POST-OCCUPANCY EVALUATION OF ENERGY AND INDOOR ENVIRONMENT QUALITY IN GREEN BUILDINGS: A REVIEW

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Abstract

The need to reduce energy use as part of a strategy to alleviate environmental stresses is widely accepted. Buildings are big end-users of energy; buildings account for 20-40% of the energy demands in developed nations, and the rate of new building construction in developing nations is accelerating. To reduce the impact that buildings have on the environment, the need for them to use as little energy as possible while still providing a satisfactory indoor environment is critical. The green building movement may be an effective catalyst for this, and various green building rating schemes are now in the marketplace worldwide. Certified "green" commercial buildings exhibit higher real-estate values, presumably reflecting expectations for reduced operating costs, and improved organizational productivity through better indoor environments for employees. However, the higher market value cannot be maintained in the long run if these buildings do not deliver their expected benefits. The early generations of "green" certified commercial buildings have now been occupied for several years, and it is time to explore whether these "green" buildings are living up to expectations in objective terms. This paper reviews several of the post occupancy evaluations (POEs) that have been performed. A limited number of POEs are available in the public domain, making it difficult to draw solid conclusions. However, early trends suggest that green buildings on average seem to be delivering reduced energy use, however a large spread in performance is often observed meaning that individual buildings do not always perform as expected. Occupant satisfaction with some aspects of the indoor environment appears to have improved compared to conventional buildings, but there are areas where expected improvement trends are not realized. This paper provides some possible explanations for the observed performance, and describes a new, Canadian-led, research project that aims to explore these issues further.

1. Introduction

As the global population increases and more people enter the workforce the need for commercial buildings escalates. In developed countries, buildings account for 20-40% of the total energy use; buildings use more energy than industry and transport in the EU and USA (Pérez-Lombard et al. 2008). In Canada in 2005, energy use was divided as follows: 30.1% buildings (13.6% commercial and 16.5% residential), 37.9% industry and 29.5% transportation (National Resources Canada 2008). Building energy consumption is also one of the primary contributors to atmospheric greenhouse gases. To reduce the environmental footprint left by the current generation, new buildings need to be energy smart, that is, use minimal energy in both their construction and operations, but still provide a satisfactory indoor environment for their occupants.

Numerous Countries or Regions have developed green building programs aimed at promoting more sustainable buildings. At the crux of each program is the use of an integrated design approach, and a points scheme that allots credits for building design features deemed to improve sustainability. These schemes have been thoroughly explored and compared previously (Cole 1998; Crawley et al. 1999; Todd et al. 2001; Bosch et al. 2003; Fenner et al. 2008; Lee et al. 2008). We will briefly discuss four here: BREEAM, LEED, Green Star and HK BEAM.

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The Building Research Establishment first released the United Kingdom's Building Research Establishment Environmental Assessment Method (BREEAM) in 1990. The current version was released in 2006 (Building Research Establishment). The United States Green Building Council (USGBC) developed the Leadership in Energy and Environmental Design, LEED program (US Green Building Council 2008) several years later and it is now being used across North America (suitably adjusted for local codes and climates). In 2003 the Green Building Council of Australia released their environmental rating scheme, called Green Star (Green Building Council Australia 2008). The Hong Kong Building Environmental Assessment Method (HK-BEAM) was released in 1996. Revisions to the original releases have been made, as experience in their use grows.

All use a point or credit system throughout the design process, rewarding sustainable practices within various categories. For example, credits are awarded in the construction phase including recycling, site selection, water use minimization, and in the post-construction stage for commitments to good management and operation. In the aforementioned schemes, a large portion of the available points are awarded for reducing energy use and improving indoor environment quality (IEQ) through various means. The current version LEED has a total of total of 70 points available of which 17 are for energy saving initiatives and 15 for indoor environment quality improvements. The current version of BREEAM assigns 24 for energy and 13 for health and wellbeing out of a total of 116 points. Green Star's current version has a total point allocation of 142 with the energy and IEQ categories providing up to 29 and 27 points respectively. For HK-BEAM some of the sub-categories in energy and IEQ are building-type dependent and therefore generalizable numbers are not readily obtained, nevertheless, energy and indoor environment are substantial contributors.

