Evaluating the performance robustness of fixed and movable shading devices against diverse occupant behaviors

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Abstract

Given the diverse operating conditions, weather conditions, space users, and occupant preferences of buildings, it is commonplace to provide occupants with multiple means to adapt their immediate indoor environment. However, numerous studies have shown that occupants sub-optimally use such controls to improve comfort during times of significant discomfort, but are much more passive when the source of discomfort is alleviated. Occupant-related building performance simulation (BPS) models continue to use very simple and rigid rules when a building's performance is predicted, despite the topic's complexity. This is likely an artifact of envelope load-dominated buildings, whose energy use is mostly dependent on their ability to isolate the indoor environment. But as envelopes and HVAC become more efficient, occupants are playing an increasingly important role on building performance; especially for highly efficient building (e.g., net-zero energy buildings). Traditionally the associated uncertainty of these effects has been excused for the designer and isolated during design by focusing on energy performance relative to a reference building. However, evidence has shown that well-designed buildings can greatly reduce this uncertainty if they are designed to have greater resilience against a wider range of conditions. One cause for people to act in energy-intensive ways is if they encounter prolonged and consistent discomfort (visual, thermal, and acoustic). Contrary to traditional occupant comfort models, which assume that occupants passively endure the indoor environment, newer adaptive models recognize that occupants play an active role in maintaining comfort conditions. Thus, the use of higher resolution models that identify possible sources of discomfort are critical to successful high performance building design and operation. This paper proposes a method using a combination of probabilistic occupant models and explicit models of adaptive comfort to gain an improved understanding of robust building design.

1. INTRODUCTION

In the past decade, the uncertainty from occupant-related behaviour and habits in buildings has been widely recognized as playing an increasingly significant role in building performance (Haldi and Robinson 2010; Hoes, Hensen et al. 2009). A number of occupant actions, including: use of appliances, lighting, operable windows, thermostats, and window shades, have all been shown to have a considerable effect on energy performance and the indoor environment. At least as notable and complex is the diversity of occupant preferences and adaptive measures, including clothing level, consumption of hot and cold drinks, and tolerance for cool or warm temperatures.

Consider the end use energy use break-downs for residential and commercial buildings in Canada (similar to US figures), shown in Figure 1. Occupants have direct control over between three and five of the categories of energy shown, depending on their access to controls. The biggest category, space heating, which has traditionally been considered one of the most predictable categories because of its strong affiliation with building envelope and the HVAC system, has also been shown to be among the most uncertain because of occupant behaviour. Gram-Henssen (2010) found a 350% variation – between 4000 and 14,600 kWh for heating energy – among five identical houses, owing to attitudes about heating and energy use, thermostat control habits, use of operable windows in the heating season, and typical occupancy schedules. Larger-scale studies have shown more modest, though still very significant, variations of 25-40% (Pettersen 1994) and 38% (Sonderegger 1978). Buildings whose occupants are not motivated to reduce their energy by economic incentives, as is the case for commercial building dwellers and bulk-metered apartment dwellers - tend to use even more energy. Navigant Consulting (2012) studied nearly 4000 apartment units in Ontario, Canada and found that units whose residents directly pay for their exact energy use consumed about 30% less than those who paid a fixed fee.

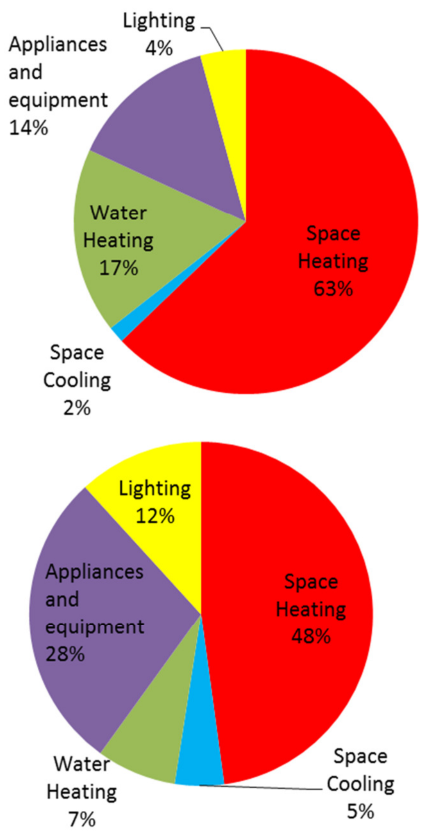


Figure 1: Energy use in residential (top) and commercial (bottom) buildings in Canada. (NRCan, 2008)

The other major categories of energy use – appliances and equipment, water heating, and lighting – are generally considered to be even more sensitive to occupant behaviour since they can usually be directly controlled by occupants. Needless to say, occupants play an unprecedented role in building performance, and this has yet to be well-characterized.

