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The Center for the Built Environment

Introduction

Adaptive Expertise

There is a growing discussion in the field of building science on the difference between "routine expertise" and "adaptive expertise" – the latter 1) innovates in how problems are solved by inventing new procedures and strategies, and 2) continually expands its scope in response to needs that arise in society (Hatano and Inagaki 1986, Sawyer, 2014). Routine experts may be very knowledgeable, but their personal growth and contributions to the field are generally based on diving deeply into existing resources, and simply becoming more accurate or efficient at doing what they have always done. This is a necessary path for people new to any field, but is not sufficient for true innovation and creativity. Adaptive expertise requires a constant questioning of normative rules and approaches, a thirst for learning, a willingness to take managed risks, and an ability to think outside the box to solve the critical problems of our time. Research in the building sciences may often start with a fundamental, well-accepted theoretical foundation. But the built environment as a whole is usually too complex for routine theory alone; think of all the participants and perspectives from which a project must be viewed before a significant change can be proposed. The idea of adaptability requires that we constantly question conventional ways of designing, operating, and studying buildings. To make a difference in the way buildings perform, architectural research must follow this model of adaptive expertise and include close collaboration with diverse stakeholders in the building industry. The Center for the Built Environment (CBE) is based on these principles.

CBE was created in 1997, under the National Science Foundation's Industry/University Cooperative Research Center Program. Our mission is to use the expertise and innovation that comes from scientific inquiry to improve building design and operation, specifically focusing on energy performance and indoor environmental quality. We believe that research in these two areas must go hand-in-hand in order to create transformational change in the building industry. Our approach is highly collaborative and interdisciplinary, built on making connections within our research team, with colleagues across campus and in other institutions, with professionals throughout the industry, and with various policymaking organizations. CBE's research projects often develop tools and technologies that improve the design of buildings, or create evaluation systems that "take the pulse" of existing buildings by measuring occupants' responses to their indoor environments, and linking them to improved measurements of indoor environmental quality.

CBE's research team currently includes 14 faculty and research staff members, with an additional 4-6 international Visiting Scholars. The academic backgrounds of our research team include architecture, engineering, physiology, and psychology, and we often collaborate with faculty and students in other departments on campus. In addition to traditional research publications, CBE researchers also influence the design and building industry by actively participating in policymaking. Our research and tools have been used in many standards and building rating systems, such as LEED, Living Building Challenge, WELL Standard, and ASHRAE building standards.

The Center's research and outreach programs are supported and guided by a consortium of building industry leaders. CBE currently has nearly 40 Partners, including architects, engineers, contractors, manufacturers, building owners, facility managers, and government agencies. In addition to providing financial support, the Partners provide guidance and feedback on CBE research activities – helping to keep it relevant to today's building industry – and are usually the first ones to use CBE's research products in their everyday practice. They also provide CBE with buildings and technologies to test, help publicize our results, and employ many Berkeley graduates. Partners benefit from meeting semi-annually to discuss research findings and network with leading practitioners in the building industry. Their affiliation with UC Berkeley bestows credibility within the industry as a symbol of commitment to promoting an improved and sustainable built environment.

CBE's research portfolio broadly falls into the following key areas:

Indoor Environmental Quality (IEQ) research investigates how people are affected by the indoor environment. Most research focuses on thermal and visual comfort, acoustics, and indoor air quality. In terms of adaptive expertise, CBE has greatly enhanced previous methods for measuring these attributes in occupied buildings, both in terms of physical measurements and occupant survey feedback. CBE's measurement carts and wireless sensing systems have led a measurement revolution that is ongoing. CBE's Web-based Occupant IEQ Survey – by far the largest of its type in the world – quantifies how a building is performing from the perspective of its occupants. Both of these provide IEQ feedback for building owners and operators, and assist architects, engineers, and builders in the development of future buildings.