Energy points are typically based on the size of the predicted reductions versus a locally specified baseline. For example, in Canada the baseline energy consumption is either the Model National Energy Code of Canada for Buildings (MNECB) or the reference energy cost according to ASHRAE/IESNA 90.1-1999 (Canada Green Building Council 2004). Indoor environment quality points are generally based on industry accepted performance recommendations (e.g. ASHRAE 62-2001: Ventilation for acceptable indoor air quality, ASHRAE 55-2004: Thermal comfort conditions for human occupancy) or expert consensus.

The first buildings that received accreditation under these green building rating schemes are now being occupied, and it is reasonable to ask, are these buildings living up to expectations? To answer this question post occupancy evaluations (POEs) need to be undertaken to measure the buildings' performance. POE can also help diagnose operational problems and commissioning errors, which may allow the building to reach a higher level of performance. If a POE is conducted, it often surveys the occupants regarding their satisfaction with various building amenities, such as lighting, air quality, temperature, acoustics, and cleanliness. Sometimes this is extended to include physical measurements of the occupant's space, which are then correlated to their perceived comfort levels (Veitch et al. 2002). Data collection on actual energy performance may also be addressed via either the collection of utility bills or monitoring with building systems.

In this paper we review the published work on post-occupancy performance of green buildings in terms of energy use and indoor environment quality. We draw some early conclusions from this published work, suggest directions for future POE studies, and introduce a new Canadian-led research project.

2. The Review

2.1 Energy Performance

Torcellini et al. (2004) conducted an overview of six high performance buildings in the USA. Extensive monitoring of energy flows including lighting loads, heating ventilation and air conditioning (HVAC) loads and plug loads for a minimum of one year was undertaken. The data was logged every 15 minutes and used to calibrate energy simulation models. Analysis showed that all buildings performed worse than predicted but all managed a saving (either energy cost or energy use) compared to an equivalent code-compliant building. Variation from the predicted savings was believed to be a result of higher than expected occupant loads and systems not performing together as designed. They concluded that the designers had been optimistic about the behaviour of the occupants and their acceptance of systems. For example, the hours of operation and building space temperatures varied from the initial design. Further to this, simulated performance could be in error because the constructed building often differed from the initial design. The authors also noted that it was difficult to define a set of metrics to measure energy consumption across all six buildings due to a large variation in the buildings' processes and capabilities.

Eleven LEED certified buildings in the Cascadia Region, USA were assessed by Turner (2006). The author compared the actual utility usage to three different metrics: design energy use, energy-use compared to a code-compliant baseline, and the average energy use of the commercial building stock. All buildings performed better than their baseline, six of the buildings performed better than their design energy use, and all but two performed better than the average commercial building stock. The authors noted that actual operational variables may have differed from those assumed in the baseline models, and that operational optimization was still underway in some buildings.

Diamond et al. (2006) investigated 21 LEED certified (LEED-NC Version 2.0/2.1) buildings. Actual energy use was determined from utility billing data. The modelled energy data for the as-designed and baseline building was obtained from the LEED certification documentation submitted to the USGBC. On average, for the 18 buildings that had both simulated whole building design and actual energy use data, energy use was 1% lower than modelling predictions (which were 27% below baseline). However, there was large variability, and some performed better than predicted while others performed worse. Further, the number of LEED energy credits obtained in the certification did not correlate with the actual energy use per floor area. The authors recommended that a comprehensive collection and publication of modelled vs. actual energy use data was needed, allowing for a closing of the gap between design simulation and as-built performance.

The largest and one of the most recent studies was undertaken by Turner & Frankel (2008). It reviewed 121 North American LEED buildings (22% of the available LEED-certified building stock) and concluded that the program on average is delivering around 25% energy savings compared to conventional buildings. Average savings also increased as the performance goals were increased (gold/platinum certification). The authors noted that there was a large amount of scatter in the energy performance of the sample of green buildings examined. Thus, the authors concluded that further refinement is required to improve the LEED program and procedure to ensure more consistent success.

Fowler & Rauch (2008) reported on a comprehensive study of 12 General Services Administration (GSA) buildings. The buildings were predominantly federal buildings or courthouses designed with either a green intent or LEED certified. The study investigated the overall sustainability of the buildings by reviewing water and energy use, waste management, occupancy satisfaction, transportation and maintenance and operation costs. Energy use was determined from at least 12 months of utility bills. Actual building energy use was compared to the Commercial Buildings Energy Consumption Survey (CBECS) national and regional averages and GSA national average goals. The authors found that the green buildings performed on average 29% better then the CBECS regional averages.

