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Progress on Enabling an Interactive Conversation Between Commercial Building Occupants and Their Building To Improve Comfort and Energy Efficiency

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Progress on Enabling an Interactive Conversation Between Commercial Building Occupants and Their Building To Improve Comfort and Energy Efficiency

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ABSTRACT

With the proper knowledge, motivation, and control, building occupants can actively reduce their energy use and increase individual comfort. Traditionally, occupant interactions with building systems consist of adjusting thermostats, blinds, and clothing. Energy interfaces provide a new level of motivational information. Many studies have reported energy savings after dashboards for operators are installed, but these provide little actionable information to the occupant and the occupant cannot report individual comfort. The Building Agent (BA), in development at the National Renewable Energy Laboratory (NREL), provides an interface for the occupant to converse with the building control system and the building engineer.

BA aims to create cohesion between building automation system (BAS) data, local measurements, and occupant feedback to provide visualizations, empowering occupants and building engineers to take diagnostic, proactive, energy-saving, and comfort-improving actions. The multilayer BA architecture consists of central server, measurement, and distributed application layers. The server layer aggregates global and localized measurements with occupant feedback to correlate perceived comfort with actual data throughout the building. The measurement layer complements BAS data with localized, environmental condition measurements at workstations. The application layer provides a bidirectional communications mechanism between the building and the occupants that accepts comfort feedback and provides energy performance information. The interface layer also uses three displays to influence building energy use: empathetic and personalized gauges, graphical data, and competitive rankings. This paper presents the architecture and preliminary outcomes of the BA-enabled feedback loop developed by NREL and tested in its Research Support Facility (RSF).

Introduction

The conversation between building and occupant requires each to have a voice. The building needs to communicate energy use information and recommendations. The occupant responds by providing comfort feedback and requesting adjustments. To sustain a productive conversation, the voices of both parties must be heard and acted upon, and changes need to be noticed. Actions may include adopting energy-saving behaviors, diagnosing and repairing facility operational problems, and adjusting set points to optimize energy use and comfort.

The building's voice is often obscured by a plethora of raw performance data and is inaccessible to occupants. Even well-attuned facility managers may not receive the localized and objective decision-enabling information they need to optimize building performance. Data visualizations may help to translate these data into useful information for different audiences. Similarly, the occupant's voice is frequently obscured by its ad hoc nature conveyance. There is usually no direct, consistent pathway for the building or its proxy, the facility manager, to interpret this feedback.

The National Renewable Energy Laboratory (NREL) has a new LEED Platinum office building called the Research Support Facility (RSF) in Golden, Colorado. The RSF was designed to be highly energy efficient, and several occupant-based control strategies had to be deployed to realize significant energy savings (Lobato et al. 2011). For instance, the RSF is equipped with automatic and manually operated windows for enabling natural ventilation, and the occupants are encouraged to place all computers into standby before leaving their desks. The RSF building provides a unique opportunity to explore a control system in which the occupants and facility manager are integral to the feedback loop.

The Building Agent (BA) framework collects control data, sensor readings, and occupant feedback and conveys this data into a central database. From those data, visualizations empower occupants to understand the impacts of their energy use behaviors and enable them with potential actions to take. Visualizations also empower energy managers to take diagnostic, proactive, energy-saving, comfort-improving actions. The facility manager can use the BA's feedback to optimize comfort and energy use by highlighting occupant preference and system setting incongruencies, subtleties that often go unnoticed in a verbal feedback loop.

The BA system has four goals: (1) use occupant feedback to help commission and tune the building system settings to optimize energy use and occupant comfort; (2) use occupant feedback and power monitoring to provide insight into control patterns of personal (e.g., task lighting) and public (e.g., natural ventilation, room lighting) systems, as well as general occupant preferences for daylighting versus electric lighting, natural ventilation, and acoustics; (3) test the effectiveness of various data visualizations for occupants and facility managers; and (4) (the most important goal) to lower energy use and demand by engaging occupants to influence behavior and empower the facility manager to make data-based decisions for diagnostics and optimization of systems.

