Learning from Buildings: Technologies for Measuring, Benchmarking, and Improving Performance

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ABSTRACT: This paper describes methods developed at UC Berkeley for monitoring and benchmarking commercial buildings’ physical environments and occupants’ perceptions. Examples of technologies we describe include: mobile instrumented carts for commissioning and research, desktop indoor climate stations, wireless sensor arrays for real-time performance analysis, web-based indoor environmental quality surveys, desk-top “right now” thermal and lighting surveys, and visualization feedback systems. These methods have benefitted from years of refinement by researchers, owners, and building industry professionals. We present some research results derived from such assessments and their contributions to reducing energy use and improving indoor environmental quality in the design and operation of real buildings. Driving this work is the belief that all stakeholders benefit from increased assessment of indoor environmental conditions, energy costs, and occupant feedback.

(Keywords: buildings, performance, measurement, survey, energy, indoor environmental quality, occupant satisfaction)

INTRODUCTION
Reducing energy use, while simultaneously maintaining the quality of the indoor environment, requires that ongoing assessment of building performance become both commonplace and reliable. After all, you can’t manage what you can’t (or don’t) measure. While there has been increasing recognition of this need in recent years, the building industry is still far behind where it needs to be in doing it as a normal part of their routines, and the technologies available for measurement and evaluation are far from ideal. The objective of this paper is to describe various technologies and methods that have been used by the Center for the Built Environment (CBE) at UC Berkeley for monitoring and benchmarking commercial buildings, including many methods that are available to building practitioners. Using the technologies as an organizing framework, we describe how they have been used in research, what we have learned, and what the implications are for reducing energy use and improving indoor environmental quality in the design and operation of real buildings, including changes in building standards. Finally, we discuss current research aimed at validating the Performance Measurement Protocol, a new method for assessing buildings in a systematic and holistic manner recently produced by ASHRAE, USGBC, and CIBSE.

ASSESSMENT TECHNIQUES & APPLICATIONS
Our methods of assessing building performance include surveying occupant perceptions and opinions, as well as assessments of the physical indoor environment, and many of our research projects use a combination of subjective and physical methods.

Occupant Satisfaction Survey
For the past 12 years, CBE has been conducting web-based indoor environmental quality surveys in office buildings to assess general satisfaction and building acceptability. The anonymous, invite-style survey measures occupant satisfaction and self-reported productivity with respect to nine environmental categories: office layout, office furnishings, thermal comfort, air quality, lighting, acoustics, cleaning and maintenance, overall satisfaction with building and with workspace (Zagreus et al. 2004). The questions asked in the survey have remained consistent over time to create a standardized searchable database for benchmarking and analysis. At this time the general survey results cover approximately 570 buildings, over 63,000 respondents, and over 4.8 million data points. Approximately 85% of buildings in the database are located in the United States. Canada and Australia each represent 5% of the database. The remaining 5% are primarily located in Europe, Mexico and Africa. Fifty-three percent of the buildings are offices. Many buildings in the database have more than one use. These references refer to primary uses only.
including elementary, secondary and post-secondary uses. Five percent each are commercial (e.g. retail) or public (e.g. libraries or courthouses.) The remaining buildings are mostly healthcare or laboratories. Building sizes start at under 1,000 square feet and peak at 2.5 million square feet. The survey can be used for individual building diagnosis and benchmarking, while the large database allows us to assess broader trends in the relative success of building design and operation, or new building technologies. Reports are generated automatically for the clients, and they have access to search and filtering tools that allow them to compare their building against others in many ways. An important feature of the survey is its branching questions. If an occupant is dissatisfied with one of the nine environmental categories, they receive a more detailed question aimed at finding the source of the dissatisfaction.

The survey is frequently used for buildings seeking LEED-EB certification, and we have used it to measure and improve the operating performance of buildings. This can be used to evaluate the performance of service providers, or to evaluate the success of design features. For example, in the LEED-NC Platinum Kresge Foundation Headquarters, the survey discovered that the building was typically over-conditioned. Thirty percent of occupants were dissatisfied with the building's temperature. Of these dissatisfied occupants, 53% reported being too hot during the winter. At the same time, 53% also reported being too cold during the summer. It was also noted that occupants were not actively using many of the personal control mechanisms available to them (task lights, blinds, operable windows, light switches, etc.) and instead brought in comfort appliances like personal heaters or fans.