Baylon & Storm (2008) examined the characteristics of LEED commercial buildings in the US Pacific Northwest, and compared them to regional non-LEED buildings. The mean energy use per floor area for the 12 LEED buildings was 10% lower than the 39 similar non-LEED buildings in the same region. This relatively small improvement was attributed to the relatively high prevailing energy standards for all buildings in the region. Again, the authors noted the uncertainty of conclusions based on such a small and varied dataset.

All of the mentioned studies on energy use of green buildings came to similar conclusions on why variations existed between the predicted and measured energy use. Some key common factors were:

- The actual occupancy hours can differ from those used in the initial design assumptions
- The final as-built building can differ markedly from the initial design on which majority of modelling is based
- The often experimental technologies proposed to save energy may not perform as predicted
- Plug loads are often very different than assumed
- The buildings may not be commissioned properly, and a knowledge transfer gap exists between the design team and end users

2.2 Indoor Environment Quality

All of the sustainable design rating schemes award credits for actions intended to improve indoor environment quality (IEQ). To date only small-scale post occupancy surveys on the IEQ in green buildings have been reported, many of which are case studies of small, specialist buildings, making it difficult to draw generalisable conclusions.

Heerwagen & Zagreus (2005) performed a post-occupancy evaluation on a single LEED building. Results showed that it rated third overall in general end-user satisfaction in the IEQ database maintained by the Centre for the Built Environment (CBE) at the University of California, Berkeley. At the time of the study there were approximately 170 buildings in the database, ten of which were LEED certified. As noted by the authors, the study building was located on the shores of Chesapeake Bay resulting in positive responses to views and nature. Add to this the powerful impact that the environmentally-focused tenant organization has on its employees, and the authors questioned whether the experiences of the occupants are truly translatable to other buildings of similar size and shape.

Abbaszabeh et al. (2006) performed occupant surveys for 21 green-designed buildings, 15 of which were LEED rated with the remaining six identified by the owner or designer as being green. The results of the surveys compared the performance of the green buildings to conventional buildings in the CBE database. They compared the median of the mean scores (of the individual buildings) for green and conventional buildings. On average occupants of green buildings were more satisfied with the building overall, and with air quality and thermal comfort compared to conventional buildings. Lighting and acoustic quality did not show any overall improvement in comparison with non-green buildings. Satisfaction scores for the green buildings for both of these components of the indoor environment clustered near the extremes of the satisfaction scale, that is some buildings performed better while others performed poorly compared to other buildings in the CBE database. The authors asked the question if there has been a deliberate effort to improve IEQ, then why was there no obvious improvement in lighting and acoustics? Their investigation of the complaints for both conventional and green buildings shows that the top three complaints in green buildings for lighting are the same as conventional buildings (i.e. not enough daylight, reflections in computer screens and the space being too dark). Sustainable designs often involve the use of daylight to reduce electric lighting needs as well as lower ambient lighting levels. The authors put the occupant dissatisfaction down to the larger percentage of people having no control over such factors, contrary to what one would expect. The introduction of the daylight into buildings involves the use of open plan offices with lower partition heights to increase the penetration depth of natural light. In addition, hard surfaces are often used to promote air quality. These design alternatives, however, can increase the number of complaints about speech privacy (people talking in neighbouring areas, others overhearing private conversations, and hearing talking on the phone).

Leaman et al. (2007) conducted a Building Use Study (BUS) survey in 22 green and 23 conventional buildings in Australia between 2003 and 2006. It was noted by the authors that the conventional buildings in the study could be better than the norm due to the survey being prompted by the designer/owner, in part to gauge the impact of a positive intervention in the building. Average results from the surveys showed that the users' ratings of the physical variables of temperature, air/ventilation, noise and lighting were overall lower in green buildings than conventional buildings except for "lighting overall". Scores on other relevant variables (design, image, needs, health and perceived productivity) were on average generally better for the green buildings than conventional buildings. A larger spread of performance was also evident in green buildings compared to conventional buildings. It was noted that noise was often worse in green buildings, but that occupants of green buildings tend to be more tolerant of their environment if items that they like are present, or if they have an understanding of how controls and facilities are meant to work.

