixed mode in buildings implies distinct seasonal modes of operation, the challenge today is for a more seamless approach to mixed mode of operation where the changeover from active to passive mode can occur on the same day. A number of technical issues and their implications have already been discussed above. In this section we summarise factors that will be crucial to successful implementation of mixed mode buildings.

Passive building - active occupant

The first of these occurs through **active occupants** who understand the design intent, and are willing to play a proactive role in the operation of the building. This approach requires systems that are simple yet robust enough to cope with some errors in operation. As evident from case studies above greatest success is achieved in owner occupied buildings, where there is already a strong interest to climate concerns and a sense of pride and ownership in the building. The approach also has the potential to provide conditions where occupants perceive a higher level of control over their environment, and consequently are more forgiving of minor discomfort and tolerate wider bands of temperature and humidity.

Active building – passive occupant

As the scope and scale of the building increases, and the potential for user participation dwindles, it becomes necessary to control the changeover from passive to active mode and vice versa using **active forms of control** via a Building Management system. Simultaneously designs of such systems move towards streamlining the path of air movement which transforms the building to one that is largely sealed (non openable windows) to the occupant, and integrates fresh air through displacement ventilation systems, under floor grilles or specially designed inlet and outlet louvers controlled by the BMS. In such cases, it is important to remember that from an occupant perspective, the building is really operating in an active building framework over which they have limited control, which alters their expectations when compared to the previously discussed active occupant framework.

Rethinking comfort

As noted, much of the guidance in codes and rating tools treat mixed mode buildings as a subset of air-conditioned buildings and mandate stringent thermal comfort conditions be applied. In addition to concerns for the standardised expectations they perpetuate (Chappells and Shove, 2005) such an approach is called into question by recent research (Arens *et al*, 2009) showing no perceptible benefits to comfort despite the increased energy that is needed to provide such conditions.

Guidelines that require mixed mode buildings to conform to the narrow comfort bands prescribed for air-conditioned buildings limit the potential for passive operation to the narrow prescribed temperature range and negate their potential for substantial carbon reduction. In many cases, the reduced savings make it increasingly difficult to justify the efforts and costs for the careful, engineering and architectural detailing needed to integrate such systems. If the prescription of a narrow comfort band continues, mixed mode systems will continue to be viewed as an expensive and more complex alternative to standard economy cycles of HVAC design that is only attempted when top end rating points may be scored.

However, the adoption of a wider temperature band is not without its own challenges as evident in the different levels of occupant satisfaction and tolerance of temperatures in buildings A and C. Here it is important to reinforce that the ability of a mixed mode building to respond quickly and satisfactorily if problems arise will determine the success and acceptance of such buildings, especially where occupants have little personal control over heating and ventilation.

The attempt to embed separate thermal comfort regimes intended for natural ventilation and air-conditioning within the same building as promoted by some of the rating tools discussed above is also problematic. Under this regime, the passive mode of operation will be constrained by the thermostat settings for the air-conditioned mode rather than any wider band of operative temperatures that might have been permissible in a passive mode.

For mixed mode buildings that rely on active controls, we recommend adoption of a floating set point based on an adaptive model of comfort (after McCartney and Nicol, 2002). Comfort limits in sympathy with concurrent outdoor conditions have the best potential to maximise a passive mode of operation, reduce energy consumed for space conditioning and ensure occupant comfort even as modes of operation changeover. This requires further research that could be a combination of simulated performance and practical trials of the strategy.

In warmer, more humid climates, the challenge is to dehumidify efficiently and provide economical air-movement in the "conditioned" space to improve the perception of thermal comfort. Dedicated outside air systems (DOAS) (Larrañaga, 2008) offer the potential to remove all latent load from the outside air (fresh air) using cooling coils or desiccant wheel technology. Ceiling fans can provide air movement within the conditioned space in a very economical manner. The independent control of space humidity provides opportunity to widen the comfort envelope by allowing space temperatures to drift higher, where there is a willingness to accept higher temperatures.

Conclusions

This paper offers strategies for rethinking comfort, simulation, implementation and operation of mixed mode buildings. There is a pressing need for a coherent set of guidelines, free from the legacy of HVAC buildings, which are explicitly developed for mixed mode building in warm and humid climates and can be referred to by building rating systems and tools.

Delivering mixed mode buildings via the current, speculative, design and construct process seems to carry an increased risk of the design intent not being carried through to the end. This maybe particularly acute in instances when there is a switch from conventional HVAC to mixed mode environmental control in order to reduce the carbon footprint, and also in larger buildings with reduced potential for user participation. There is a case to rethink the commercial process to ensure it promotes the successful design and delivery of mixed mode designs in such situations.

The case studies show that the greatest success stories for mixed mode buildings are in owner occupied buildings, where *active occupants* show strong interest to climate concerns, and have a sense of pride and ownership in the building. Where these occupants perceive a higher level of control over their environment, they are more forgiving of minor discomfort and tolerate wider bands of temperature and humidity.

As building scale increases, it becomes necessary to use *active forms of control* via a Building Management system, and the building become largely sealed to the occupant, integrating fresh air through specially designed, automatically controlled inlet and outlet louvers. In such cases occupants have limited control over their environment, which alters their expectations and makes them less forgiving.

There is also an urgent need to rethink the definition of comfort, particularly in parts of the world where the narrow, HVAC based, temperature band has not yet become entrenched, and codes and standards need a coherent series of guidelines, based on adaptive models of comfort, to be developed for mixed mode buildings. Decoupling humidity control from temperature via the use of efficient DOAS based dehumidification strategies, coupled with simple air movement solutions like ceiling fans can offer wider bands of acceptable comfort, resulting in greatly reduced greenhouse footprints for mixed mode buildings in warm humid climates.

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