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Getting into the Zone: How the Internet of Things can Improve Energy Efficiency and Demand Response in a Commercial Building

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ABSTRACT

While building automation and controls have long used data and analytics to improve building performance, the proliferation of connected devices and sensors adds a new dimension with greater insight to the end user's impact on energy consumption. The application of the Internet of Things (IoT) in building systems allows connected devices to communicate and provide enhanced control functions. The increasingly improved visibility at the zonal/room level suggests several ways to improve both energy efficiency and demand response.

UC Berkeley researchers have worked to interface wireless networks with existing building automation systems (BAS) as well as creating virtual BASs by interconnecting control and sensor hardware. The simple Monitoring and Actuation Profile (sMAP) delivers and labels data from various sources into a single compact database; the eXtensible Building Operating System (XBOS) provides the platform for applications to access this data.

This paper describes a collaborative research project between Electric Power Research Institute (EPRI) and UC Berkeley that builds on this work by examining data from several sources: the BAS of a commercial building on campus, wireless indoor environmental sensors (temperature, light, humidity, motion, carbon dioxide), browser-based thermal comfort voting, a networked heated-and-cooled chair, and connected plugload sensors. We describe the results of testing the individual tools, and next steps.

Background

Overview of IoT in the Building Automation Industry

IoT or "digitizing the physical world" is estimated to create value potentially between $3.9 trillion to $11.1 trillion a year by 2025. Most of the value will come from operation and optimization of buildings, public health and transportation, mainly from nine potential settings: human wearable devices, home, retail environments, offices, factories, worksites, vehicles, cities and places outside urban environments (Manyika 2015). In the building automation and controls industry, the technology development indicates a clear trend of convergence between building systems and IT (e.g., energy information analytics). In the last decade, more building system components such as cooling, heating and lighting systems are being connected either directly or through the building energy management system (BEMS), internally and externally. The number of sensors and controls, including wireless devices is increasing. In parallel, IT development suggests a trend from automated commissioning, energy information modeling with computer-aided tools, and automated demand response (DR) to Software-as-a-Service (SaaS) and IoT. We can see that building systems and devices are beginning to embed analytical software for

communications and enhanced control functions. We also see a trend that BAS is moving from a building level up to enterprise level and eventually to the cloud. The benefits to occupants are comfortable zones through presetting of preferences and/or real-time feedback through SaaS platforms and sensor networks. However, we also see an integration gap between building systems and IT, which is the lack of interoperability between systems with high resolution energy data. It is projected that the interoperability issue will be resolved in the next decade by both control system upgrades and IT development.

The IoT enabled intelligent building energy management is the kind of system or platform that has the capability to take in various forms of granular data and transform the data into control actions and apply back to the building for desired global or local objectives. A data-driven analytical platform is required that prioritizes the parallel and sometimes conflicting objectives of a building to provide control actions for increased energy efficiency, comfort, productivity and security. Data input to the platform include the following four sources, and are marked as dashed arrows in Figure 1; control actions are marked with solid arrows.

Figure 1. Data flow and control actions in an intelligent energy management system

The key drivers for the advancement of building automation are found on both the technology side and the building operation side. The growth of Internet protocol (IP) based technology provides the possibility and the need of integrated and interoperable buildings, and also accelerates the development of applications (i.e., Apps or software) providing occupants, tenants and facility managers a broad range of opportunities. These items drive the building controls to evolve further towards an open architecture of both physical and control systems. The technology advancement also has evolved standards for building operations, which are targeted at improved operational efficiency, improved occupant comfort and financial optimization to deal with rising operational cost and demand charges.

Why zones?

Why are we focusing on zones? Office workers consume energy in their space through the HVAC system, overhead or task lighting, and plug loads. The area that each person occupies is controlled by several independent systems. Moreover, the HVAC zone of control—typically in the U.S. VAV boxes—does not coincide with the lighting zone of control—typically light switch banks or panels. HVAC VAV systems are zoned by carving out convenient areas of the floor

plan (e.g., into roughly equal groupings of adjacent spaces) and expected HVAC load (e.g., different for interior versus perimeter zones, solar exposure, conference rooms). General ambient lighting is also zoned by convenient groupings, governed by floor plan adjacency, lighting requirement, fire and safety (e.g., egress) and circuit breaker capacity. Plug loads/outlets are typically not controlled by zone; (however recently adopted code requires automatically controlled outlets).[1]

Typically an individual in a commercial office building cannot control the HVAC and lighting in his/her area. In open place office environments, an individual cannot control the temperature. Often two or more private offices share an HVAC zone, so at least one might be able to control the temperature to his/her preference. However, often the thermostats are locked out to prevent changes. Likewise, in open plan office spaces, an individual cannot control the ambient lights. They might be able to control them in a private office, however, often the user interface is so poor, users do not interact with them.