Two case studies in the United Kingdom were reported in 2007. The Rivergreen Centre in Durham is a naturally ventilated office (Bunn 2007a), and is in the top 17% of the BUS UK dataset for occupant satisfaction. However, the authors report that the building was excessively noisy for the occupants, being well below benchmarks and putting it and in the bottom 7% of UK dataset for noise. "In general, BUS finds that bigger green buildings tend to score lower than smaller ones because it is more difficult to create good thermal comfort and acceptable noise conditions in bigger buildings" (Bunn 2007a). Environmentally, the building emitted 24.5 $kgCO_2/m^2$ compared with the best practice benchmark of 37.7 $kgCO_2/m^2$. The second UK building was studied by Bunn (2007b). Located in Swindon and owned and operated by the National Trust. No conclusive energy data was available due to several commissioning problems and systems not operating as planned. The occupants were satisfied with the building as a whole. It rated in the top 40% for the UK green building dataset. The building was rated satisfactorily for design, needs, space and lighting. It rated poorly however for some of the noise variables, and temperature and air variables.

Paul & Taylor (2008) compared two buildings in Australia; one green and one conventional, which belonged to two different universities in Wodonga Victoria. They concluded that there was insufficient evidence to support the hypothesis that green buildings outperform conventional buildings in terms of aesthetics, serenity, lighting, ventilation, acoustics and humidity. The only noticeable difference was the negative results with respect to temperature in the "green" building, but this was put down to the fact that a part of the cooling system was not operational at the time of the survey.

Paevere & Brown (2008) conducted BUS surveys as well as focus group sessions on the newly completed CH_2 (Council House 2) building owned and operated by the City of Melbourne. CH_2 was Australia's first 6 green star rated building. Interestingly, a critical part of the business case for the building was an assumed 4.9% increase in staff productivity due to improved IEQ. Results of the survey were compared to the first council house (CH_1) building across the road, which was not green-intent designed. CH_2 was still going through commissioning while the surveys were being undertaken. The occupants were highly satisfied with the building overall, with generally higher satisfaction ratings than for Australian BUS benchmarks. Both lighting and noise were two attributes that rated poorly with the occupants. Physical measurements of ambient noise levels, reverberation times and lighting levels were considered appropriate, however.

The 12 GSA buildings as reported by Fowler & Rauch (2008) had higher than average satisfaction scores in general building, general workspace, thermal comfort, air quality, lighting, acoustic quality, cleanliness and maintenance. Occupant satisfaction was determined from a modified version of the CBE occupant survey to include questions regarding the commute to work. An interesting result was that occupant satisfaction for lighting and acoustics was slightly higher than for non-LEED buildings. A result that is in stark contrast to the other studies reviewed here.

3. Discussion

Green building organisations that administer green building certifications do so on a building-by-building basis, with the overall goal of the organisation to reduce the aggregate energy consumption on a community or even global scale. Certification under a green building program is possible without achieving points in the respective energy category (besides meeting the mandatory provisions), by accumulation of points outside of the energy category. If average energy performance of green certified buildings is good, then the program has potentially achieved its societal goals. Nevertheless, if individual buildings do not save energy as expected then the program creates false expectations. The building owner who invested in the system may become disillusioned and not invest in such programs again. Further this may not encourage the wider uptake of green building practices. The same is true of indoor environment quality performance. Green buildings are often marketed with the expectation that there will be improved organizational productivity due to an improved indoor environment, a link which is generally supported by research (Charles et al. 2004). The improvements in organizational productivity in green buildings will only result, however, if the improvement to IEQ is delivered. For example the business case for CH_2 included a 4.9% improvement in productivity (Paevere et al. 2008). If this improvement is not observed however, the pay back period maybe extended, letting down the owner. The results of a recent real estate survey suggest that the market is attaching substantial monetary value to green buildings (Fuerst et al. 2008). Clearly, this green premium cannot be maintained if in the long run these buildings do not deliver their assumed performance benefits in either indoor environment quality or energy consumption. Therefore, it is critical for the integrity and value of the green building rating system that buildings deliver on their expected performance.

On the surface the programs seem to be producing, on average, energy savings across the analysed building stock. The reporting of the energy savings varies from study to study, but with no clear benchmark with which to compare buildings it is difficult to determine and compare energy savings. Given the large variation seen between the actual and modelled energy use, how much faith can be placed in baseline models? Comparisons can be made of green buildings available against the average local building stock, but how fitting is this indication of how the building is actually performing? Conventional buildings are often older than green buildings and may have differing end-uses and ownership profiles.