CBE research projects on *Building Envelope Systems* are developing new tools for evaluating occupant comfort and energy efficiency of facades, especially of window systems. These have been used to assess shading and daylighting systems, the effects of direct sun on people, electrochromic dynamic window glass, the effectiveness of window operability for comfort control and natural ventilation, and mixed-mode strategies combining operable windows and low-energy mechanical cooling.

The Human Interaction research area is adaptive both in its development of new technology, and the ways in which those very technologies change society's needs to measure, understand, and optimize the performance of building systems. We are developing applications for sensing and controlling buildings using wireless communications technology, micro-electromechanical systems (MEMS), and Web-enabled software systems. These technologies reduce the very large costs of running wires to sensors and controls, enabling a higher density and better placement, and improving the control of the indoor environment.

Working closely with design teams, owners and manufacturers, our research on *HVAC Systems & Controls* develops and evaluates new design strategies and technologies with potential for energy savings and occupant satisfaction. While routine expertise in this field finds ways to make these systems more efficient, CBE has particularly focused on more innovative applications, where the architectural and mechanical systems are integrated, and diverse members of design teams use common information to optimize performance. These projects have broad scale and depth, ranging from developing the necessary fundamentals through lab and field testing, to eventual incorporation of validated technologies into professional standards and building codes and regulations. The prime examples of these technologies have been underfloor air distribution, radiant systems, mixed-mode design, wireless sensors and actuators for buildings, and personal comfort systems.

In the *Sustainability and Whole Building* category, CBE has used the full range of its capabilities to conduct comprehensive case studies of noteworthy projects, and to publicize exceptional performance. The evaluations include energy performance analysis, measurements of indoor conditions, surveys of building occupants, and interviews with facilities staff. Occasionally

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these have also involved economic analyses, and evaluation of additional sustainability issues such as water use.

Tools & technologies for building performance

You cannot manage what you cannot (or do not) measure, and in the building industry this has been most evident in the conformity to established practices and norms, and the absence of ongoing performance assessment. The tools available for measurement and evaluation of energy performance and indoor environmental quality are far from ideal. They are typically low resolution (such as whole-building electrical meter readings), and lack the information needed for understanding problems and making intelligent operating decisions. Following from this, detailed information on building performance rarely gets back to design and development teams, resulting in future designs that are not incorporating feedback from built experience, and designers who are not able to perform objective research in buildings.

Information Feedback Loops for Building Energy Performance (Arens & Brown, 2012)

What follows are selected examples of tools and technologies that CBE is developing and testing to solve these problems. They are often based on adaptive expertise –using technological innovations from other fields and adapting them to the needs of the building professions.

Examples of tools for evaluating building performance

Occupant Satisfaction Survey

Energy is still much cheaper – by an order of magnitude - than the salaries of people who work in buildings. Therefore, owners are unlikely to invest in energy efficiency if there is concern that the changes might negatively impact the occupants. Within the green building movement, there is a focus on health and wellness that is sweeping the industry. Responding to the growing need to better understand the effect of our buildings on occupant experience is another manifestation of adaptive expertise. Such impacts may be measured with surveys, along with a diagnosis of their physical causes. They allow one to objectively gauge which building services and design features are or are not working, and help prioritize the steps needed to improve occupant satisfaction and workplace productivity.

For the past 16 years, CBE has been conducting web-based indoor environmental quality (IEQ) surveys in office buildings to assess general satisfaction and building acceptability. At present, the survey results include responses from over 100,000 occupants in close to 1000 buildings. A core survey focuses on occupant perceptions with respect to nine environmental categories: office layout, office furnishings, thermal comfort, air quality, lighting, acoustics, cleaning and maintenance, and overall satisfaction with building and workspace. The questions asked in the core survey have remained consistent over time to create a standardized searchable database for benchmarking and analysis. In addition, CBE has developed a variety of optional modules addressing additional aspects of the workplace environment in more detail, such as daylighting, operable windows, or innovative HVAC systems like underfloor air distribution and radiant conditioning. The survey is used worldwide and has been translated into multiple languages, including Chinese, Danish, Dutch, Finnish, German, Italian, and Spanish.