Background

Influencing Occupant Behavior

Energy savings achieved via occupant behavioral changes could be as high as 25%, and could rival savings achieved by technological measures (Ehrhardt-Martinez & Laitner 2010). For example, energy audits often show that more than 50% of the energy used in a building is consumed at night. Occupants leaving equipment and lighting on after they leave work is a large contributing factor (Masoso & Grobler 2009). Similar savings opportunities have been identified when occupants were away from their desks 50% of the time, while most of their computers, lights, and other equipment remained powered on (Mahdavi et al. 2008). As an example, the RSF has an aggressive whole-building demand-side requirement of 25 kBtu/ft^2/yr. To meet the design and operation goal, occupants will have to put their computers in sleep or standby mode when they are gone or not using their computers (Lobato et al. 2011), a task which can be aided by technology but potentially met more effectively with behavioral changes.

Occupants often do not know if or how they can adjust building systems. In a study of a four-story LEED Silver office building, 52% of the responding occupants reported little to no understanding of their building systems (Brown & Cole 2009). Those who reported a moderate knowledge indicated higher satisfaction with the building. The paper recommended that new tools be developed for training and communicating with occupants.

Several studies have shown that occupant behavior can be changed through an educational campaign including access to real-time energy data (Henryson et al. 1999). In a study of college dormitories, continuous real-time visual feedback and incentives resulted in a 55% reduction in energy use and weekly feedback resulted in a 31% savings (Peterson et al. 2007). The longer an information delivery approach was implemented, the longer the energy-saving behaviors continued (Henryson et al. 1999).

Systems that encourage competitions amongst occupants are also effective for saving energy. A research project to reduce plug loads at the U.S. Environmental Protection Agency (EPA) Region 8 headquarters in Denver tested three approaches. Emails including educational materials about plug loads demonstrated no measurable reduction (Metzger et al. 2011). Control technology measures provided the best plug load reductions (21%), but at a higher cost than behavioral methods. In this case, controls automatically turned off a load when no one was in the area for 15 minutes. Competition visualizations allowed comparison of each person's workstation energy use to others. This reduced energy use by 6%.

Competitions are social motivators, and they may focus on individual comparisons as in the EPA building study, or group comparisons such as the ENERGY STAR® National Building Competition (Grevet et al. 2010). In the 2010 ENERGY STAR National Building Competition, the winner was a residence hall at the University of North Carolina at Chapel Hill that reduced its consumption by 36% (Rudolf 2010).

Incorporating Occupant Feedback for Control

Many approaches to digital building control often remove the human element and rely on algorithms and sensor feedback to adjust conditions based on comfort standards. Alternate control approaches attempt to explicitly integrate humans into the control loop by incorporating comfort feedback. The Energy efficient Behaviour in Office Buildings project (Zeiler et al. 2008) is one such human-in-loop design. It provides occupants with a choice of four comfort settings along with feedback on the cost and energy consumption associated with each setting. The office building tested reported a 10% reduction in energy use. Most occupants chose the most energy-efficient setting.

Another approach was described in the SMART-technology study (Zeiler et al. 2006), which provided a user agent to allow occupants to vote on raising or lowering the temperature settings. These data informed a room agent, which negotiated with the BA to adjust system settings. The SMART-technology project illustrated some of the challenges of these complex voting-based systems. In addition, the slow response of the HVAC system relative to user voting input caused confusion and dissatisfaction.

Design and Visualization Approaches

Building energy data can be communicated with traditional charts and graphs, artistic visualizations, and social displays. The traditional dashboard can be effective for those who are already motivated to save energy. Social visualizations can encourage individuals or groups to commit to goals and competitions to save energy. Another approach, artistic visualizations, may encourage discussion and self-reflection, connecting the viewers' decisions to their impacts on the environment (Pierce et al. 2008).