Recent years have seen a surge in publications that focus on the stochastic nature of occupants. The most common areas of study include window opening (Rijal, Tuohy et al. 2007), electric lighting (Boyce 1980), shades (Inoue, Kawase et al. 1988; Rubin, Collins et al. 1978), or some combination of these (Pigg, Eilers et al. 1996; Reinhart and Voss 2003). Others studies have examined thermostat use (Karjalainen 2009), clothing changes, consumption of hot/cold drinks (Haldi and Robinson 2008), and position in a space (Jakubiec and Reinhart 2011). A common conclusion to these studies is that behaviour is stochastic; not deterministic (Nicol and Humphreys 2002). The result is that occupants' decisions to take action are quite complex and somewhat random (e.g., Figure 2).

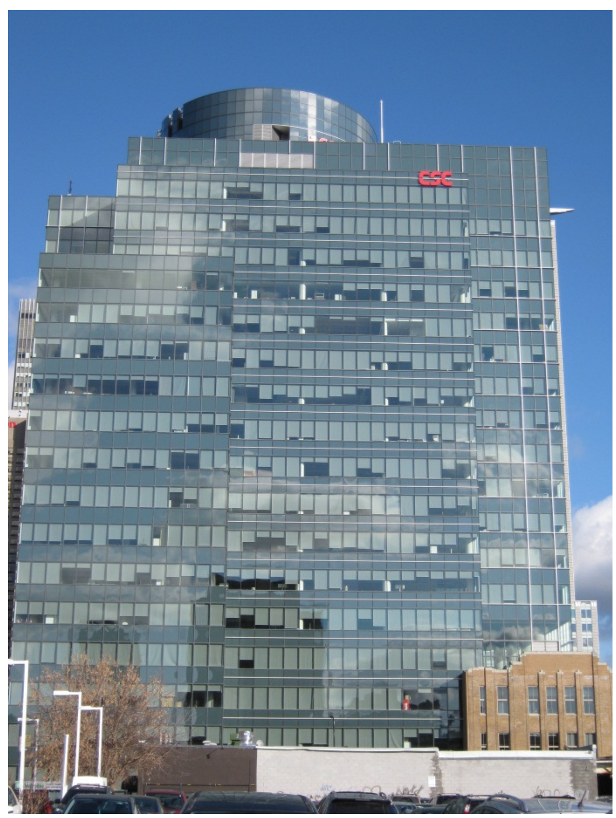


Figure 2: Typical shade deployment levels of a south-west facing office building façade in the winter.

The emphasis of stochastic occupant behaviour modelling research to date has been on improving the accuracy at which building performance has been predicted. However, little attention has been given to how accurate knowledge of occupant behaviour can be used to improve building design (Hoes, Hensen et al. 2009). This paper proposes robust building design: the notion that buildings can be designed "off-line" to provide greater comfort while relying less on occupants to adapt their environment and themselves. A simple example is provided to demonstrate that the presence of an overhang reduces the probability of glare and actually decreases lighting energy because occupants are less reliant on window shades.

2. THE ROBUSTNESS CONCEPT

About three decades ago, Genichi Taguchi proposed the idea that the quality of manufactured goods could be improved by designing them to be more resistant or *robust* against a wide variety of operating conditions (Phadke 1995). Taguchi suggested that designers should minimize the signal-to-noise ratio. That is, the resulting variability in product performance should be minimized relative to the magnitude of the deviations from nominal operating conditions.

In the current context of occupant-building interactions, robust design means we do not want to attempt to control occupants and their adaptive actions, but instead we want to design buildings that are less sensitive – more robust – to diverse occupant behaviour and weather conditions (noise). In fact attempting to modify occupant behaviour has shown to yield only modest returns (Abrahamse, Steg et al. 2005).

Rather than naively assume that BPS will yield accurate predictions in absolute terms, we must recognize that it is primarily valuable in relative terms and that results should be expressed in probabilistic terms, accordingly. Figure 3 shows the energy performance results of two designs: one that has greater robustness (lower standard deviation) and also a lower mean energy use than the other. The signal-to-noise for designs for which we want to reduce both the mean performance and variability ("smaller the better") is normally quantified as:

$$S/N = 10Log\left(\frac{1}{\overline{y}^2 + \sigma^2}\right) \quad (1)$$

Where S/N is signal to noise, $\bar{y}$ is the mean of the data and σ^2 is the variance.