This project employs the Sutardja Dai Hall (SDH) on the campus of UC Berkeley for demonstration. The building has approximately 141,000 sq. ft. with a nanofabrication lab, offices, classrooms, conference rooms and an auditorium. The building runs one of two 600 ton chillers (one absorption chiller using steam and one centrifugal chiller), depending on the time of year. SDH is equipped with 138 variable air volume (VAV) boxes with steam reheat supply conditioned air on the office portion of the building. SDH has over 6000 sensing points from the Siemens Apogee BAS as well as other additional sensors, such as temperature sensors on the chilled water supply and discharge air temperature sensors at most of the HVAC zones.

Figure 2 shows some inherent problems with occupant-centric control over individual spaces, using the SDH's floor plan for example: the zones of the different systems typically do not coincide. The area supplied with conditioned air from VAV S4-12 (red square below) has overhead lighting controlled by two zones. Likewise the lighting zone 4 (orange rectangle) contains conditioned air from three HVAC zones. Furthermore, these zones are not typically known or mapped out; the two below were developed by graduate students through a painstaking process of going through mechanical drawings and empirical testing.
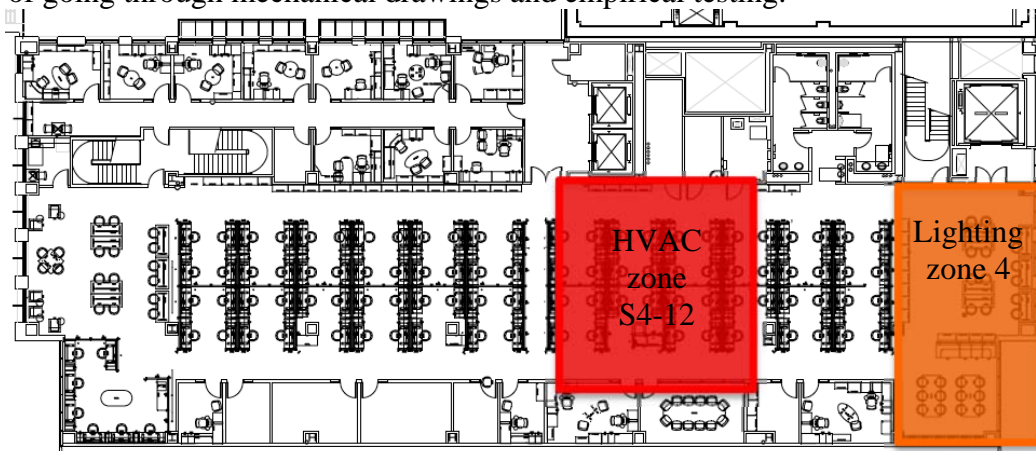