Combining survey results with field visits proved exceptionally useful here. Although a plurality of occupants reported understanding how to use these controls on the survey, conditions in many workstations and free text comments suggested that occupants were not using the controls as the designers intended. Several comments reported occupants closing shades (reducing daylighting) and turning on both task and overhead lamps. These conditions were confirmed during field visits. It is these kinds of findings that help designers improve their design process. In this case, the design team might do well to capture feedback about occupants’ control usage patterns and preferences before design. (Goins 2011).

Figure 1 presents the average building scores for each category in the survey across the entire CBE database (orange diamonds), and for green and all certification levels of LEED-rated buildings (blue squares). Overall, thermal comfort and acoustics receive the lowest relative scores, with air quality being the third lowest. The LEED/green building we’ve surveyed are showing the largest improvement in air quality, and slight improvements in thermal comfort. But on average they were performing about the same in lighting (the symbols are exactly lined up) and acoustics. Green building lighting complaints were often associated with glare. Complaints with acoustics were more often associated with speech privacy than with noise, often coming from, open plan office layouts and high ceilings for daylighting and natural ventilation, and from the harder surfaces that may be selected out of concern for indoor air quality.

Figure 1. Average scores from CBE web-based survey for LEED/Green buildings and overall database

“Right Now” thermal comfort surveys
In thermal comfort field studies, one must obtain occupants’ subjective responses about how they are feeling about the thermal environment at a given moment in time, along with coincident physical measurements of the environment (described later). In the 1980’s and 90’s our ‘right-now’ survey of thermal sensations and acceptability ratings were administered on a laptop that the researchers carried around the building, and now they are more often presented over the web. The form of these questions has evolved over time, but we believe the ideal combination is to complement the traditional thermal sensation question with two more questions about acceptability and preference (Fig 2), so one can analyze rather than make assumptions about what thermal sensations and physical conditions are ideal. The correlation between sensation and preference behaves intuitively,
with respondents requesting warmth when too cold; the opposite is also true ($r=-0.71; p<.001$). The correlation between sensation and acceptability is more elastic however ($r=-0.27; p<.001$), with no strong relationship expressed. Occupants may report being cool and that this is acceptable. The opposite is also true.

These questions are an excellent diagnostic and research tool when paired with environmental measurements. They can also be complemented by other “right now” questions related to lighting, indoor air quality, or acoustics. Example research results will be described in a later section.

**Thermal comfort automated polling stations**

In buildings with transient occupancy or where employees do not have access to a computer, occupant reactions can be surveyed through an automated polling station. The type shown in Figure 3 has been used in demand-response precooling studies in stores, banks, and a museum. The building managers’ question was how might their customers be affected by temperature manipulation during demand response events? One can distinguish customers having short versus long exposures within the store by contrasting results from units near the entrance with those at the checkout counter. The polling station has colored diodes that flash to attract attention to the device and then assist the users as they make their selections by pressing buttons. A time delay imposed between entries discourages multiple entries by children, etc. An internal datalogger records both the votes and the unit temperature.

So far, we have found that store employees are more affected than the customers. This presents an opportunity in that there may be efficient ways to maintain employees’ comfort through localized or intermittent conditioning. In addition, by simply notifying employees in advance that a demand-response event is expected, they bring appropriate clothing and are less affected by the temperature fluctuation.

**Workstation comfort – mobile instrumented cart**

ASHRAE Standard 55 requires that indoor thermal environment measurements assess the seated comfort zone at three levels: 0.1, 0.6, and 1.1 m, with the additional level 1.7m for standing. We have built a series of mobile instrumented carts (see example in Fig 4), collapsible for transportation, that measure these three heights at the same time and automate the data collection. The instrumentation is laboratory grade, including air temperature, omnidirectional velocity, globe temperature, humidity, plane radiant temperature asymmetry, and illumination. The cart incorporates a chair seat and back to provide the directional shielding from radiation and draft that an occupant would experience. In use, the cart is moved into the occupant’s workstation for 5 minutes while measurements are taken, and is often combined with the “right now” survey described earlier.