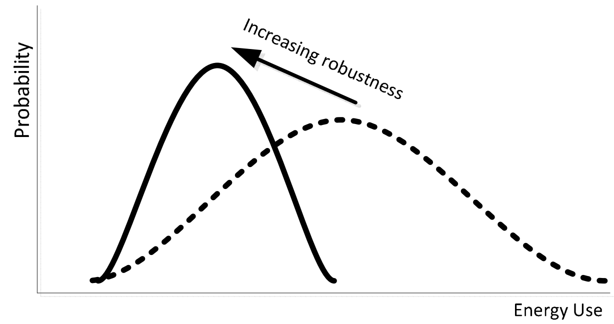
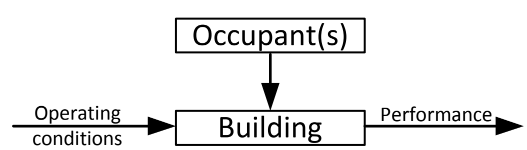


Figure 3: Illustration of the robustness concept: lower mean and standard deviation of building performance

Hoes et al. (2009; 2011) are the only researchers, to the author's knowledge, to explicitly apply Taguchi's robust design method to buildings and their performance. In their first paper, they varied several parameters such as thermal mass and glazing area. They used the occupant blind algorithm from Lightswitch-2002 which dictates that blinds are closed by occupants if solar radiation on the façade exceeds 50 W/m^2 and it "hits the work place" (Reinhart 2004). For their second paper Hoes et al. optimized a simple building with multi-objective optimization (comfort and energy use) and BPS engine ESP-r to establish a Pareto front. Using a "relative standard deviation" indicator, which is essentially the signal-to-noise ratio, they suggested that designers should select the most robust of the building designs among those on the Pareto front.

The important feature of the currently proposed methodology is that it considers that the response of occupants is directly tied to the design of the building and the conditions that result from it (see Figure 4). An important feature for future occupant models used for robust design is that they are sufficiently generalizable for the entire range of building design features being considered.



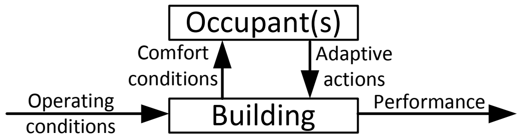


Figure 4: Robustness model: without considering influence of building on occupants (top) and with direct influence of building design on occupants (as discussed in this paper; bottom).

The key phenomenon that is being addressed here, by robust building design, is that occupants are known to attempt to adapt their environments at times of discomfort, but do not respond nearly as quickly when the source of discomfort is alleviated – especially if an alternate (often energy-consuming) option is available. For example, occupants often close window shades quite promptly to protect themselves from severe glare. But if a building has electric lighting, then the occupants remain relatively comfortable, insofar that they can still function because there is adequate illuminance. Thus, their only motivation to re-open shades would be to admit daylight or enable views to the outside. Because many low-energy building strategies rely on weather conditions – which are often cyclical – this phenomenon of prompt discomfort alleviation but slow system restoration is quite common. Thus, the goal here is to minimize the frequency at which the 'crisis of discomfort' (Bordass, Leaman et al. 1994) events occur. An excellent example of this is by Rijal, Tuohy et al. (2007) who found that addition of thermal mass and fixed horizontal solar shading (i.e., an overhang) to an office reduces the fraction of time when occupants rely on open windows for reducing overheating by about 85%. Thus the potentially negative effects of leaving windows open (e.g., loss of useful solar gains and noise from outside) are avoided. Meanwhile, less effort is required from the occupant to maintain comfort.

Many of the popular passive strategies that are used to achieve low energy in buildings encounter periods of discomfort, including:

- Daylight: glare, high levels of incident solar radiation on occupants
- Passive solar: overheating, high/low radiant surface temperatures
- Natural ventilation: drafts, noise

One final example of robust design is the National Renewable Energy Laboratory (NREL) Research Support Facility (RSF) (Guglielmetti, Pless et al. 2010). It uses windows whose upper portion have fixed light louvers that are specifically designed to redirect beam solar radiation up onto the ceiling – regardless of solar altitude - thereby protecting occupants from glare. The result of this design is that movable shades are not needed, thus not requiring occupant interference. It should be noted that light louvers operate best under sunny conditions, which this Colorado building has plenty of and on the south-facing façade.