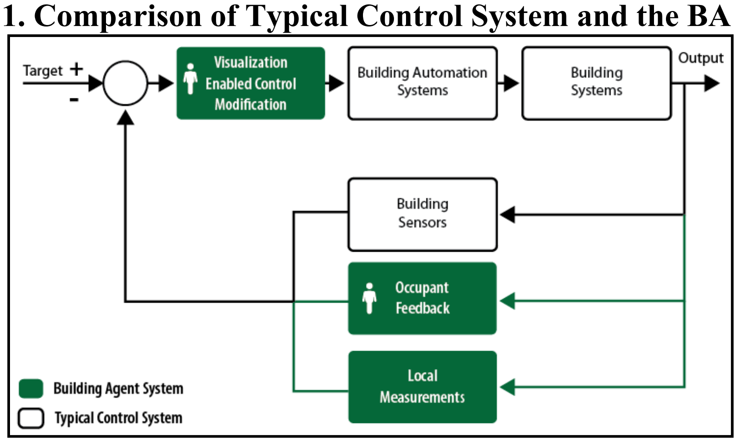
Eco-visualizations, a type of artistic visualization, offer an emotional representation of consumption and energy data. By representing data empathetically, eco-visualizations seek to tap into the individual's concern for the environment to motivate change. Holmes (2007) created an animation that displays oak trees in a kaleidoscope pattern for a university building. As energy use increases during the day, trees are replaced with hair dryers and other appliances. The experience also includes the sound of birds if energy use is low and building mechanical sounds as the energy use increases. A similar design used a fitness monitoring system, UbiFit, with mobile phones and a garden metaphor to represent physical activity. Users responded well to the garden and could interpret their status at a glance. But they expressed a desire for a variety of visualization options. This would allow for different preferences and reduce boredom (Consolvo et al. 2008).

Yet another category, interactive visualizations, provides the opportunity for exploration and discovery. Being able to look at data in different ways may lead to findings that are not evident in static displays (Rheingans 2002). Interactive approaches may seek to create hybrid visualization approaches that appeal to a range of occupants. Such considerations are especially important in engaging diverse occupants in conversations with their buildings. Previous research on designing persuasive interfaces suggests four strategies to consider: ambient, aesthetic, emotionally engaged, and metaphor (Fang and Hsu 2010).

The Building Agent System

Typical control systems do not have occupant feedback incorporated into the control loop. They do not provide facility managers with tools to analyze building performance in detail. Integrating occupants into the control system could lower costs, reduce energy use, and increase occupant comfort (Zeiler et al. 2006). Figure 1 illustrates how the human component of occupant feedback, workstation conditions (i.e., local measurement), and the visualizations of the BA system fit into the typical control system architecture.

Figure 1. Comparison of Typical Control System and the BA System

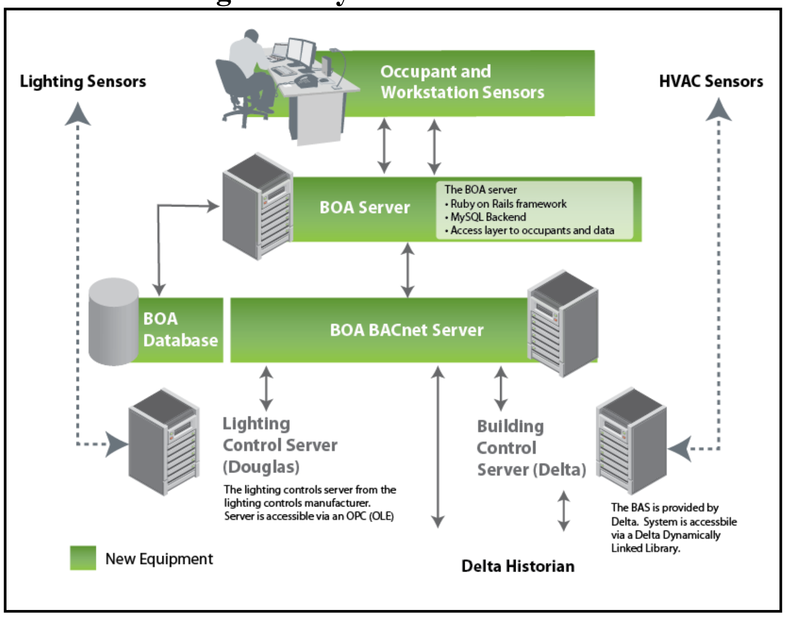


Credit: Marjorie Schott / NREL

The System Structure

The BA system (Figure 2) consists of multiple layers: data and Web servers, sensor and building automation system (BAS) integration subsystems, and user application interfaces. (The control system details are not described in this paper.) A desktop interface on all computers collects comfort feedback and delivers notifications, such as guidance to open or close operable windows. A sensor layer provides local measurements of temperature, humidity, and lighting levels at individual workstations, and supplements data available from the BAS. All these data are collected, cleansed of erroneous values, and stored consistently (same units, time stamps, etc) in the server layer. The BA website presents data in a range of visualizations for use by the facility manager to improve comfort and energy savings, and for consumption by the occupant application.