Figure 2: Fourth Floor plan of Sutardja Dai Hall, UC Berkeley

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[1] California Title 24 2013, Section 130.5(d) requires "Automatic Receptacle Control" in private offices, open offices, lobbies, copy rooms, kitchenettes, and conference rooms.
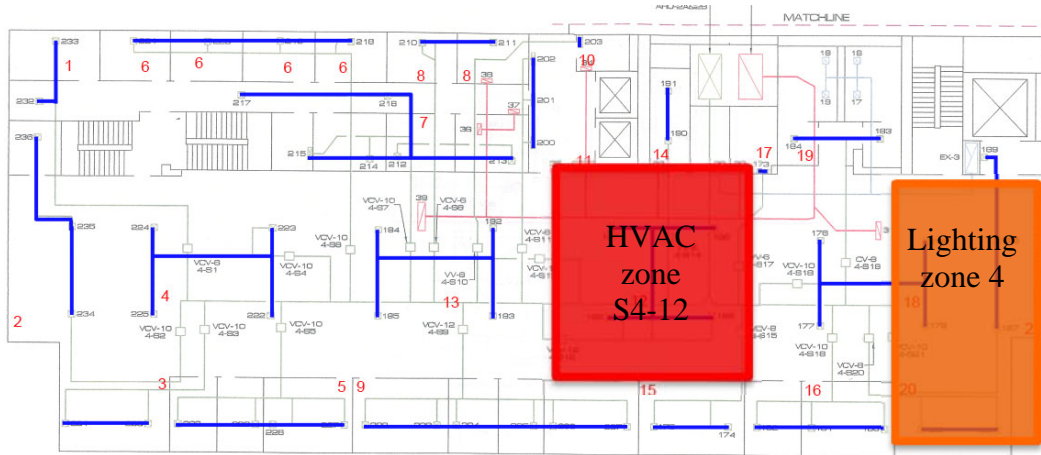
Figure 3: HVAC zones for fourth floor, SDH. Each blue line indicates the duct layout for an individual VAV box (courtesy Andrew Krioukov)
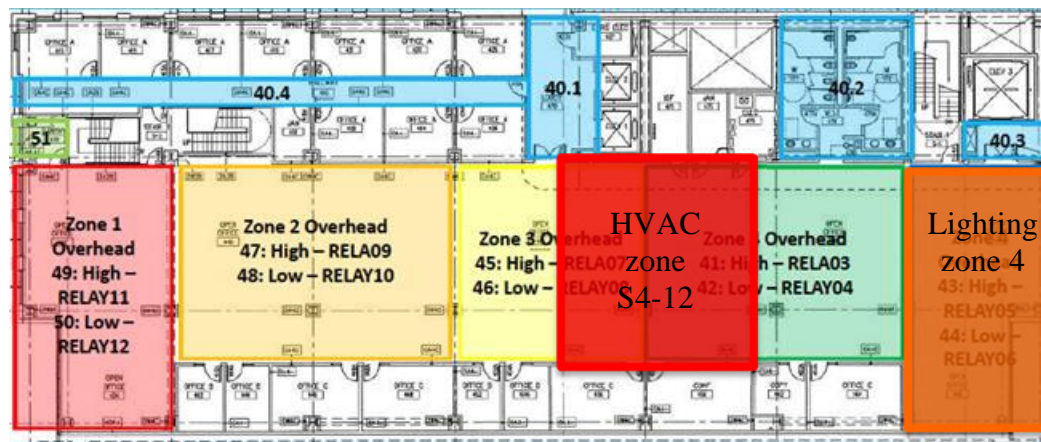

Figure 4: Lighting control floor plan (courtesy Michael Sankur). [Each private office (no color) has its own overhead light controlled by an occupancy sensor switch.]

Research Design/Method

The objective of this research is to investigate the role of local control and sensors for EE and DR applications. What tools from the IoT space can enable more personalized, decentralized zonal control, and lead to better comfort, satisfaction and reduced energy consumption? This section describes the development and testing of several tools: a software platform to enable applications, wireless sensors, networked heating/cooling chair, and a cloud-based plug load controller.

Software platform and applications

UC Berkeley researchers developed a Building Operation System Services platform (BOSS) (Dawson-Haggerty 2013) that provides a data management system (simple Monitoring and Actuation Profile or sMAP) to "tag" time-series data with descriptors or "metadata" and store these in a compact database that allows custom queries (Dawson-Haggerty 2010). These sMAP "drivers", are the interface from the hardware devices (e.g., sensors and actuators) that

enable data from that device via network protocols (e.g., wired Ethernet, WiFi, ZigBee, ZWave), to enter the data historian and storage system. The BOSS platform allows researchers to write applications on top of the existing Application Stack. Current work, the eXtensible Building Operating System (XBOS) provides the platform for applications to access this data (Fierro 2015). The goal of these systems is to provide the interoperability necessary for researcher- or third party- control algorithms, graphic user interfaces, visualization tools, analytics, diagnostics and so on that can enable EE and DR while still maintaining a comfortable and productive environment. Here are several implemented applications:

- Personalized web-browser based lighting controller (Krioukov 2011). Krioukov developed a browser-based lighting control interface that allowed occupants to easily control the lighting to the level desired without having to use the cryptic wall switches. The interface allowed adjacent occupants to see each other's votes to encourage communication and reduce conflicts. Users could also see real time lighting energy use on their floor. This lighting application saved 50% energy overall, mostly at night. Students would often re-enter the building after the BAS turned off the lights for the night and turn the lights on, but not turn them off after they left. The new controller automatically turned off the lights after a time interval, thus saving energy.

