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OCCUPANT-PROOF BUILDINGS: CAN WE DESIGN BUILDINGS THAT ARE ROBUST AGAINST OCCUPANT BEHAVIOUR?

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ABSTRACT

Uncertainty from occupant-related matters is typically shrugged off by building designers as beyond their control. However, evidence suggests that careful attention of designers can help prevent occupants from behaving in energy-intensive ways; not by policing their behaviour, but by improving comfort. This paper examines the concept of bi-directional robust design – an attempt to design systems to be as resistant as possible to the noise of inputs – as an objective. Rather than modify occupant behaviour, which has shown only modest success, robust design strives to improve buildings to cope with diverse weather conditions and occupant behaviour. An example with fixed and movable shading demonstrates that lighting energy use can be significantly reduced in both absolute and certainty terms, if designed properly. Finally, some robust building design approaches are discussed.

INTRODUCTION

Buildings are designed first and foremost to provide shelter and ultimately maintain a high standard of occupant comfort. Accordingly, they are normally equipped with an array of automated and manual systems for providing comfort and alleviating discomfort. These manually-controlled systems (e.g., window blinds, operable windows, light switches) are provided for three primary purposes:

1) Avoid discomfort during certain weather phenomena (e.g., daylight glare);
2) Adapt to different space uses (e.g., presentation with a data projector); and,
3) Adapt to different occupant preferences.

The different parties involved in the design, operation, and use of buildings have contradictory views of occupant behaviour in buildings. Building designers are often optimistic about occupants (Donn, Selkowitz et al. 2009) in assuming they will operate buildings optimally (from an energy standpoint). Designers who are aiming for ambitious performance objectives, like net-zero energy, may be very tempted to make optimistic assumptions about control setpoints, lighting and appliance use, and operable window and shade control. This probably makes sense since after all, we ourselves, as designers and researchers, understand building physics and have above-average motivation to operate our homes and workplaces to use less energy.

Mechanical and electrical engineers tend to make conservative assumptions about occupant behaviour because they are motivated to ensure that occupants do not complain about the indoor environment and ultimately to minimize their own professional risk.

Occupants normally attempt to maximize comfort; though a multitude of contributing factors are at play including, but not limited to: net benefit of taking the adaptive action, financial cost to take the action, and perception of long-term effectiveness of taking the action (as discussed later in this paper). While it is generally understood by the literature that occupants are provoked by various environmental conditions with some predictability, occupants do not always make logical choices and they act stochastically; not deterministically (Nicol 2001). Notions by building designers that occupants are active building users are overestimated; many occupants find a system state that alleviates discomfort for the long term and "causes the least trouble" (Bordass, Cohen et al. 2001). For instance, Rubin, Collins et al. (1978) observed that only 40% and of the blinds were moved in any given day in a set of large buildings, with a range between occupants of daily and "never". The level of occupant passiveness is further reinforced by the notion of the hysteresis effect: statistically, occupants often act to alleviate discomfort at a much higher environmental variable threshold than when they return the system to its default state. Reinhart and Voss (2003) observed that occupants closed blinds at an average of 50 klux (exterior vertical illuminance) and reopened them only when it declined to an average of 25 klux. In other words, they were able to tolerate high luminances when closing the blinds, but they were not motivated to stand up and reopen them until daylight illuminance was significantly lower.

Obvious, but poor, approaches to addressing the tremendous amount of uncertainty attributed to occupant use of manual control over indoor environmental conditions include: 1) removing the manually controlled systems altogether or 2) eliminating all sources of discomfort by building highly-conservative buildings (e.g., windowless, highly-insulated, and tightly-controlled). If provisions for alleviating discomfort are not provided, occupants often "MacGyver" a solution in unforeseeable, semi-permanent, and often energy intensive ways, as shown in Figure 1.

Windowless boxes fail to deliver the psychological benefits of daylight and views (Boyce, Hunter et al. 2003) and may even be more energy-intensive than buildings with reasonably-sized windows. Furthermore, providing occupants with a sense of comfort and understanding of systems, alone, has been shown to improve tolerance to a wider range in indoor environmental conditions – regardless of the actual comfort conditions (Paciuk 1989).