Figure 2. System Architecture



Credit: Marjorie Schott / NREL

Deployment Plan

The BA system follows a multiyear deployment plan that is iterative, flexible, and responsive to feedback. To date, key elements of the system have been deployed and tested and a pilot of the complete system is underway. Several of the key tasks (either completed or in-progress), descriptions, and encountered challenges are described below.

- Installed desktop application that tells the occupant when to open/close their building windows. This was more challenging than expected to deploy stable/functional software to more than 800 computer workstations with differing architectures.
- Built underlying server architecture and incorporated lighting and building meter data. Needed to overcome access to meter data including data security, validation, and cleansing.
- Released updated desktop application with one-time LEED survey and continuous comfort interface.
- Collected occupant comfort data and environmental conditions. Deployed display on the BA website. It was challenging keeping the occupants engaged to report comfort.
- Working on deploying updated desktop application to provide three visualization approaches: data-based (energy use charts), empathetic, and competitive.
- Installing and enabling 100 local measurement devices (with lighting, temperature, and humidity sensors). A visualization update with two visualization approaches and sensor deployment is scheduled for mid-May 2012.

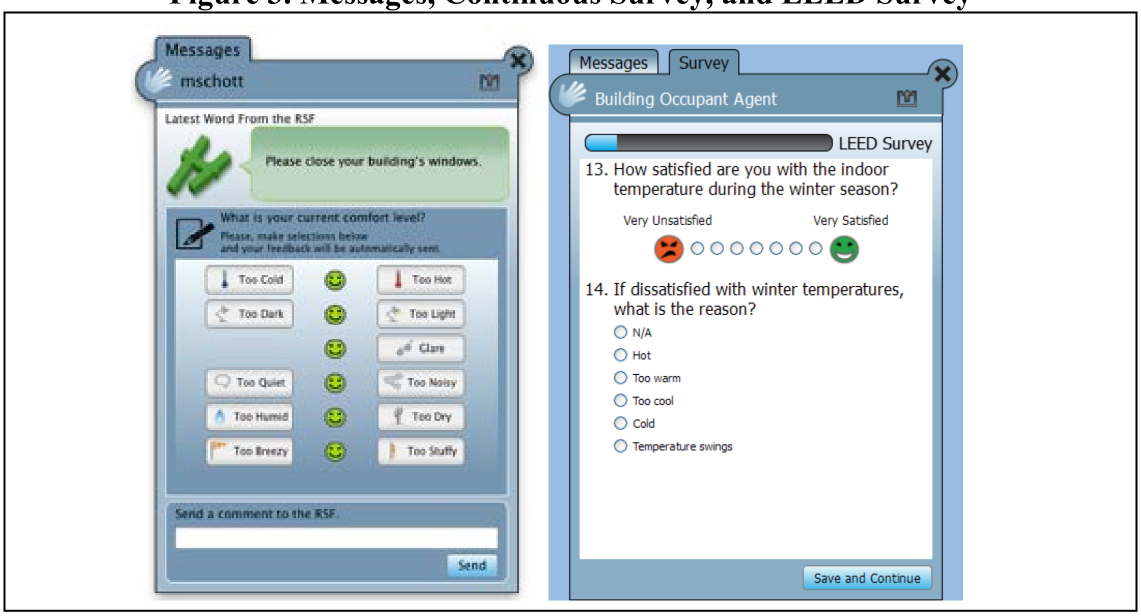
- Redesigning the RSF lobby dashboard to include a color map visualization of comfort data.
- Developing an educational campaign to support competitions, explain the functionality of control systems, and clarify goals.
- Deploying an NREL campus-wide dashboard for each building.

