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Abstract

We report on an experimental case study of personalized lighting controls built on top of an infrastructure designed to enable rapid development of applications in commercial buildings. Our personalized lighting controls (PLC) use an existing standard commercial building lighting automation system and require no new hardware to deploy. PLC presents occupants with a "shared virtual light switch" accessible online and easily viewable on smart phones by scanning a QR code. It embodies three important design principles: individual empowerment with localized human-centered resolution, token effort for energy consumption and return to a low-power state when inactive. After deploying our lighting controls on two new floors of a large research building on campus, we show a sustainable reduction in lighting energy of 50% to 70% on both floors over 12 weeks, continuing to this day. These savings are found to come from a combination of reducing brightness and keeping lights on less often, especially during evenings and weekends.

Categories and Subject Descriptors

C.3 [**Special-Purpose and Application-Based Systems**]: Real-time and Embedded Systems

General Terms

Design, Experimentation, Management

Keywords

Lighting Controls, Web Interface, Energy Management

1 Introduction

This paper reports on an experimental case study of personalized lighting control built upon a traditional commercial building automated lighting control system augmented with a rich building information infrastructure intended to provide a foundation for innovative applications. It embodies three important design principles: individual empowerment with localized human-centered resolution, token effort for consumption, and quiesce to a low-power state. These principles are actualized in the design and implementation of a simple "shared virtual light switch" application for smartphones and browsers that provides lighting control on each individual lighting zone in a large open-office academic research environment. Occupants began using this facility on their own (with enthusiasm) before the second slide of the presentation intended to introduce it. They continue to use it full time today, twelve weeks later, and have cut their energy consumption for lighting in half by easily exploiting the part time, part space, partial power nature of individual needs.

We all understand how to turn on and off a light by "flipping the switch" or "pushing the button" and have been well trained to avoid waste through countless repetitions of "turn off the light when you leave the room." It is a natural interface, typically associated with the act of entering and leaving a modest sized space. And yet, in commercial buildings we typically lose this simple form of personal control; instead, lighting is controlled automatically through schedules and overrides, sometimes augmented with motion detectors or daylight sensors. Often, a single lighting zone is shared by several occupants and is situated within a large space without a natural association between the particular region over which we want to exert control and the means for doing so. And, as a result lights are often on when they are not needed.

1.1 Baseline Usage Model

This situation was addressed explicitly in the design of our target building – Sutardja Dai Hall, the headquarters of the Center for Information Technology in the Interest of Society, a large, seven floor building with large open "collaboratories," in addition to traditional offices, classroom, labs, and an experimental semiconductor manufacturing facility. Figure 1 shows a typical floor plan (floor 7) with its large collaboratory spanning the east-west extent of the building, elevator access in the center of the north side, and individual office space along the north side. It was a design goal to have a green building consistent with the mission of the center. Collaboratories were divided into multiple sub-zones, typically five per floor. A typical working zone has three lighting power settings, low, medium, and high. A BACnet-based WattStopper automated lighting control system [10] was deployed throughout the building to control these zones and several switches (a pair for each zone and a pair for all zones on the floor) were placed on the north wall of the col-

BuildSys'11, November 1, 2011, Seattle, WA, USA.

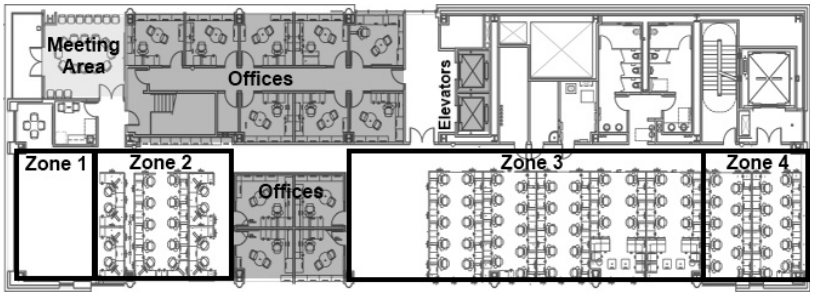

Figure 1. Floormap of the 7th floor showing a large open collaboratory and a smaller area of individual offices. The collaboratory is broken into 4 independently controllable lighting zones. Side zones 1 and 4 have large windows facing West and East respectively. Zone 1 is a common space used for meetings; all other zones consist of individual desks.

laboratory. Through the automated lighting control system, the facility manager programmed the lights to a schedule in which all zones of a floor are on high, the maximum brightness setting, during weekdays from 10 am till 7 pm. The lights were off during nights and weekends, unless someone pushed one of the wall's override switches, which causes the whole floor or the associated zone to be on for a period of three hours, depending on which switch was pressed. It is also possible to specify the lighting level by pushing an appropriate combination of (unlabeled) switch pairs, but this is rarely used.