Figure 5: Exterior of NREL RSF space showing fixed shading (lower portion) and light louvers (upper portion).

Eventual building simulation models should include greater awareness of uncertainty since virtually all inputs have some uncertainty and express predicted performance not as a single definitive value but as a probability distribution (Figure 6). This includes building materials and construction quality, climate, occupant behaviour, space uses, etc.

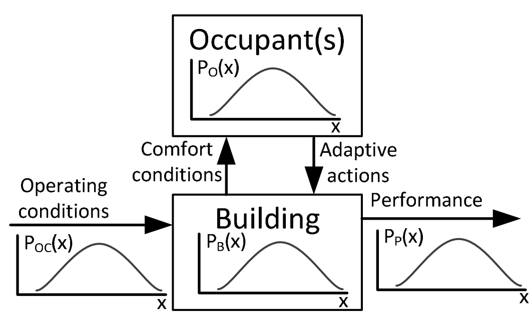


Figure 6: High-level modelling methodology for robust building design, whereby one or more inputs in provided to the BPS engine as a stochastic process rather than deterministic or absolute value. The output (generated with multiple simulations).

3. CASE STUDY

To demonstrate the concept of robust building design, a quasi-stochastic window shades model was implemented in EnergyPlus. The building model is a single 3-meter cube office in Toronto with a south-facing window (window-to-wall ratio of two-thirds), fixed shading device as shown in Figure 7. The fixed shading device is designed to completely block the direct solar radiation from hitting the workplane during the six warmest months of the year. It extends far in the east-west direction only because to simulate a long row of identical offices. The office is assumed to be occupied 9 to 5 on all weekdays. The office is modelled to be equipped with motion sensors and a daylight sensor that turns the electric lights off if workplane illuminance in the centre of the office exceeds 500 lux.

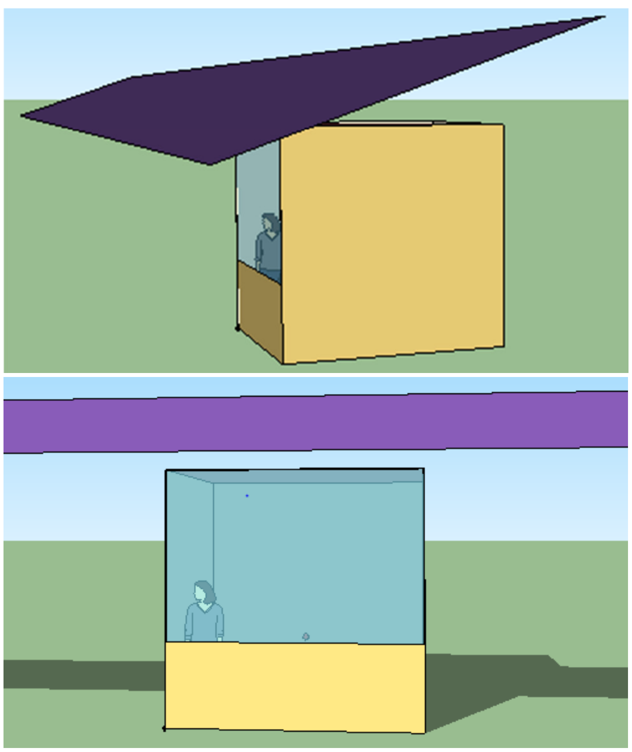


Figure 7: Screenshots in SketchUp/OpenStudio showing the south-facing single-occupancy office and fixed shading device.

The top-down roller shade (visible transmittance 5%) is assumed to be manually controlled in the following way.

1. Start simulation year with shade open.
2. If workplane illuminance exceeds I_{max} and there is direct solar radiation on the workplane, close it and keep it closed for $t_{inactive}$ days.
3. Re-open if $t_{inactive}$ days have elapsed and an occupant is present (i.e., 9-5 weekdays).

Where I_{max} and $t_{inactive}$ are determined at the beginning of each simulation year by randomly obtaining a value from the two normal distributions in Figure **8** and Figure 9. The values are based on reasonable values provided by the literature (O'Brien, Kapsis et al. 2012; Reinhart 2004), but do not follow any particular model; they are intended primarily for illustrative purposes. 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). Values under this indicate a particularly sensitive occupant or an office which is prone to glare (e.g., large monitors). Values above the mean would correspond to a more tolerant occupant, a space use which is not prone to glare, or a shared office in which there is a diffusion of responsibility regarding closing the shades, for example.