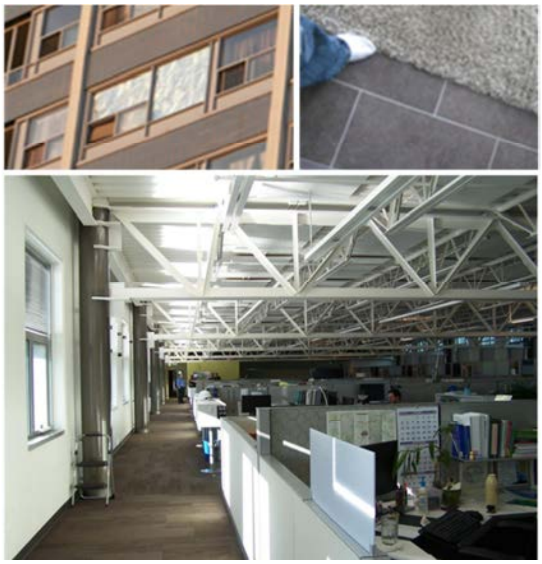

Figure 1: Examples of semi-permanent adaptations that occupants have used, presumably because of discomfort. Clockwise from top-left: foil-covered west-facing residential window; shag carpeting to reduce cold sensations of feet on a thermally-massive floor in a passive solar house, EcoTerra; protective daylight partition on cubical in NREL RSF building.

Despite this, significant research has focused on comfort as something that is passively endured by occupants (De Dear and Brager 1998) and simply measured; thus assuming that energy and comfort performance are independent of each other. Often, the design space has been viewed as a trade-off between comfort and energy. This notion is contradictory to observed behaviours; sun-blinded occupants often cover windows, cold occupants may activate portable electric heaters, hot occupants attempt to open windows in the middle of the heating season. All of these actions can drive up energy use beyond levels ever imagined by the designer – particularly if the building was intended to passively exploit naturally-occurring sources of energy (e.g., daylight and passive solar gains). It is evident that the adaptive measures may have a neutral effect on energy use (e.g., clothing change) or even reduce it. But given that building designers are generally more knowledgeable than occupants about building physics, it would seem appropriate for the designers to provide an energy-efficient means to comfort rather than leave it up to the occupants.

The key problem investigated in this paper is that occupants usually act to improve their comfort at times of "crises of discomfort" (Haigh 1981) but are much slower to respond when the source of discomfort passes (Cole and Brown 2009). Often the systems that alleviate discomfort (e.g., operable windows, window shades, electric lights, ceiling fans) are more energy-intensive than the status-quo if they are left in their activated state once the source of discomfort no longer exists. For instance, leaving window blinds closed after glare occurs often means that electric lighting is needed to compensate for the lack of daylight. This problem is particularly acute when occupants do not even notice that the system is still activated (Reinhart 2004) or when a back-up energy-intensive alternative that provides a high degree of comfort is available. For example, if air-conditioning and electric lighting are available, occupants have minimal motivation to actively operate window blinds to attempt to control solar gains and admit daylight. Inkarojrit (2005) found that occupants were less active blinds users and chose a lower mean occlusion (30% versus 49%, on average) if their offices were air conditioned.

Figure 2: Examples of unintended results of actions taken by occupants who were presumably uncomfortable: open window in winter (right) and high shade occlusion level (left)

It is notable that most examples presented to this point have involved window shades and visual discomfort. This is a particularly interesting subject because extraneously closed shades do not cause discomfort, per se, other than dark conditions (which are normally corrected with electric lighting). In contrast, many adaptive measures can actually cause discomfort in their new state. For instance, operable windows can cause cold and drafty conditions if they are left open once overheating has been mitigated. For this reason, preferred window shade positions are significantly less predictable than other systems and the focus on the example in this paper.

Some major progress has been made in the field of occupant behaviour modelling (e.g., (Haldi and Robinson 2010)), but those who are following it could argue that the results have been largely untapped. One of the major underdeveloped topics in the research is: how can designers and simulationists actually utilize knowledge of occupant behaviour to improve building design (Hoes, Hensen et al. 2009)? Furthermore, given the aforementioned nature of the occupants, is it possible to design buildings to avoid these triggers of discomfort and reduce the uncertainty of building performance, while providing improved comfort to occupants at minimal effort to them?