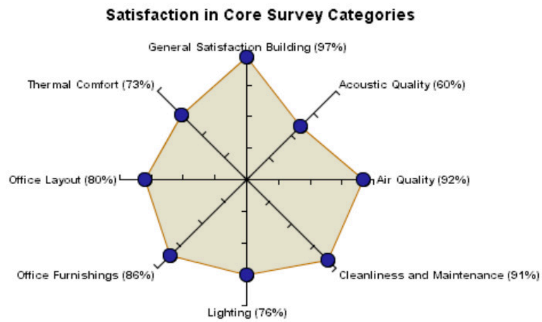
The CBE IEQ Survey database is the world's largest of its kind, allowing researchers to assess broad trends in the relative success of building designs, modes of operation, technologies, or to better understand how occupants are using many of the personal control mechanisms designers have made available to them (task lights, blinds, operable windows, light switches, etc.)

The CBE IEQ Survey is also directly impacting professionals. Building owners and operators use it for diagnosing and benchmarking individual buildings, and it helps them be aware of the occupants' perceptions of the building. They use the information to justify facility expenditure to management, assess the effectiveness of improvements by comparing before-and-after surveys, and enhance communication between corporate real estate, facility operators, and building occupants. Architects use the survey to understand the impact of their design decisions on occupant experience, and to inform those decisions when designing future buildings. The survey can be used to obtain credits for LEED certification, and has also been used by some architects to demonstrate compliance with the Living Building Challenge certification.

The survey is also the gatekeeper in the **Livable Buildings Awards Program**, organized by CBE to showcase buildings that excel in design, operation, and occupant satisfaction. The program is unique among building industry awards, as it is the only one to include the preferences of building occupants in its selection criteria (challenging the very nature of design awards programs). Buildings that exceed an established performance level on the survey are eligible to participate in the awards competition. Owners and design teams of qualifying projects are invited to provide project images, energy data, and other relevant information for review by a jury composed of leaders in their professional fields.

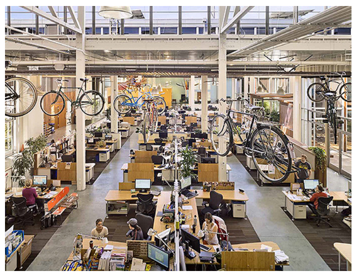
Physical performance evaluation toolkits

While routine experts might rely on existing off-the-shelf instrumentation to monitor buildings, CBE has instead developed a series of custom-made, intelligent building evaluation toolkits, incorporating both wired and wireless sensing devices to measure and record numerous indoor environmental parameters. These can be used to



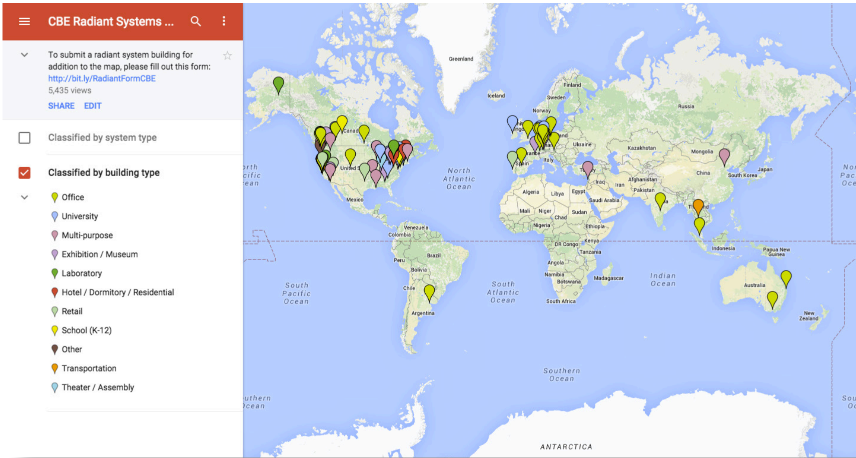
CBE Livable Buildings Award and example of survey results