- Demand-controlled ventilation (DCV) (Taneja 2013). CO_2 sensors and motion sensors were installed in conference rooms throughout the building; data were tagged with location and deposited in the time series database. Meeting schedule data from an online calendar were scraped, tagged, and added to the database. A simple script written in Python interacted with the BAS to flush the rooms with air right before a scheduled meeting. The algorithm monitored the CO_2 levels in the room, and provided high air volume when levels exceeded 800 ppm. When no one was in the room, the ventilation levels dropped to a minimum level (less than 100 cfm).

- Web-based personalized controller allowed the user to request a local temporary blast of heat or "coolth" from the nearest VAV box. Once a request is made, that user is locked out or prevented from making another request for 10 min. Human thermal sensation is sensitive to changes in temperature; thus a temporary "blast" often provides a long period of comfort. This product is now commercially available as Comfy by Building Robotics[2]. Comfy learns the voting patterns from occupants over time to change the temperature setpoints to optimize for comfort and energy consumption. This has improved comfort and satisfaction as reported by the occupants, and on average has also widened zone temperature setpoints in buildings in which Comfy is deployed. This product has been installed at floors 3 through 7 of Sutardja Dai Hall since March 2014. The baseline temperature deadband was 70-74 °F; Comfy adopted a wider temperature deadband of 68-75 °F and then adjusted each zone according to the votes of the occupants.

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[2] Comfy is a personalized indoor air comfort control product offered by Building Robotics. http://buildingrobotics.com/comfy/
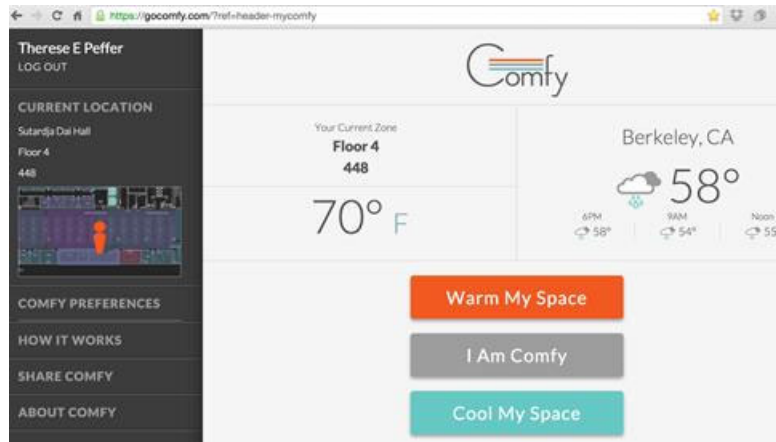
Figure 5: Web-browser of Comfy, allowing occupants local control of their temperature even in a large commercial building.

Sensors

Along with our research colleagues from the Korea Electronics Technology Institute (KETI), we have developed a sensor platform based on the miniature computer, the Raspberry Pi2 as shown in Figure 5. Raspberry Pi2 is a single board computer whose compact volume makes it a good choice to collect data from several sensors at low cost. The initial prototype has a CO_2, temperature, and humidity sensors. A sMAP driver allows the automatic uploading of data via the WiFi connection to the local network.

Figure 6: Raspberry Pi2 mini-computer with carbon dioxide and temperature sensor.

Personal Comfort System Chairs

The Personal Comfort System (PCS) chair, developed by the Center for the Built Environment, is a mesh type office chair with two heating strips and three fans built into the chair structure. The fans, located inside reflective plenums in the seat and back, generate a cooling airflow. The heating elements locally heat the back and the seat of the chair, and the reflective material reflects back part of the radiant heat emitted by the body. The heating strips use a maximum of 16 W, while the fans use a maximum of 3.6 W allowing the 280 W·hr

rechargeable battery to power the chair for several days of average use. A pressure switch senses occupancy and shuts off the heating and cooling automatically when the chair is unoccupied, minimizing energy use and extending operation between charges. The chair also has temperature and humidity sensors. The chair provides heating and cooling needs of an individual and eliminates the need of heating and cooling of the entire zone, providing an energy efficient solution for individual offices.