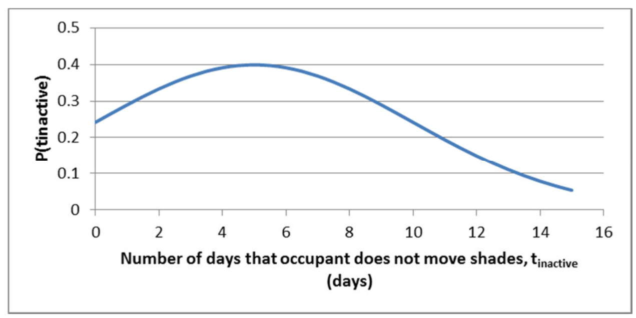


Figure 8: Probability distribution for the number of days (rounded to nearest integer) for number in inactive days after a shade closing event.

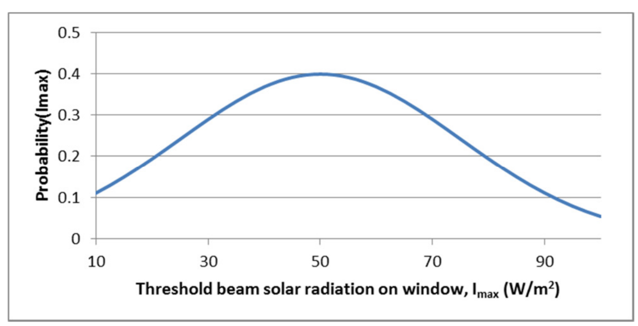


Figure 9: Probability distribution for the threshold of solar radiation on the window, above which the occupant closes the shade.

One of the major limitations of most of the existing field studies on shade movement behaviour is that the movement is studied as a direct function of exterior weather conditions. This reduces the universality of results because of the unique nature of many buildings (Haldi and Robinson 2010). Thus, the interior conditions, those that *actually* prompt shade adjustment, are unknown (or at least unpublished). Many of the simulations based on field studies exaggerate the level of responsiveness of occupants by eliminating the passive occupants. Most field studies upon which stochastic models are based use a method to screen out inactive users or increase movement (O'Brien, Kapsis et al. 2012). 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 occupants! 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 the same thing: a 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 86%, which is consistent with measured values for south-facing facades (like for the building in Figure 2). It should be noted that intermediate shade positions were not considered; only completely open or closed.

The shade control algorithm was implemented using EnergyPlus' Energy Management System (EMS), which allows users to write some code to be executed at runtime. A limitation to this approach was that the random number generator obtains its seed from the simulation time, not computer clock time. This resulted in identical random numbers for each simulation. To resolve this, the EnergyPlus simulation was called from a MATLAB script which randomly selected the seed.

To study the behaviour of multiple occupants (e.g., in a large office tower), 100 simulations were run for the office with and without the fixed shading device. This is essentially Monte Carlo simulation with random selection.

The results from this case study are quite profound. They show that the building with fixed shading uses approximately half the energy, on average and with considerably less variation, than the building with no fixed shading. From the logic of the model, this occurs because the conditions required to close the shades are rarer with fixed shading. The mean shade occlusion of office with the fixed shading is 27% versus that for the office without fixed shading (86%). In human terms, the occupant in the office with fixed shading was confronted with glare much less frequently than the occupant without it. 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.

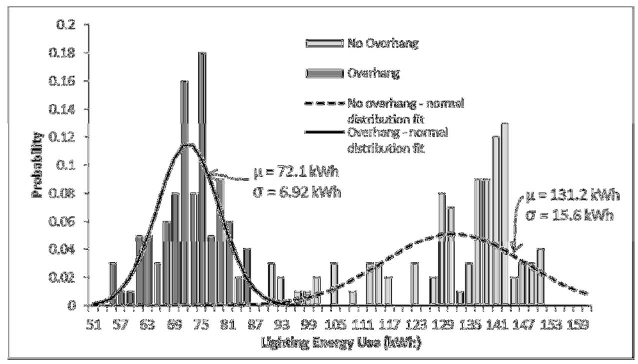


Figure 10: Probabilities distributions and normal distribution fits for the lighting energy use for an office with and without a fixed shading device.