There is a substantial amount of evidence detailing the characteristics that office workers like in their work environment. Characteristics generally include views, natural light, natural ventilation and a high quality of air, as well as control over their environment (Leaman et al. 2007). Green building rating systems encourage the provision of such features, that might have been left out of conventional buildings in recent years. Results show that, in general, occupants of green buildings have higher satisfaction with air and thermal comfort, whereas other features like lighting show little or no improvement between green and conventional buildings.

A clear trend exists with a decrease in acoustic satisfaction associated with green buildings. A decrease in acoustic satisfaction may be a logical consequence of the current LEED credit scheme, which offers credits for building design features such as low partitions to allow natural light to penetrate and allow views, and hard ceilings and floors to improve air quality. However both of these features have negative effects for acoustics (Bradley et al. 2001). This is compounded by the fact that no credits for acoustic performance currently exist potentially resulting in acoustic quality not being considered at all in the design. A proposal has been made to hopefully counteract this trend (Jensen et al. 2008).

The overall aim of the green building movement is to construct buildings that use less energy than their predecessors, without compromising indoor environment quality. Generation of a highly efficient building with poor IEQ will not be sustainable, as no one will want to use such a building and refurbishment may quickly follow final construction to set the IEQ right. An interesting question to think about is the potential trade-off between investing in improved energy efficiency over IEQ, or vice versa. For example the green building in Paul (2008) used $1/12^{th}$ of the energy of the conventional building, but there was no improvement in indoor satisfaction observed. Would a better option be to have used slightly more energy and improve the conditions for the occupant? Or is the fact that the environment has not deteriorated in any way satisfactory? More POE data will help address such questions.

Green building rating schemes currently provide certification based on as-designed performance. Placing a post occupancy or as-built certification label on the building as proposed by Bordass et al. (2004) should drive the need for greater emphasis on build quality/process and commissioning of the building. Further to this, outcomes of post occupancy evaluations facilitate the fine-tuning of the building so that it may operate as designed, and predicted energy saving targets may be reached. If pursued, practitioners will be required to learn appropriate POE techniques. Administration of the POE will be place a greater burden on the industry, but should result in much more useful data with which to continue to improve the rating systems.

A new Canadian research project, led by the National Research Council – Institute for Research in Construction, is in design. The project will be an in-depth evaluation of the energy and IEQ performance of several green and conventional buildings. The evaluations will involve the comparison of environmental measurements, occupant surveys and energy performance data. On-site measurement of the physical environment will also be performed (e.g. lighting, air quality, temperature, acoustics). Occupant surveys will feature questions relating to: environmental satisfaction (e.g. lighting, air quality, privacy, workstation), job satisfaction, organizational commitment, and well-being. If available, relevant data from organizational records (e.g., absenteeism, turnover rates, performance assessments) will be collected as well as energy performance data from existing systems; e.g. utility bills, ECMS logs, lighting control system records. For the green buildings, validation and calibration of building energy models as a means to explain any erroneous energy performance will be tackled. Results will be compared to archival records concerning building design goals and energy use predictions. The results will be used to help identify what aspects of green buildings work and what aspects need improving, with the potential to propose revisions to rating schemes. The results will also inform the development of post-occupancy measurement protocols by the Green Building Councils, or similar organizations pursuing post-occupancy certification of buildings.

4. Conclusions

There are a number of green building programs available worldwide to chose from to help design more sustainable buildings. The rate at which owners are getting their buildings certified green has increased over the last few years. The first and even second generation of these buildings are now being occupied. The question was asked whether these green buildings deliver on their original design intent? Answering this question is difficult at this point in time with only a limited number of publicly-available post occupancy evaluations to draw upon. It seems that, on average, buildings designed with an emphasis on its environmental impact do use less energy when compared to conventional buildings. However, this reduction in energy use is not apparent for every green building. Satisfaction levels of the majority of the indoor environment variables show, on average, improvements in green buildings compared to conventional buildings. A general trend of a decrease in satisfaction levels with acoustics is the stand-out result of most of the reported studies. Nevertheless, studies to date often only involve a limited number of buildings, making it difficult to draw strong conclusions.

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