Figure 7: The Personal Comfort System chair with heating strips and fans for cooling.

The PCS chair is network-capable with both Bluetooth and 802.15.4 to communicate and interact with building controls in real-time via Internet. The chair can be controlled via a phone interface or two knobs that control the back and seat heat/coolth separately. Fifteen PCS chairs were given to office workers on the 3rd floor of SDH during the week of August. 13-19, 2015. We also conducted several occupant surveys. The participants had one week of an adjustment period with the digital PCS chairs and then were invited to take 'post-chair' right-now surveys (post-surveys). The survey queried users for thermal comfort satisfaction, clothing level, and basic usage and satisfaction with the PCS chairs. We expect the PCS chairs could provide improved satisfaction during demand response events, in providing comfort to occupants while allowing a wider temperature range. The Bluetooth connection can enable notification messages to be sent to occupants' mobile devices before the DR event so that they are prepared.

Enmetric plugload controller/sensor

Another tool we explored was a four-outlet plug load control and monitoring system, called the Enmetric PowerPort. Multiple PowerPorts communicate electric power data to a bridge which conveys the data to the cloud. A laser printer, laptop, computer monitor, and PCS chair were plugged into the device. The PowerPort recorded baseline data, and then was programmed to turn off power to three outlets when the laptop was not plugged in; this was used as a proxy for occupancy.

Figure 8: Enmetric Power Port plug load control and monitoring system.

Results

We explored each tool. The first tool, Comfy, has been operating successfully at SDH, allowing occupants to enter the web browser and request a temporary blast of heat or coolth. Figure 9 shows the heating and cooling setpoints for many of the VAV zones in SDH. Here, horizontal axis shows the zones and the vertical axis shows the temperature bands. The original default heating and cooling deadband was between 70 °F and 74 °F. In the majority of zones, the occupants accepted the new wider temperature setpoint range. In about 10 zones, the occupants found 68 °F was too cold; in just a few zones, occupants found 75 °F was too warm. Overall, the wider setpoint range requires less cooling and heating and thus saves energy—about 14% so far.
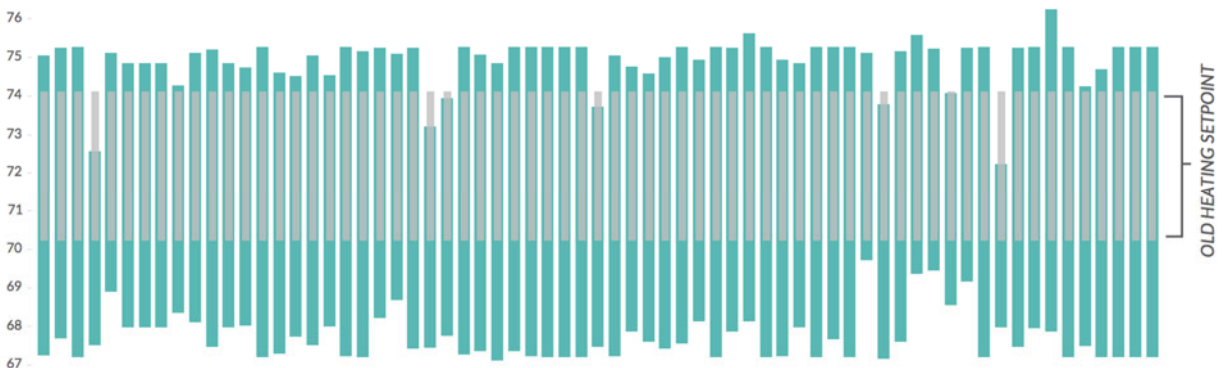

Figure 9: VAV zone temperature setpoints before and after Comfy was deployed.