evaluate the IEQ qualities of a building, to test the performance of specific building characteristics and technologies, or to commission buildings to ensure they are successfully operating as designed. There are both desktop and mobile versions, collecting environmental attributes such as air temperature, humidity, air velocity, mean radiant temperature, radiant asymmetry, and illumination. The desktop versions allow one to record a detailed record of a workstation climate over extended periods of time. These had to be inexpensive because one usually requires a large number of them, and they are left in the location for long periods of time. The mobile versions are usually instrumented carts that an attendant moves within a building to collect data over large areas.



Examples of Livable Buildings Award Winners: Packard Foundation and Clif Bar Headquarters

Recent wireless networking allows real-time remote monitoring of data – a major improvement in functionality and cost.   A mobile cart with this capability was developed and used to commission the HVAC system in the New York Times headquarters in New York, designed by Renzo Piano and FXFOWLE Architects. The cart acquired data from an array of 70 wireless sensors, updating every few seconds



Interactive web-based map of radiant systems worldwide (Karmann et al., 2004)

through a mesh network and internet connection to our database in Berkeley. The building's commissioning process was highly accelerated because of this. The cart's ability to transmit data in real time to remote observation locations makes it useful for both experimenters and building operators.

Examples of new technologies we are testing and developing

Radiant Systems

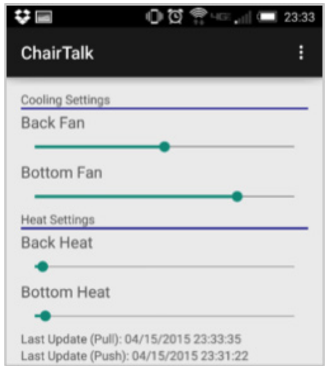
Radiant heating and cooling technology, while common in Europe, is relatively unfamiliar to the U.S. building industry at large. The design of radiant systems requires close integration of the architectural and mechanical systems, especially since buildings with high performance envelopes or operable windows may offer the best opportunities for this technology. While designers are starting to pay more attention to this rapidly evolving building technology, particularly for its promising application in zero-net-energy (ZNE) and other low-energy buildings, they are challenged by a lack of case studies and reliable design tools.

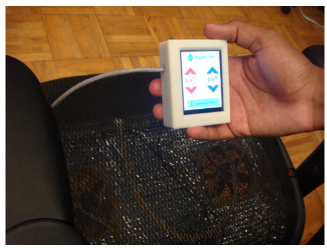
With support from CBE's Industry Partners, as well as a recent $2.9 million grant from the California Energy Commission, CBE is collaborating with several professional firms to expand its research on radiant systems. The goal is to better inform the design community on how to design and operate these systems to optimize both energy and comfort performance. The research will assess energy, cost and comfort using a wide variety of methods, including simulation, laboratory experiments, and field studies. Outcomes of the research will include web-based tools for both design and operation, and updates to relevant building standards. One tool already available to practitioners is an interactive web-based map of buildings with radiant systems that represent best practices in diverse climate zones across the U.S. That project was done by PhD student Caroline Karmann, who joined our program with a background in architecture from France, and professional experience with Transsolar in Germany.

Personal Comfort Systems

One set of technologies that is challenging conventional norms, and getting a lot of attention from industry, is our development of personal comfort systems(PCS). People are familiar with the notion of task-ambient lighting, where energy is saved by dimming the lights in the general office space, while enabling everyone to personally control a task light at their desk. CBE researchers are promoting a similar paradigm shift in the way we offer thermal comfort, the biggest source of dissatisfaction in office buildings. Providing occupants with devices to control their local thermal environment allows them to remain comfortable over a wider range of ambient temperatures. Rather than use enormous amounts of energy to heat or cool buildings to a single temperature, which cannot satisfy everyone, personal control relaxes the level of temperature needed in the building, saving very significant amounts of energy, and providing the means for occupants to be more comfortable (Hoyt et al, 2014).