Occupants as Comfort Sensors

In most commercial buildings, occupants may submit comfort complaints, which are resolved with limited systematic process for visualization or pattern recognition. The BA desktop application enables occupants to quantify and communicate their comfort levels to the "building" at any time. By integrating this occupant feedback directly into the overarching control and visualization system, occupants become, although subjective, sensor assets. The application invites feedback in various comfort dimensions, including temperature, light, glare, airflow, noise, and humidity (Figure 3). The occupant can also send a free-format text field message to the facility manager. Comfort feedback submissions are time stamped and associated with physical locations along with local measurement data at the same time stamp.

Four of the six thermal comfort factors defined by ASHRAE Standard 55 (ASHRAE 2004) are addressed in the BA feedback interface. The occupants report their experiences with air temperature, radiant temperature, air speed, and humidity. Future versions of the application will add methods to collect details on occupant clothing and metabolic rate, the two remaining comfort factors. (The scope of this project does not include deploying workstation sensors for all reportable variables.)

Figure 3. Messages, Continuous Survey, and LEED Survey



Credit: Marjorie Schott / NREL. Left: the area at the top allows the building and facility manager to send messages to the occupants. The close or open windows message is automated. The message tab of the occupant interface allows occupants to quickly report their current experiences. Right: The survey questions and response options were edited by the administrators on the BA website. The survey creation tool could be used for other surveys.

In addition to this on-demand questionnaire, the Sustainable NREL and Commercial Buildings groups developed a one-time LEED survey that was delivered through the desktop application (Figure 3). The survey was part of the LEED Platinum certification for the RSF. It consisted of 65 questions based on the LEED survey requirements and examples from the Center for the Built Environment. The questions were provided to the U.S. Department of Energy, Protection of Human Research Subjects group for review. Survey results were collected in the secure database.

A campaign to encourage occupants to fill out the survey included an email from executive management, notifications on the NREL Intranet site, and reminders from the desktop application. Occupants had more than a month to complete the survey before the survey tab disappeared. This mechanism remains embedded in the application, and may be used to disseminate other surveys in the RSF or in other buildings across the NREL campus.

Local Sensors

The application collects temperature, humidity, and light readings at a few workstations through a local "Phidget" sensor interface (Phidget 2012). The Phidget plugs into the USB port on a computer and provides local measurements to the BA database at a specified interval or whenever the occupant submits comfort feedback. These spatial data are also time stamped as they are added to the BA database. In May 2012, Phidgets will be installed at 100 workstations.

The Building Agent Database

The foundation of the system is a highly scalable database providing a flexible, fast, and horizontally scalable document database. It is readily extensible, and does not require a refactor when new metadata are added. In addition to storing time-stamped and location-specific comfort and local measurement feedback from the distributed BA desktop applications, the database collects information from the RSF's lighting controls, BAS, and metering subsystems. This creates a coherency in the data that is critical for interactive visualizations that combine all available information for diverse users.

Collecting these data in a single server represented a new network interoperability requirement for the NREL campus. Various departments collaborated to bridge multiple data networks. The BAS subnetwork operates safety-critical systems across the laboratory, so security was of particular concern. A gateway server was installed to provide communication from the BAS subnetwork to the BA server. Control actions (e.g., set point changes) presently require the intervention of a facility manager; however, well-designed visualizations are intended to aid in efficiency for this human-in-loop control process.

The Building Agent Website

The BA website provides various levels of information for occupants and facility managers. For example, the visualization described in the Visualizing the Data for Diagnosis and Action section will be generated dynamically by the Web server and displayed within the desktop application. Additional visualizations, including general information about the BA project, building-wide comfort reports, and views of the public dashboard, will be made available through Web browsers. Facility managers will have access to all these views, along with charts of metered data and specialized visualizations that break data down to the workstation level. The website also provides a means of sending messages to occupants through the BA interface described later. Figure 4 shows screenshots of different areas of the site.