Few researchers have explored the potential of buildings that are designed to be robust against occupant behaviour. Hoes, Hensen et al. (2009) are the first researchers, to the knowledge of the author, to explicitly use the term *robust* in this context. They examined the standard deviation and mean performance for several basic building designs under the Lightswitch-2002 occupant model. In a later paper, Hoes, Trcka et al. (2011) used the principle to select the most robust design from a pareto front that resulted in multi-criteria optimization.

To answer the above questions, this paper explores the modified application of a formal robust design methodology based on work of Taguchi (Phadke 1995). A "bi-directional robust design methodology" (BDRDM) is proposed; it recognizes that the system design can affect the operating conditions and vice versa. The methodology is applied to a simulation-based example of a simple single-occupancy office. The results demonstrate tremendous success in achieving lower energy use by better characterizing occupant behaviour. Finally, general robust design principles and techniques are discussed.

ROBUST DESIGN METHODOLOGY

The robust design methodology (RDM), initially developed by Taguchi in the 1940s, proposes that products should be designed such that their performance is maintained at desired levels without trying to control the inevitable variability of operating conditions (Phadke 1995). The underlying principle of RDM is that it is more expensive (or impossible) to control the variability of these operating conditions than to simply design the system to be less sensitive to them. Robust design is normally illustrated as a block diagram, which is known as the P-diagram (Phadke 1995), whereby the engineered system is exposed to noise (e.g., unpredictable operating conditions), a signal input (e.g., an HVAC system), design parameters (e.g., building envelope), and outputs (e.g., energy performance) (see Figure 3). The notion of "off-line control" that Taguchi championed says that products should be designed and manufactured to have greater tolerance and fault resistance rather than requiring external interference during their operational phase.

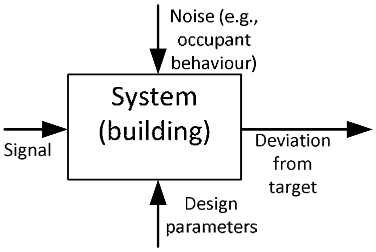

Figure 3: the P-diagram used to illustrated robust design methodology (Phadke, 1989)

The essence of the procedure is that the designed system is exposed to the range of expected conditions and then different design variations are assessed for their ability to perform well when despite this "noise".

In the context of buildings and occupant behaviour, RDM means that we do not want to attempt to control occupants, but rather control buildings to be less sensitive to occupant behaviour. In the past, attempting to modify occupant behaviour has shown mixed and generally modest improvements (Abrahamse, Steg et al. 2005). Similarly attempting to modify occupant behaviour using strict control (e.g., bolting operable windows closed) is likely to decrease their tolerance for greater variation in indoor environmental conditions (Paciuk 1989) and may negatively affect productivity and possibly increase energy use.

METHODOLOGY

The current work acknowledges the value in robust design for buildings, but also suggests that the input in the P-diagram from noise factors has some degree of bidirectionality to it. That is, the behaviour of occupants is not completely independent of building design; but rather, a function of it (see Figure 4). For instance, the probability of preferred temperature setpoints for thermostats may depend on drafts caused by the openness of a space or large cold windows. The argument being made here, is that building designers have substantial influence over many of the factors that are currently perceived as beyond their control.

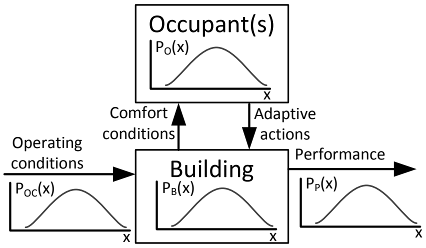

Figure 4: Bidirectional robust design methodology applied to buildings and occupants

In order to utilize the robust design concept while also recognizing that building designers have some impact on the supposedly fixed though unknown noise factors, a hybrid approach which is being called the bi-directional robust design methodology (BDRDM) is proposed. This design approach is focused on occupant behaviour and suggests that buildings should be designed to both have a greater tolerance to diverse occupant preferences and that the range in diversity of occupant preferences can be shaped by the provision of comfort by using appropriate fixed geometry and building materials.