This program defines our baseline usage model, in place prior to this study for a year and a half since initial building occupation. Generally, occupants disliked this facility-controlled lighting schedule. The lights were on all day long, regardless of occupancy, but when the lights shut off after working hours, someone would have to run over to the north wall and push the physical override button every hour. Generally, that turned the entire collaboratory on high, since few could figure out the per-zone switches or the proper incantation for intermediate lighting levels. Various efforts were made to incorporate motion sensors, as well as daylighting sensors in the end zones, but these were disabled after occupants grew frustrated with improper control actions, such as flapping their arms to keep the lights on while trying to concentrate.

1.2 A Personalized Automated Lighting Control Alternative

We learned of this less-than-optimal situation while engaged in a variety of deep energy efficiency efforts with this building, which included development of a rich infrastructure for energy usage monitoring and simple web-services based control (described below). The lighting control frustration provided an opportunity to test the ease of application development on our infrastructure, while benefitting the people in the building and hopefully saving some energy. Since prior studies have shown occupants are happier with direct personal controls [5, 8], we gave them a virtual light switch, accessible by their smartphone or browser. As illustrated in Figure 2, one click to locate the floor in the building and one to identify the zone, provides the "action page." There, a click on the "Reset Timer" button turns on the lights for a period of time. This page can be bookmarked or placed on the wall paper for easy access. In addition, QR-codes in the zone contain the URL and so take the smartphone directly to the action page with a camera snap.

Other prior studies indicate that people react poorly to extremely bright or excessively dim environments [7]. Embracing the principle of personal empowerment in a shared setting as an opportunity for energy savings, the action page also makes it easy to specify the light level or turn it off. The action is experienced by all in the lighting zone and whoever is viewing the action page. Although these stakeholders may have different preferences, we do not automate the resolution in contrast to more complex personal lighting control systems [6, 9]. The occupants are all present in a small physical area and can resolve lighting preference discrepancies through human-to-human interaction. The webpage reflects only the resultant action. It also provides a simple history of power usage for lighting in the zone and a sense of the cost associated with the available options going forward.

The user does have to expend a token amount of personal energy (clicking the reset button) to keep the lights on, thereby continuing to consume electric power. We introduced the personalized lighting controls in an informal meeting (on a Friday afternoon) with occupants of the fourth floor and discussed the trade-offs of a bit more irritation for more energy savings, and vice versa. The collective compromise was to use a three hour timer during working hours and a one hour timer all other times. This achieves the principle of quiescence at low power at a relatively fine grain, because each zone, if left alone for a couple of hours will go off.

At that introduction, lighting controls were switched from facility manager control to personal control–and were left that way since. A community exchange, replete with Facebook pages and tweets, has formed around lighting usage in the collaboratory and there is a sense of pride in the achieved improvement. The early adopters have become advocates in spreading the facility to other floors. A new plateau of lighting energy usage has been obtained, in part because there is no extra effort to be efficient. Somebody pushing a button somewhere every so often is mandatory to keep consuming. However, we do see that people make the extra effort to turn lights off when they are the last to leave the zone, even with a timer. We note that this was not intended to be a "human factors" study nor a deep examination of human-computer-building interface design. We have not performed a latitudinal study and can not claim that our findings are representative of open office space in general, nor have we performed a longitudinal study. We built a simple,

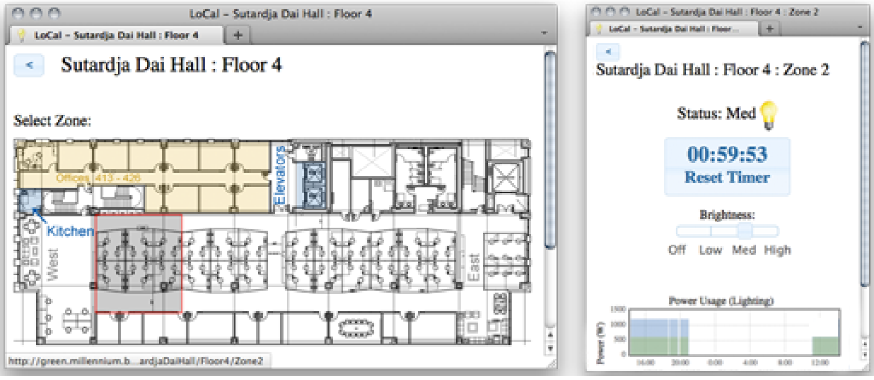

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Figure 2. Screenshot of the personalized lighting control interface. Users select a zone by clicking on the floormap and then press the reset timer button to activate the lights and select a desired brightness level.

principled tool quickly to gain experience with an infrastructure intended to support innovation in energy applications and asked an interested community to give it a try. Here we report on how it was built and how it has worked so far.