**Figure 2. Sample thermal comfort questions in ‘right now’ web-based survey**

**Figure 3. Comfort polling station screen, and kiosk positioned in a bank**

**Figure 4. Example of cart used in building field studies**

Starting in 1985, such carts were used in a set of studies initially commissioned by ASHRAE to see whether buildings were actually following the provisions of their thermal comfort standard, and whether the standard’s laboratory-based thermal comfort zones matched field observations in operating buildings (Schiller et al. 1988). The studies expanded worldwide, and ASHRAE had the data assembled into
a public database (de Dear 1998). This database allowed us to analyze the differences between the comfort requirements of occupants in buildings with natural ventilation versus those in buildings with central air conditioning (de Dear and Brager, 2001). This research led to development of the Adaptive Comfort Zone, now part of ANSI/ASHRAE Standard 55 (2004), applicable to buildings with operable windows.

**Workstation comfort – fixed desk-based monitors**

Similar instrumentation can be stationed on a worker’s desktop to record a detailed record of the workstation climate over extended periods of time. Termed indoor climate monitors (ICMs), and shown in Figure 5, the units have shielded air temperature, humidity, a rugged hooded anemometer with properties close to omnidirectional, globe temperature, and (by splitting the globe on newer models) plane radiant asymmetry. The units were designed to be inexpensive because one tends to need a large number of them, and they are usually left in the office for long periods. We often extend the area covered using conventional temperature loggers. Data is recorded on an internal datalogger, but recent mesh-networked wireless versions allow real-time remote monitoring—a major improvement. The worker is prompted a few times each day to respond to a short “right now” comfort survey on the internet. In the case of the lighting station, the survey is carried on the device itself.

**Mesh network – building commissioning cart**

Another mobile cart, shown in Figure 6a below, was developed to facilitate the initial commissioning of the underfloor air distribution (UFAD) system in a major corporate headquarters tower in New York. The cart has a telescoping thermocouple array that measures temperature profiles with rapid response time. Infrared sensors measure floor and ceiling temperatures, and supply air plenum pressures are measured. The cart carries a laptop computer that serves to acquire data, analyze data, and serve as the operator’s graphic user interface. In addition, the cart acquires data from an array of 70 wireless sensors that measures supply air temperatures in floor-mounted diffusers, updating every few seconds through a mesh network using the Dust Networks protocols. The mesh network communicates to a base station positioned somewhere mid-array, and this station communicates with the cart through WiFi. The cart data is also uploaded to our Berkeley database via the internet (Figure 6b). Detailed commissioning procedures and pass/fail criteria are contained in the cart software, letting the operator immediately know whether the commissioning was successful. A more advanced, all wireless version of the portable wireless performance monitoring system (PWMS) is under development at CBE that will support the ASHRAE PMP (see following).

In the UFAD commissioning application, the cart was particularly useful to help determine the amount of room air stratification that occurs across the large floorplate (Figure 6c). This helps to identify the need for improving it by adjusting controls or possibly changing the number of diffusers. This type of

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**Figure 5. Indoor climate monitors and their uses in field studies.**

One example of research using these technologies allowed us to re-evaluate the limits on air movement imposed by ASHRAE Standard 55, which are very restrictive in neutral- to warm conditions. Providing air movement indoors is typically much more energy-efficient than additional air conditioning. A study combining the desktop ICMs and the “right now” survey (Brager et al, 2004) demonstrated that in neutral to warm conditions, about half the building’s population wanted more air movement and only 4% wanted less (Zhang et al. 2007). Providing air motion above 0.2 m/s (40 fpm) was equivalent to lowering the air temperature by 1°C. These results from field assessments led to significant changes in ASHRAE Standard 55 (2010) to allow for higher levels of air movement. The Standard now allows up to 0.8 m/s (4°C) in jointly-occupied warm spaces (ASHRAE 2010). In studies of personal control systems we have found that such air movement can be provided at less than 4W per occupant (Zhang et al. 2010).
commissioning cart also has general applicability in assessing buildings, in that it can quickly and continuously obtain simultaneous environmental conditions over large indoor areas. Its ability to transmit data in real time to remote observation locations makes it useful for both experiments and for building operators.