The BDRDM seeks to minimize the occurrence crises of discomfort such that occupants are seldom provoked to act to alleviate their discomfort. Not only do these adaptive acts burden occupants (Paciuk 1989), but they often lead to unexpected energy performance.

In order to test the robustness of buildings, quantification of several items is desirable: a detailed building model, a model of how occupants respond to as many conditions as possible, and weather data.

Rather than perform a single simulation to predict performance, the proposed methodology is to expose numerous design concepts to a range of occupant behavioural patterns. Monte Carlo Analysis (MCA) (similar to Hoes, Hensen et al. (2009) and Macdonald and Strachan (2001)) shall be used to determine the robustness of different designs based on probability distributions for occupant profiles. The intended procedure is demonstrated with an example, as follows.

CASE STUDY

The BDRDM was implemented on a single office model and simulated in EnergyPlus V7.2. The three meter cube office has a large south-facing double-glazed, clear window (top two-thirds of the façade) (Figure 5). The office is single occupancy and equipped with one manual control system: an interior roller shade with 5% transmittance.

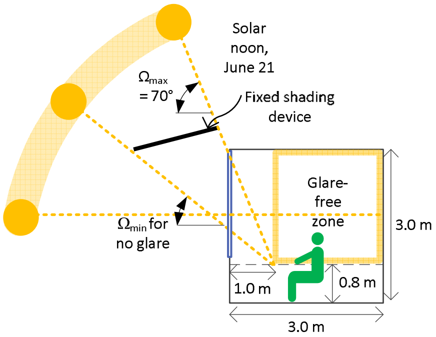

Figure 5: Cross-section of the south-facing office in example showing key geometry features, including range of solar profile angles. Note that the occupant is only shown for scale and that their orientation and position are not directly used to detect glare.

The electric lighting (10 W/m^2) is dimmable and controlled according to occupancy (assumed 100% weekdays, 9AM to 5PM) and daylight. The lights are controlled to be shut off if the workplane illuminance at the centre of the workplane exceeds 500 lux.

The fixed shading device, in the cases where it is present, extends 2 meters out from the façade (and infinitely far eastward and westward), as shown in Figure 5.

To study the stochastic nature of occupants, a probabilistic model that is based on the blinds aspect of Lightswitch-2002 was implemented in EnergyPlus' EMS (energy management system) object. EMS is a feature that enables some custom code to be executed at simulation run-time. The shades were assumed to operate in the following way.

1. Start simulation year with shade open.
2. If solar radiation on the exterior of the window exceeds I_{max} and daylight penetration exceeds 1 meter (at workplane level), close the shade and keep it closed for $t_{inactive}$ days.
3. Re-open if $t_{inactive}$ days have elapsed and the occupant is present.

Where I_{max} and $t_{inactive}$ are determined at the beginning of each simulation year by randomly obtaining a value from the normal distributions whose parameters are shown in Table 1. The solar penetration depth was calculated based on the solar profile angle and office geometry.

Table 1: Normal probability distributions for stochastic occupant model

	MEAN	**STANDARD DEVIATION**	**RANGE**
I_{max} (W/m^2)	50	25	(0,∞)
$t_{inactive}$ (days)	3	3	(1,∞)

The above solar thresholds are based on reasonable values provided by the literature (O'Brien, Kapsis et al. 2012; Reinhart 2004). The mean threshold for beam solar radiation on the exterior of the window of 50 W/m^2 is based on Lightswitch-2002 (Reinhart 2004). Lower threshold values indicate a particularly sensitive occupant or an office which is prone to glare (e.g., large monitors). Higher threshold values might correspond to a more tolerant occupant, a space use which is not prone to glare, a shared office in which there is a diffusion of responsibility regarding closing the shades, or a shade that is difficult to control. It should be noted that intermediate shade positions were not considered.