Figure 4. The BA Website

Credit: Marjorie Schott & Nicholas Long / NREL

Preliminary Results

LEED Survey Preliminary Analysis

A preliminary analysis of the survey data was completed to provide a quick understanding of the results relevant to the design of visualizations of the energy data. Of the 629 occupants, 273 responded. One survey question asked: “Do you feel that you receive information about the energy performance of the RSF?” Of the responses, 152 reported “yes.” Another 24 reported receiving some information, but not regular, clear, real-time, and convenient information. The current energy display (Figure 5) is viewable on two displays in the RSF lobby. The survey responses included some occupant feedback to the energy display and included:

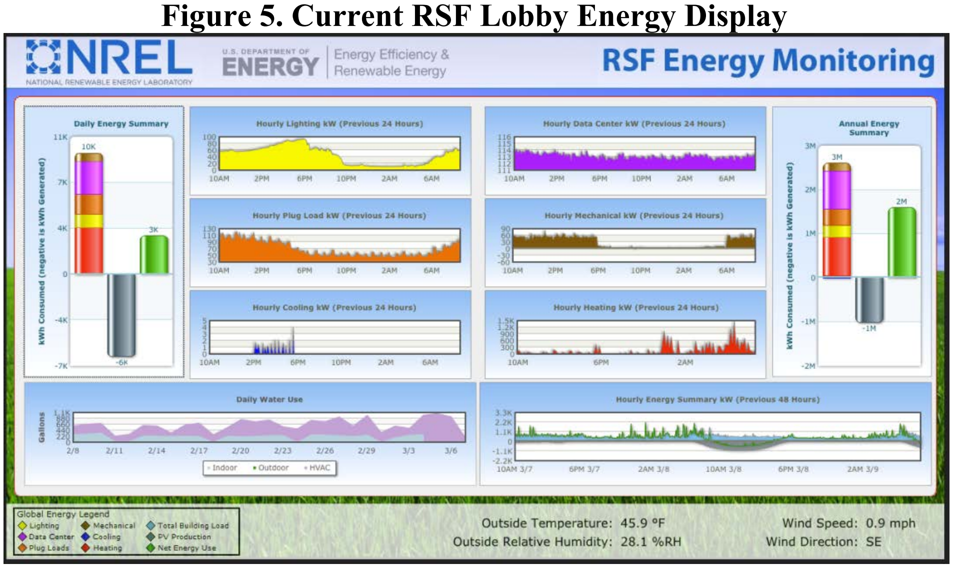
Would be great if the energy summary on display in the lobby of RSF is made visible at workstations

Would like to see real-time charts of energy consumption

Visual display is confusing -rounding not adequate

I would like to see bi-annual reports on energy performance

Figure 5. Current RSF Lobby Energy Display



Credit: Setpoint Systems Corporation. The energy use in this chart is for the RSF1 and RSF2.

Occupants also expressed confusion about the building systems. When asked about their satisfaction with the thermal controls, 66% of the respondents had never adjusted the controls. Twenty-six percent did not know if they could adjust thermostats, how to adjust them, or where to find them. A question about satisfaction with the air diffusers on the raised floor of the building recorded that 73% of the occupants did not know how to adjust them.

The survey asked, "What primary barrier do you see to saving energy in the RSF work environment?" Nineteen percent of respondents reported that they do not have enough control over the building systems. The most common barrier, reported by 30%, was that the occupants get busy and forget to adjust the system. The BA is expected to help overcome these barriers by providing reminders to occupants to adjust the system; this will also remind occupants to report on their comfort. If the BAS is able to control on comfort, and the occupant can notice changes based on their comfort feedback, more occupants will likely interact with the system.

Continuous Comfort Survey Preliminary Analysis

Since the deployment throughout the RSF, 238 unique users have logged on and been identified. Five hundred eighty comfort reports have been received through the desktop application since January 10, 2012. There have been 159 unique users; see Table 1 for an overview of their reports.

Table 1. Occupant Comfort Feedback Summary before January 10, 2012

Type of Feedback	Number of Reports	Percent of Reports
General Comfort	158	27%
General Discomfort	62	11%
Too Cold	91	16%
Too Hot	31	5%
Too Dark	22	4%
Too Light	21	4%
Too Much Glare	23	4%
Too Quiet	4	1%
Too Noisy	20	3%
Too Humid	1	0%
Too Dry	9	2%
Too Breezy	3	1%
Too Stuffy	10	2%
Temperature OK	34	6%
Lighting OK	21	4%
Noise OK	13	2%
Humidity OK	19	3%
Air Movement OK	20	3%
Glare OK	18	3%
Written Comments	16	3%

Future Work

While each piece of the BA architecture is under development, different levels of completeness and integration exist. The following section describes the goals for project conclusion.