Note that there is only a very small probability (and none of the 200 simulations indicated it) that the unshaded office performance exceeds that of the office with fixed shading. Theoretically, a "hyperactive" occupant can always beat the case with fixed shading by constantly adjusting the shade to optimize daylighting while avoiding glare. However, because the minimum allowed delay between closing and opening the shade was set to one day, this cannot occur. The literature suggests that such hyperactive occupants are not commonplace.

It should be noted that considerable effort (trial and error) was required to design a shading device that adequately avoided glare while not significantly reducing the number of possible daylit hours. Furthermore, this exercise would be significantly more difficult for east and west-facing windows which are notoriously difficult to shade with fixed shading because of the low solar altitudes. This exercise was somewhat impeded by the coarseness of EnergyPlus' built-in daylighting methods. Incorporation of more detailed lighting simulation engines, such as RADIANCE, into a growing number of BPS tools will facilitate greater design freedom. For instance, using fixed shading devices to redirect diffuse daylight into the space would likely further advance robust design of shading devices.

4. CONCLUSION AND FUTURE WORK

This paper introduced the concept of robust building design – the notion that good fixed design can help eliminate or significantly reduce some sources of occupant discomfort, resulting in a lower frequency of adaptive measures by occupants. This is important because many of the current intended and invented adaptive measures cause buildings to use more energy than expected. Furthermore, and at least as important, every action that an occupant has to take to improve their comfort decreases their satisfaction with the building. Although providing occupants with the perception of control is very important and can trump quality of the indoor environment itself (Paciuk 1989), a building that minimizes periods of discomfort by its use of geometry and materials is highly desirable.

While, robust design can be largely tackled using traditional building design models, including rules of thumb, pattern guides, and case studies to guide new building design, BPS provides a cost-effective and quantitative method that surpasses all other methods. However, occupant behaviour models are currently in their infancy with only a handful having evolved from research-stage to a level at which they are incorporated into publicly available BPS tools. There is a need for BPS tools to incorporate both occupant variation and adaptive measures taken by occupants. The most promising and popular method in the literature for understanding occupant behaviour is stochastic modelling; but it is not without limitations, including:

- Lack of generalizability: stochastic models are mostly based on a single field study of specific buildings, climates, cultures, and technologies. It is known that subtleties such as motorization of window shades has a profound effect on frequency of movements. Variations in research methodologies have further contributed to the difficulty of establishing universal
- Difficulty in implementing: stochastic modelling requires some knowledge of statistics and furthermore, most BPS tools do not readily allow it. To the knowledge of the author, EnergyPlus is one of the few BPS tools that readily enables development of new features without compiling source code.
- Lack of standards: due to the infancy of the research base, industry and government have not adapted stochastic modelling. As previously noted, the industry is accustomed to making very conservative assumptions about occupants in order to mitigate risk of undersizing HVAC equipment.

Future research is required in robust building design, including:

- Incorporation of a more comprehensive occupant model that includes as many adaptive occupant measures as possible.
- Use of more accurate specialize models (e.g., RADIANCE) to assess glare.
- Formalized robust design methodology and incorporation into tools and design guides.

In closing, this paper proposes occupant focusing design on "robust" features that function well and provide comfort under diverse conditions. Only once such opportunities are exploited, automated adaptive controls with manual overrides should be used. Relying on occupants to provide comfort, and particularly to avoid discomfort, should be avoided for the sake of building performance certainty, as depicted in

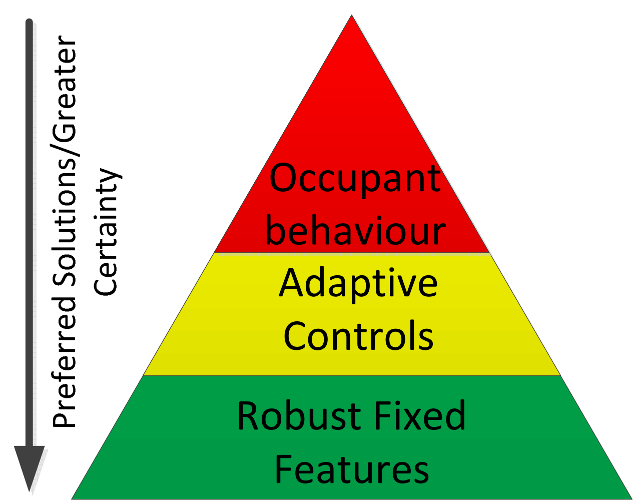


Figure 11: Preferred order of building design features that provide occupant comfort.

Acknowledgements

[To be provided in final copy due to anonymity issues]

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