Many of the occupant models that are based on field studies inflate the level of responsiveness of occupants by eliminating the passive occupants. For instance, Inoue, Kawase et al. (1988) assumed that if a shade remained unmoved all day that the occupant must not be present. This amounted to 60% of all windows! Reinhart (2004) introduced the notion of different occupant types and divided the population equally among four types for lack of literature on a more appropriate distribution. The current case study uses a different approach to achieve similar results: a

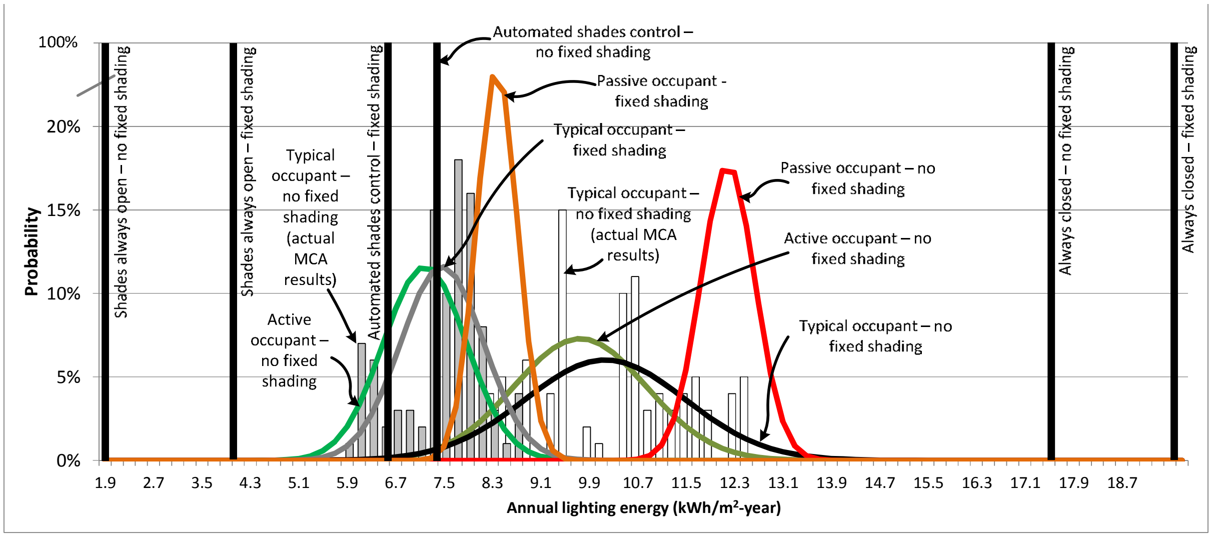

Figure 6: Probability distributions and normal distribution fits for annual lighting energy

stochastic function regarding the number of days a shade remains closed after the initial closing event. Using this method, the resulting mean occlusion for the simulated office with no fixed solar shading device is 71%, which is in line with measured values for south-facing facades (like for the building in *Figure 2*). To assess the sensitivity of the nominal 3-day lag period, 1-day (active occupants) and 10-day (passive occupants) delays were also explored. To study the behaviour of multiple occupants (e.g., in a large office tower), 100 simulations were run for each of the cases of the office with and without the fixed shading device.

The results (Figure 6) from this case study are quite profound. The upper and lower bounds along with the case with automated controls with no override are considered deterministic. The actual MCA results of the nominal ("typical") occupant models with and without the fixed shading are also shown. All others are represented by normal distributions that approximately fit the MCA results.

The office with fixed shading uses 27% less lighting energy, on average, and with considerably less variation, than the office with no fixed shading. In practical terms, this occurs because the glare conditions that prompt the occupant to close the shade are rarer when fixed shading is present. Because the window is quite large and even a moment of glare can cause occupants to close shades and leave them closed for many days, this is quite detrimental to daylighting performance. The mean shade occlusion of the office with the fixed shading is 30% versus 71% for the office without fixed shading. It is worth noting that even the passive occupants who are assumed to leave the shades closed for an average of 10 days after closing them use much less lighting energy than the case with shades always closed. This is because glare (as defined by solar penetration and incident beam solar radiation the façade) does not occur for much of the summer – even in the office with no fixed shading (see Figure 7).

In should be noted that the BDRDM for this example would be much more challenging for east and west-facing windows which are notoriously difficult to shade with fixed shading because of the low solar altitudes. Complementary work could use shading geometry optimization (e.g., (Marsh 2003)).