Visualizing the Data for Diagnosis and Action

To test the effectiveness of various visualizations, occupants will be provided data displays through the BA desktop application. Occupants may select an empathetic display or a more objective chart. The empathetic option allows the user to select from provided images or personal images on the interface to visualize the status of the building energy use. There are three image options: good, predicted, and bad. (The ranges will be determined based on first-year metered data, which has been verified with respect to the energy model as meeting the building's energy target). The interface for selecting images (left) and an example (middle) are shown in Figure 6. The visualization also provides a linear gauge to show if the current energy use is low, within target range, or higher than expected. These views are scheduled for release to occupants in May 2012. The second visualization option shows weekly data on the energy consumption by end use (Figure 6 right). The visualization also displays weather information for the week.

Figure 6. Desktop Application Visualizations

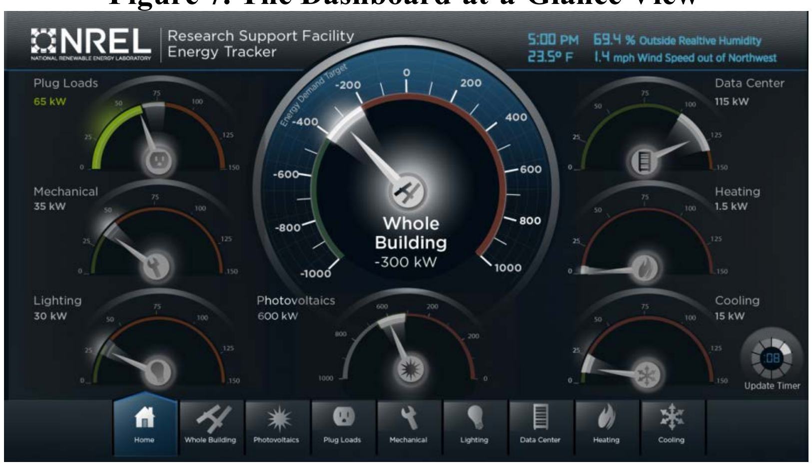
Credit: Marjorie Schott / NREL. Personalization of the images allows the occupant to use metaphors that are meaningful and motivational to them.

Redesigned Interactive Building Dashboard

A dashboard in the RSF lobby and on the Web will provide data about the RSF. A replacement for the current dashboard will include a touch screen that allows the user to explore building performance information at a casual level or to drill down to see more detailed data. The default screen (Figure 7) provides a quickly interpreted display that highlights any aspects of building performance that are inconsistent with user expectations. Target values are calculated from weather information and simplified modeling predictions. Such predicted ranges provide valuable context, as viewers do not have to be familiar with typical building energy use values to know if the goals are being met. The user can explore the display and view more detailed data, such as the chart in Figure 8.

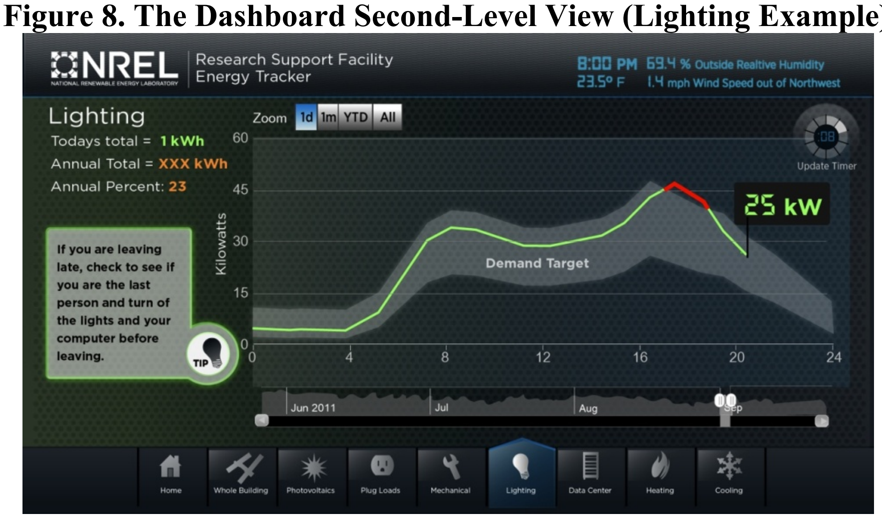
Predictive strategies could allow the facility manager to warn occupants about potential comfort issues and allow the facility manager to adjust the system ahead of weather changes. As the system extends to other NREL buildings, the energy use of the whole campus will be tracked and predicted.