2 Physical Infrastructure

The study was conducted in a new, seven-floor, 140,000 sq. ft. building located at a latitude of 38 degrees north. The lower three floors contain building system infrastructure, classrooms, administrative offices, instructional labs, restaurant facilities, server and communications facilities, and an auditorium. Attached to the building on the fifth floor is a large semiconductor manufacturing facility, which shares chilled water and power with the rest of the building, but is otherwise self-contained. Floors four through seven have large "collaboratories" of open office spaces stretching the east-west extent of the building with glass walls at the east and west ends providing the only day lighting. As illustrated by Figure 1 for the fourth floor, this bay is divided into five primary zones along the east-west extent. Additional zones cover kitchen, entry, and various floor-specific areas. The end zones are utilized largely as meeting areas. Workspaces fill the middle three zones, with multiple research groups forming contiguous blocks. The number of lighting fixtures varies with zone size. A fixture typically contains three T-8 fluorescent tubes and two ballasts; one illuminates a single tube for low lighting, the other two tubes for medium, and both together for high.

The building as a whole consumes 800-850 kW, with the fabrication facility accounting for approximately 600 kW. The HVAC system is controlled by a proprietary Siemens Apogee Insight BMS that contains over 6,000 points spanning two cooling towers, two centrifugal chillers, one evaporative chiller, two office air-handling units, 16 fab air-handling units, and 130 variable air valves. A portion of these points are accessible over BACNet [1] through a BMS add-on. Floor-by-floor power meters were installed to measure lighting and receptacle load as part of larger energy management effort. Lighting is controlled by a separate WattStopper lighting control system that provides a facilities management console and a BACNet interface. Overall, the power consumption of the office portion of the building is roughly 143 kW, with 20 kW on average for lighting. Power consumption per collaboratory in its typical "all zones on high" mode is shown in Table 1. Measured power consumption is 25 watts per tube.

Floor	Area (sq. ft.)	Zones	Peak Power (kW)
4	10,654	5	7.3
5	10,923	5	6.5
6	5,599	2	2.5
7	7,102	4	4.9

Table 1. Lighting power in collaboratories.

3 Information Infrastructure

In order to enable application development for energy analysis and modeling, as well as advanced building control and cross-system energy efficiency optimizations, we developed a uniform, web-services based information infrastructure over these various physical subsystems. It provides both real-time monitoring and control, historical data, and allows integration with external data sources.

Our system infrastructure is shown in Figure 3. It consists of two main tiers: the physical instruments and the application layer. This division allows for an important separation of concerns: driver writers interface with physical devices, while application authors can write code independently of the specific instrument being accessed.

The sMAP interface [2] specification provides the common language between a physical instrument and the application tier. The sMAP interface is a RESTful web service [4] with resources defined by the instrument driver. Each resource consists of either a set of measurements or a control point. Applications interact with sMAP by issuing HTTP GET requests to read a resource, HTTP POST requests to control actuators or by registering a report to receive new measurements as they are taken. sMAP contains provisions for using SSL to secure access and has a discovery protocol for finding sMAP sources as well as sMAP resources.

For the personalized lighting control application, we wrote a sMAP driver that connects the WattStopper controller to a higher-level application. This driver connects to the WattStopper device via BACnet [1] and exposes all available relays as readable and controllable points.

At the application layer, the personalized lighting controls consist of a web app written in Django [3] that pro-

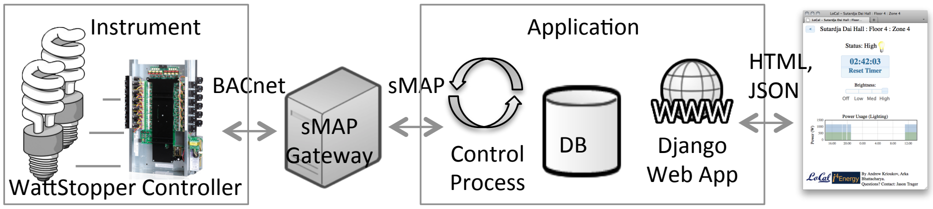


Figure 3. Design of the lighting controls and underlying infrastructure.

vides the user-facing interface with a control process that enacts the desired light settings. The web application provides screens for selecting the appropriate building, floor, and zone. It then shows the action screen with the current timer countdown value and brightness setting. When a user hits "Reset Timer" or modifies the brightness settings an asynchronous JavaScript (AJAX) call is made to the server which records the change in a database. Since multiple users may access the web application simultaneously, a consistent view of the current settings is essential. This is done through periodically polling the server settings in JavaScript and reflecting any changes on the page. Finally, an independent control process on the server periodically reads the light settings recorded in the database and turns on and off the appropriate bulbs by interacting with the WattStopper controller through the sMAP interface.