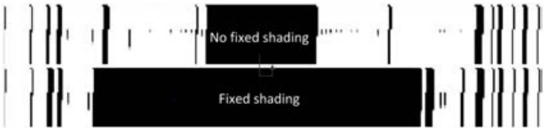

Figure 7: shade states for the nominal occupant model (horizontal scale = day of year, starting at left; vertical scale = hour of day, starting at top; black means shade open and white is shade closed).

Incorporation of more detailed lighting simulation engines, such as RADIANCE, into a growing number of BPS tools will facilitate greater design freedom and potentially greater accuracy with regards to daylight prediction. EnergyPlus' capability to characterize occupant interactions with more complex shading geometry (e.g., lightshelves) is limitted for this example. Finally, it should be noted that the occupant model was based on Lightswitch-2002, which was largely derived from field studies for a particular building, orientation, location, culture, and space use. While this example assumed that the model could be generalized, it has yet to be tested for this particular office configuration.

To connect the current example to the initially posed question, it is evident why an optimistic designer would not provide any fixed solar shading since occupants *could* keep the shades closed only when there is glare. However, accounting for more typical occupant behaviour, the presence of fixed solar shading is actually predicted to reduce lighting energy use for the majority of occupant types. Meanwhile, the conservative designer would overestimate even the most passive occupants. This example helps to explain why there has been a trend away from passive design and why there should not be.

DISCUSSION

While the physical indoor (and outdoor) conditions play a major role in influencing occupants' motivation to take action to improve their comfort, researchers have given significantly less attention to other circumstances - largely because they are difficult to quantify or generalize. This section focuses on the other factors that play a role in occupants' adaptive measures. These are not only important for improving accuracy of occupant models, but also important for design.

Consider that in any given moment in a building an occupant is faced with numerous conflicting factors contributing to whether they take an action to improve their comfort or not. This decision is represented by a balance, with benefits, costs, and a "stiffness". The stiffness represents the secondary factors that dampen the occupant's decision to take action (Figure 8). Each of these factors is explored below and certainly warrants future research.

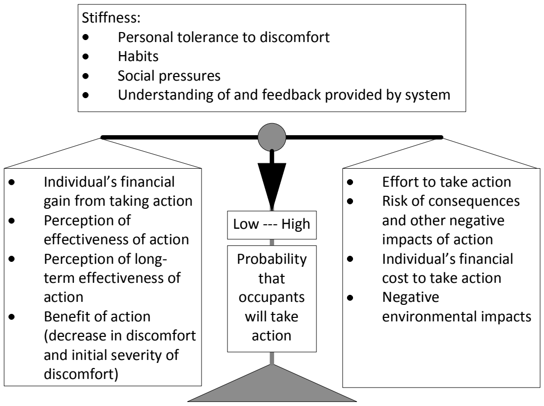

Figure 8: Cost-benefit balance for taking adaptive actions to improve personal comfort

Personal financial gain and cost have been shown to have a profound effect on energy use (e.g., sub-metering (Navigant Consulting Inc. 2012)) but may be negligible if there is a diffusion of responsibility.

It is important for occupants that their action is effective in alleviating discomfort and that they believe it will be effective for a longer period. As noted above, occupants have been found to usually set shades to a position that reduces or eliminates glare for weeks or months rather than hours.

Certain systems that alleviate discomfort may also have practical risks (e.g., rain infiltration or safety from leaving windows open) that could weigh against the decision for acting.

Systems that take less effort to use are more likely to be used (Lindelöf and Morel 2006; Sutter, Dumortier et al. 2006). This could mean not having to walk to the controls or having a single-button action, rather than a tedious operation.

Environmental impacts have been shown to have a modest impact on occupant behaviour but changes in behaviour usually require constant stimulation (Nisiforou, Poullis et al. 2012).

A number of "stiffness" factors affect the balance in Figure 8, including:

Inter-occupant tolerance variations have been documented (e.g., (Karjalainen 2007)) and ultimately influence the threshold of discomfort before an occupant acts.