Figure 7. The Dashboard-at-a-Glance View



Credit: Marjorie Schott / NREL

Figure 8. The Dashboard Second-Level View (Lighting Example)



Credit: Marjorie Schott / NREL

Spatial color maps of the building will encourage additional exploration of available data (Figure 9). This view will be of particular value to facility managers who can use the maps to quickly visualize spatial sensor readings alongside comfort information in a range of dimensions, including temperature, humidity, and glare. This visualization becomes a key source of feedback for optimizing building set points, assessing complaints, and diagnosing system performance issues. Such visualizations may prove helpful to occupants as well. If an occupant feels the lights need to be on, he or she may look at the visualization and determine if others in the area also feel it is too dark. If not, perhaps the occupant can decide to turn on a task light instead of overhead lighting.

Figure 9. Interactive Spatial Color Mapping

Credit: Marjorie Schott / NREL. This public visualization shows how one can view data spatially. The white icons indicate that more than five occupants in a defined area are reporting that they are too hot or cold.

This visualization also highlights the potential for privacy challenges. Although the facility manager needs to be able to identify the specific location where the complaints originated, that level of information should not be available to all users. A lack of anonymity in feedback could have a "chilling" effect on gathering quality feedback from occupants. We propose to address this issue by displaying coarsely grained comfort data on publicly available color maps. A single complaint will not be displayed in public visualizations, but if five people in an area of 16 complain, the system will display an icon for that area to identify the potential problem source. Another possible solution is to let users flag their comments as public or private.

Motivating Through Collaboration and Competition

Several survey respondents suggested interdepartmental competitions to improve energy savings. The dashboard and desktop displays would visualize competition results. Occupants could encourage and educate each other to make better energy choices. Social postings on the website could report on how individuals and departments are saving energy.

Individual goal setting and comparison could also be implemented. Reporting individual plug load information could be part of the desktop application. An occupant could compare—anonymously or not—his or her personal energy use to others. To support this level of detail, a method for measuring workstation plug loads would have to be implemented.

Improving Educational Materials

Survey feedback indicated considerable confusion about thermostats, diffusers, and lighting controls. Many occupants were unsure about what they could adjust and how to adjust the comfort controls. Several suggested more education and training.

The interactive dashboard, and eventually all interface options available at any location, could provide energy-saving tips and links to videos about the RSF thermostats, diffusers, and other topics that could help occupants become more comfortable and in control of their environment. The dashboard could be valuable for informing new employees and occupants in recently completed buildings

Implementing the Dashboard and Desktop Application Campus Wide

All NREL buildings would eventually be part of the BA system. The RSF was designed to be a highly metered building. End uses can be tracked in detail. Some buildings have only a couple of meters and different control systems. These challenges will help NREL develop a system that can be used in a broader range of buildings.

Summary

The BA goal is to facilitate a conversation between building, occupant, and facility manager to increase energy savings, comfort, and satisfaction on a building and campus scale. The BA will combine the comfort feedback, local sensor data, and control system measures into interactive visualizations. Facility managers can explore solutions, optimize settings, monitor comfort feedback, and send messages, through the BA desktop application, to let occupants know they have been heard and adjustments are being made. Occupants will be given information and suggested specific actions to take to improve energy savings and comfort.

Measuring the energy savings resulting from different phases of this research will provide a clearer understanding of which visualizations and approaches work best. Contests, individual comparisons, and education can all help raise awareness and empower occupants.

RSF occupants reported wanting more control over and more information about their building control system so they can help to optimize comfort and energy use. The current desktop application gathers occupant feedback and provides a method of informing them about actions energy use and energy-related actions. Several challenges have been overcome during the initial deployment phases, but significant work is still needed to further integrate the components of the BA architecture. The addition of custom energy displays, better desktop application graphs, and competitions will better engage the occupant to provide feedback and subsequently provide feedback to facility managers to operate the building more comfortably and efficiently.

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