Regarding the Raspberry Pi sensors, there were a few issues with intermittent readings and connecting to a secure university network. Some of the sensors required calibration. However, these issues were resolved, so we were able to get CO_2, temperature and humidity measurements. Figure 10 shows readings from a conference room over six days, where the two middle days were a weekend.
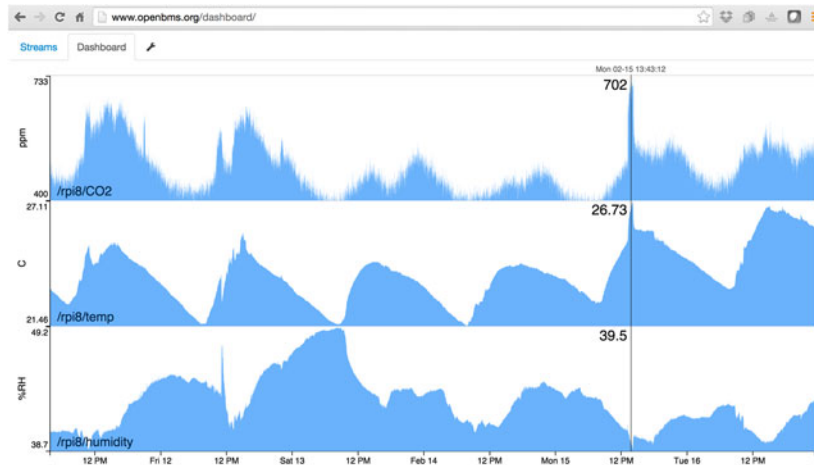
Figure 10: Sensor readings on a web-browser from the Raspberry Pi.

The data collected through the chairs and by occupant surveys produced a wealth of information about individual comfort preferences and use patterns of the PCS chairs. Understanding what drives the chair heating and cooling use can have important energy use and DR participation implications. Frequent heating usage among the occupants sharing the same zone indicates that the zone is overcooled and the cooling set-point could increase. Brief chair cooling use in the morning may indicate that the people need assistance with cooling down from their morning commute. Zone set-points may be selected based on thermal comfort at the beginning of the day and may not be an accurate reflection of what people might prefer for the rest of the day. This is particularly relevant when occupants have control over their own thermostat either directly, or through an online voting software such as the Comfy software. Offices with conflicting thermal preferences can benefit from the chair's localized conditioning so that temperatures can vary within a far wider range, and so that overall occupant thermal comfort is significantly improved. With the PCS chairs integrated with building systems over the Internet, the chair information can be used as feedback to optimize HVAC control and save energy. The use patterns of PCS chairs can be further interpreted as customer's acceptance on HVAC load shed (i.e., thermostat setpoint setbacks) of certain zones. Frequent chair cooling might indicate that occupants in that area would be sensitive to thermostat setpoint setbacks for DR events and would be likely to either complain or override the setpoint during the DR event. However, some zones that are less occupied may able to undergo a deeper temperature setback, thus the zones do not have to follow the same thermostat setback rules (e.g., 2 °F or 4 °F) and achieve a deeper DR participation.

Overall, occupants used heating more frequently than cooling usage—possibly due to overcooling, but possibly "medicinal" (e.g., to relieve backaches). Throughout various seasons, we found some people used cooling even at cooler temperatures while others used heating at warmer temperatures within the exposed temperature range. This indicates that people's thermal preference in their local environment is less dependent on the actual ambient conditions when the ambient temperature is within an acceptable range. We think the acceptable ambient temperature range—both for EE and DR—can be deeper if occupants are equipped with the PCS chair.
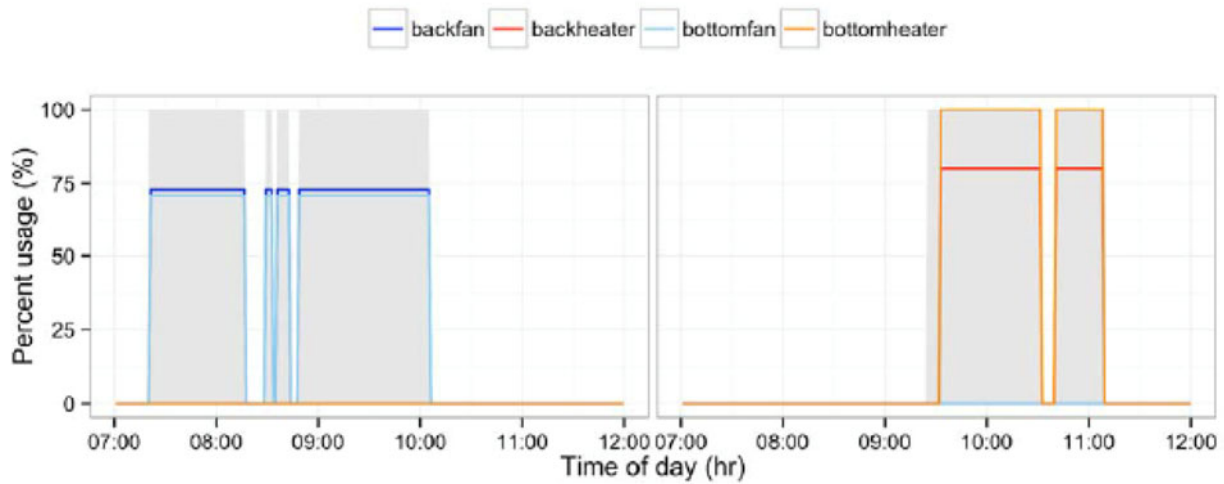
Figure 11: PCS usage behavior from two users sharing an office in the morning, one using cooling and one using heating. (Grey bar indicates chair occupancy).