Systems that can be clearly understood by occupants because of their simplicity and provide immediate feedback to indicate that they are functioning are important (Karjalainen 2009).

Occupants have been shown to be creatures of habit; we become tolerant of certain long-term conditions and tend to respond only when deviations to those conditions occur (De Dear and Brager 1998).

In multi-occupant spaces people may face social pressures regarding their decision to act, since their action likely affects others. Furthermore, they have a much greater sense of control when they are the only occupant in a space (Bordass, Bromley et al. 1993). On the contrary, occupants in shared spaces often take less ownership over conservation measures because they have feel less responsibility over their environment (Reinhart and Voss 2003). Future research is needed to understand these complex relationships.

Robust design principles

Based on the literature and findings from the current example, some robust design principles are provided, as follows.

- Where possible, used fixed design features to reduce the occurrence of "crises of discomfort", without significantly compromising passive features (daylight, solar gains, natural ventilation).
- Provide easy-to-use and easy-to-understand means to alleviate discomfort that provide

immediate feedback to occupants that they are operating correctly. Do not assume occupants will act in energy-conserving ways. Thus, make the least energy-intensive comfort provisions also the most appealing to use, where possible.

- Design spaces that allow occupants with flexibility to reorient and shift positions; this can yield vastly higher opportunities for glare avoidance without requiring the occupant to close the blinds (Reinhart and Wienold 2011).
- Provide individualized controls where possible so that occupants feel responsible for their own energy use and comfort.
- Consider systems that time-out for energy-intensive systems that occupants may forget to deactivate (e.g., lights).
- Minimize trade-off situations where improving one form of comfort can harm another.

Review of robust building design strategies

A short list of robust building technologies and design strategies is provided below. These systems improve long-term comfort while requiring no input from occupants.

- Advanced fixed light louvers can be designed to protect seated occupants from all beam solar radiation while reflecting a significant portion of it up onto the ceiling where it is redistributed diffusely (see e.g., (Guglielmetti, Pless et al. 2010)).
- Overhangs and other simple shading surfaces like the one in this paper can control solar gains, seasonally, thus reducing glare and preventing overheating. Rijal, Tuohy et al. (2007) showed that occupants were 85% less likely to open windows with the presence of overhangs and greater thermal mass.
- Thermochromic/photochromic windows have different properties depending on temperature and solar radiation and require no external input.
- Thermal mass and phase change materials reduce temperature swings and can avoid discomfort that could lead occupants to having to take action.
- Low-emissivity interior coatings – particularly on glazing – reduces the long-wave radiative heat exchange with occupants, thus protecting them from extreme surface temperatures.
- Deciduous vegetation provides a natural means for seasonal solar shading and can be timed and sized to reduce summer overheating.
- Sound-damping natural ventilation louvers reduce the trade-off effect by enabling users to increase outdoor air supply without as great a penalty of noise.

CONCLUSION

This paper demonstrated that without accurate occupant models, poor building design choices can be made. However, implementing more passive features (fixed solar shading, in this case) can significantly reduce both energy use and the uncertainty associated with occupant behaviour. The example used the strategy of greatly reducing the frequency of discomfort events in order to trigger occupant interventions less often. In order to properly incorporate occupant behaviour into building design, two major areas of development are required: 1) both the obvious and subtle factors that influence occupants should be characterized (e.g., beams of light through small gaps in blinds) and 2) we should recognize that expressing building performance at a specific deterministic value may be deceiving and that a probabilistic performance is more representative of reality.

Recognition of the fact that occupants behave in ways that are sub-optimal from an energy perspective revitalizes passive techniques.

Future research areas include:

- More field studies should be carried out to increase confidence of generalizability of occupant behaviour models;
- A better understanding of relationships between adaptive measures (e.g., which actions are taken first);
- Stochastic models that are easier to implement in tools (and tools that can incorporate them); and,
- Higher resolution models that characterize subtle design features (e.g., specular window frames or small gaps between blinds and window frames that still transmit a thin band of beam solar).

NOMENCLATURE

I_{max} = the solar radiation on the façade that triggers shades to close

$t_{inactive}$ = the number of days for which the occupant does not reopen window shades

Ω = solar profile angle

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