**Figure 6a  Commissioning cart with extended mast**

**Figure 6b. Wireless network connections**

**Figure 6c  Screen shot of air temperature stratification measurements**

**Performance Measurement Protocol**

Based on our experience in doing field measurements and surveys in buildings, CBE contributed to the Thermal Comfort chapter in *Performance Measurement Protocols (PMP) for Commercial Buildings*, published by ASHRAE in collaboration with CIBSE and USGBC. The PMP is a standardized set of protocols for assessing building performance, covering a range of accuracies and costs. In the Kresge Foundation Headquarters study mentioned earlier, we tested a combination of the PMP Levels 1 and 2 techniques to address specific issues such as UFAD system performance. Level 1 measurements are primarily from occupant surveys, with spot measurements in problem areas, while Level 2 measurements involve systematic physical measurements of space and energy performance. Figure 7 shows results from measurements of stratification made by the commissioning cart, showing northside zones to be overcooled and overaired. The measurements identified several energy-related issues (lighting, IAQ, thermal comfort) that would not have been obvious from the survey results alone. Figure 8 shows a comparison of results from the various evaluation protocols used in the Kresge study. The study found several shortcomings with the PMP procedures for acoustics, water use, site issues, and underfloor systems.

**Figure 7  Thermal comfort measurement results for Kresge Foundation study**

**Energy visualization systems**

As interest in measuring energy use grows, a growing number of hardware and software solutions are allowing for the effective visualization of building energy data. This includes products that offer information displays with features and interfaces tailored for building owners, operators, and occupants. Distinct from conventional Energy Management and

Control Systems (EMCSs), these information “dashboards” typically do not provide detailed system operation and control capabilities, but visually display trends and anomalies to educate a broad range of building stakeholders about building performance, and to influence the behavior of building occupants. Such products frequently include real-time information displays, weather information, water, solar energy generation, and green building features.

Recent research at UC Berkeley and Lawrence Berkeley National Laboratory has attempted to categorize these products (Granderson 2009) and to learn how they are used by industry professionals (Lehrer & Vasudev 2010). The Berkeley study documented the energy information practices, needs and preferences of “expert users” — industry professionals who are experts in energy monitoring and analysis. While approximately three fourths of the respondents currently have access to building energy monitoring displays, most of them view the data only once a month or less, and they noted a number of shortcomings with the displays. Many energy experts still rely on the data being downloaded by the design or operations team, and on spreadsheet programs such as Excel to manually manage data for visualization. In spite of the proliferation of new energy monitoring tools, for many energy experts the process of downloading and visualizing energy data still remains a time-consuming process, and there is significant work that is still needed in this area.

The Berkeley study also found that energy experts and building managers expressed a strong interest in having better methods for communicating with building occupants, providing further evidence of the value of tools such as the CBE occupant survey. Based on this finding the Berkeley research team is now investigating the potential benefits of combining energy feedback with social media features (Lehrer & Vasudev 2011).

CONCLUSIONS
Building designers, operators, owners, and occupants all benefit from increased assessment, and from the sharing of lessons learned about indoor environmental conditions, energy costs, and occupant feedback. The tools and research findings presented in this paper have relevance to a variety of people who benefit from assessing building performance. Researchers use these technologies for collecting their own data, which may then lead to refinements in building standards and design guidelines. Designers can make more informed design decisions given reliable performance information from previous examples. Building owners, employers and operators get value from diagnosing causes of complaints, adjusting operational setpoints of equipment, prioritizing investments to improve the quality of their buildings, or finding ways to improve employee satisfaction and productivity. Occupants who have access to feedback about building performance can play a more active role in managing their own environmental conditions.
All of these stakeholders will benefit from increased assessment of building’s physical conditions, energy costs, and occupant wishes. Fortunately the Web and wireless advances make this technically and economically possible. System performance should be diagnosed during initial commissioning and be continuously monitored thereafter. In the future, we should expect a combination of sensors, actuators, and occupants to work together to improve both the efficiency and the quality of the indoor environment. It is unclear whether these improvements will be sufficient to reverse the increasing damage to the global environment, but we do know we must do our best to make them happen.

REFERENCES