The Enmetric PowerPort was quite useful in visualizing individual appliance load profiles as well as controlling these to save energy. Figure 12 shows the baseline case, 0.175 kwh/day of base load, mostly from standby loss. Figure 13 shows the smart case, with just the laptop using energy. We had expected to see the phantom loads of the other devices when the laptop was plugged in, but learned that the "automatic shutoff" was overridden by the manual control of the switches. The smart case reduced energy consumption by 33% in eliminating standby loads, and we learned more about the operation of the device.
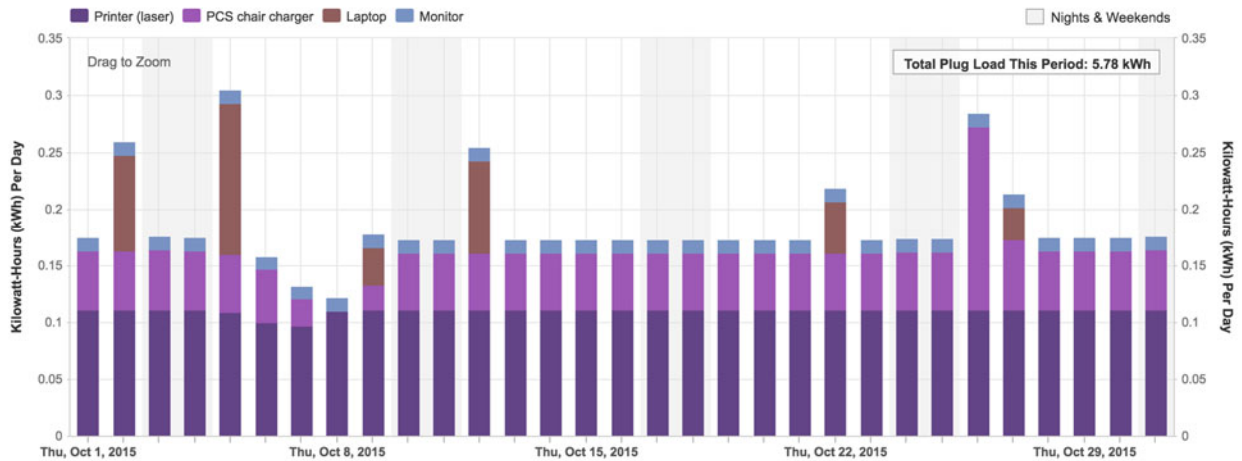