CBE has developed a series of very low-energy personal comfort systems: a desktop fan, warmed/cooled desktops and wristpads, under-desk radiant foot warmers and leg warmers, and heated and cooled office chairs – already in commercial production (Pasut et al, 2014). The chair operates with rechargeable





Personal comfort system (PCS) chair (top); touchscreen controls (middle); phone app controls (bottom) batteries so that it can be untethered in use and charged overnight. It uses very little energy (a maximum of 3.6W in cooling mode and 14W in heating mode – compared to the more typical 1000W heater people put by their desks), has a very fast reaction time, and most importantly, occupants have full control of its settings. All of these devices have occupancy sensors so that they turn off automatically when not in use. Tests have shown that the chair keeps people comfortable in room temperatures ranging from 64°F to 84°F.

The PCS chairs are already making an impact on the industry. BuildingGreen – a leading online resource for sustainable design strategies – included the PCS chair in their list of Top 10 Products for 2016. Our patent has been licensed to a commercial company. The first 70 chairs were shipped to the Rocky Mountain Institute in Colorado for their new Innovation Center, which is being designed with the goal of being the highest-performing building in the world.

The Internet of Things

The mainstream and technology media are currently flooded with hopeful predictions surrounding the Internet of Things (IoT), a synthesis of technologies that are anything but "routine", and are beginning to connect and bring intelligence to millions of diverse devices and objects, expanding our ability to monitor, understand, and control the world around us. The improved sensing and connectedness promised by the IoT could be used to manage buildings, especially in tailoring indoor conditions to suit the occupants preferences, reducing unnecessary energy use during unoccupied periods, and controlling HVAC, lighting, operable windows, shades, and plugged-in devices. All of this is relevant to many of the research activities at CBE.

A CBE project from a PhD student nearly a decade ago (Peffer, 2009) was a networked wireless thermostat that became the precursor to the Nest. More recently, the CBE PCS chair includes digital controls that communicate with its occupant's phone app and also with the building HVAC system in real-time. The communication is via sMAP (Simple Measurement and Actuation Profile), an ambitious open-source building communication framework created by faculty and students in the Electrical Engineering and Computer Science Department (EECS). The sMAP framework provides a common platform for metadata to be stored and rapidly accessed, allowing instantaneous visualizations and actual control of the building's HVAC system, using data collected by the chairs. CBE is collaborating with EECS in testing the PCS chairs on the occupants of Sutardja Dai Hall on campus, using their input to save HVAC energy and provide individualized comfort.

CBE is also performing two comprehensive field studies using the integrated solution of PCS in commercial buildings – one is an advanced net-zero-energy building featuring a radiant floor slab, occupied by design engineers

Comfy app for personal control, Building Robotics

and architects; the other is a more conventional design with a civil service occupancy. These three field-study sites provide testing grounds for evaluating many new ideas about how future buildings will be managed for comfort and efficiency.

Summary

An important feature of adaptive expertise is the ability to continually respond to societal needs, challenge conventional norms, and potentially transform the market. Several start-up companies have been launched based on our research, further expanding our impact on the profession. Examples of these include Adura Inc. (a developer and manufacturer of personalized lighting controls, based on mesh-networked radio communication); Building Robotics (whose Comfy app allows workers to vote for their local temperature setting, and get short-term instant gratification from the system); and Personal Comfort Systems (the company manufacturing our heated & cooled office chairs).

The tools and technologies presented here have relevance to a variety of stakeholders who benefit from assessing a building's physical conditions, energy costs, and occupant wishes. Interdisciplinary collaboration is an essential requirement for finding promising and innovative solutions to challenges in our built environment. Collaboration between academics and practitioners is also crucial to ensure that research is being conducted on problems that concern the design and building professional communities. These are the most vital elements of "adaptive expertise", and are the foundations that keep building science research relevant and useful to designers, builders, and all of us who occupy and inhabit buildings.

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