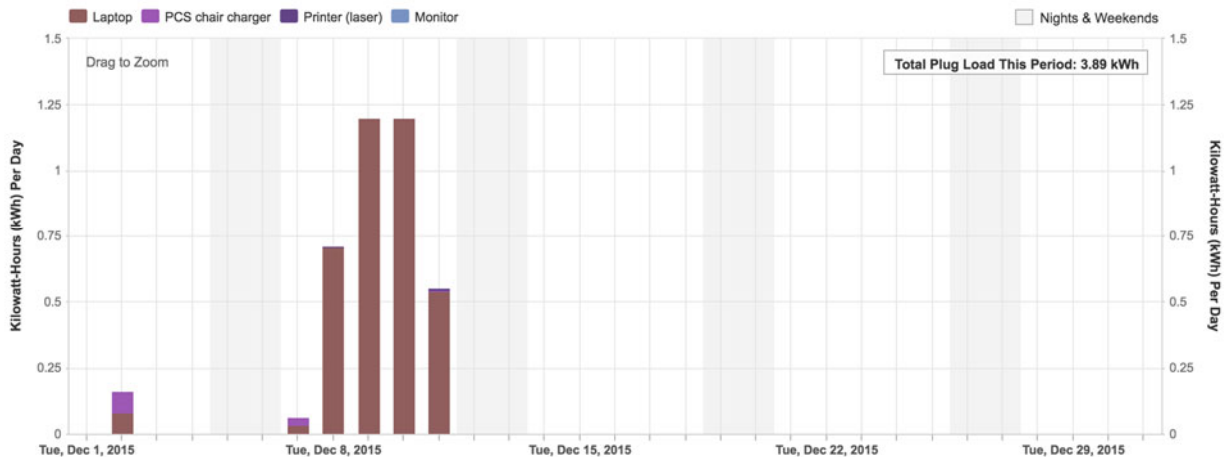Figure 12: Baseline energy consumption of four office appliances.

Figure 13: The "smart" case of eliminating standby losses, and mostly using energy as needed for the laptop.

Discussion

We investigated using several tools to explore improving comfort and convenience for occupants in the zone of occupancy. Detailed occupancy information, whether through the PCS, CO_2 sensors or plug load monitor, introduces valid privacy concerns that must be addressed.

The next steps are to integrate the sensors, PCS, and BAS to improve performance. For example, as more and more office workers use standing desks, the PCS would not provide comfort, but Comfy could. In some situations (e.g., two adjacent offices in the same zone but with very different heat loads, say due to solar gain), Comfy might not provide comfort to both occupant, but the PCSs would. Integration of the chairs—especially the occupancy and temperature data—with the BAS could provide zone temperature and ventilation control automatically. Studies of personal control and adaptation have shown wider temperature ranges when occupants have control. Preliminary Comfy data suggest that people remain comfortable with a higher level of variation over time and across zones, thus energy modeling rules could allow more zone temperature variation. Occupants have a means to address discomfort when the variable temperatures cross their comfort threshold.

Another way zones are problematic is when a handful of zones dictate the conditioning for the entire building, so-called "rogue" zones. Next steps include developing and testing solutions to rogue zones through improved controls and use of personal control systems, including identification of optimum number of zones to ignore or suppress, automated diagnostics and reporting of rogue zones, and use of PCS to reduce rogue zones.

An issue worth exploring is using the information gleaned from how people adjust their temperature during the day and over the seasons. We know from adaptive comfort research that thermal comfort is greatly affected by outdoor temperature, both daily swings and seasonal changes. We could use this input to automatically anticipate these thermal preferences in adapting the temperature deadband over the course of the day and the year.

Conclusion

As IoT enabled devices and systems proliferate, building automation is beginning to undergo a technology revolution driven by rapidly falling costs for electronic hardware, and

wireless communications along with the enhancements in the world of digital User Interfaces (UI). Building occupants may have direct real-time control on the local environment for improved productivity. Building owners and operators could improve the building's energy performance through control systems upgrades and wireless sensing networks, and the building can participate in DR events with fewer complaints from occupants. Software solutions can provide inexpensive solutions compared to costs of salaries and reduced productivity due to dissatisfaction with lighting, air quality or thermal comfort. There are also technical issues, such as low-cost data acquisition and communication, privacy concerns and understanding of customer behavior. This paper described research that focused on the zonal and individual occupant level data and employed several advanced controls of the BAS, wireless indoor environmental sensor networks, browser-based comfort voting, PCS chair and plug load sensors to improve both EE and DR. These tools were tested individually and are found effective to engage occupant and improve comfort and satisfaction. We found that gathering data at the zonal level provides additional insights on energy use patterns, but also requires extra effort to transform the information to control actions to the building for EE and DR.

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