For security, the web application ties the existing campus Central Authentication Service (CAS) for access. Users login with the same account used to access the wireless Internet or register for classes. If users are already logged in to a different campus service, they will not be prompted to login again. We currently do not restrict access to exclusively the occupants of a specific floor or even building. Students and visitors are constantly coming and going so maintaining an access list would be prohibitively difficult. Instead, we track users accessing the system by their CAS accounts and have the ability to block any abusers of the system. In the past month and a half of operation there has been no reported abuse. Tracking accesses also allows us to gather statistics about how occupants are using the controls and the number of unique users.

4 Energy Savings

We first deployed the personalized automated lighting application on one floor, the fourth. This was to gain confidence in the infrastructure and experience with the approach, as well as to provide an empirical control group within a living laboratory. Half the research groups situated on that floor focus on energy and climate issues, contributing to user enthusiasm. We enabled the system on May 13, 2011 with a local member of the floor serving as the point of contact. With changes in work pattern and season, we expected to use the other floors as a reference in assessing the impact on electrical energy consumption. The system was actively used with 40 unique users in the first two weeks.

We use two methods of obtaining the lighting power consumption. Our building has per-floor lighting circuit submetering which provides us with total floor lighting power consumption every 5 seconds. This does include lights outside the collaboratories that we are investigating. To estimate collaboratory power we obtain relay states (i.e. on/off) for all lights in the collaboratory and multiply by the number of bulbs controlled by each relay and the typical power consumption of a light bulb. From this we obtain the collaboratory lighting power. Combining these two, relatively fine grained monitoring streams allows us to isolate the factors contributing to savings.

Figure 4 shows the measured total floor lighting power usage for the 4th and 7th floors before and after deploying personalized lighting controls (PLC). The 4th floor personal controls were enabled on May 13th and are followed by a 47% reduction in the average weekly power consumption. Over the same time period, power consumption for unchanged floors (e.g. floor 7 shown in figure) remained constant, suggesting that PLC was the cause of the 4th floor power drop. Some weeks later, we also deployed personal controls on floor 7, resulting in a 50% drop in power consumption.

Week	Avg. Floor Power (kW)	Avg. Collab. Power (kW)	Collab. Savings (%)
Before	3.47	2.84	-
5/13	1.83	1.19	-58%
5/20	1.47	0.90	-68%
5/27	1.44	0.87	-69%
6/3	1.86	1.04	-63%
6/10	1.97	1.34	-53%
6/17	1.64	1.00	-65%
6/24	1.65	0.90	-68%
7/1	1.20	0.71	-75%
7/8	1.37	0.84	-71%
7/15	1.78	1.09	-61%

Table 2. Fourth floor energy savings over time. The energy savings do not drop off with time.

Week	Avg. Floor Power (kW)	Avg. Collab. Power (kW)	Collab. Savings (%)
Before	3.31	2.62	-
7/15	1.66	0.99	-62%
7/22	1.78	1.27	-52%

Table 3. Seventh floor energy savings over time.

Table 2 shows the total and only collaboratory weekly lighting power consumption of the 4th floor over the duration of the study. Savings of the collaboratory lighting power range from 53% to 75% compared to the week before installation. These savings are retained over the 10 weeks shown

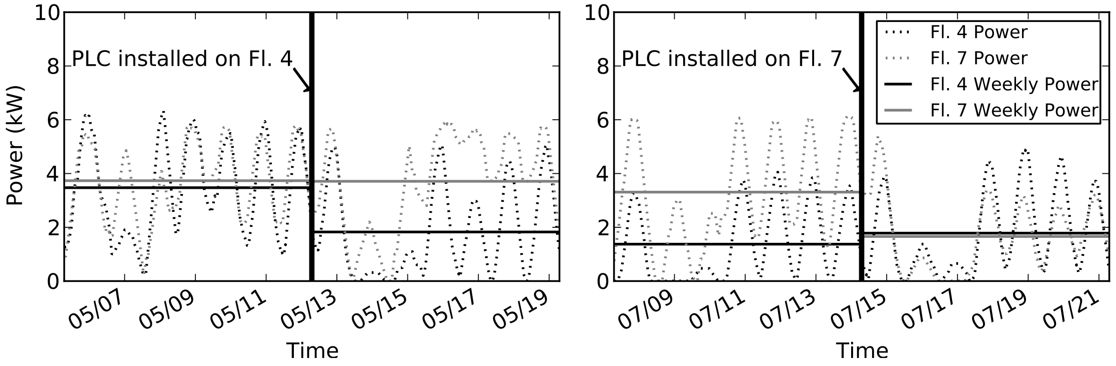
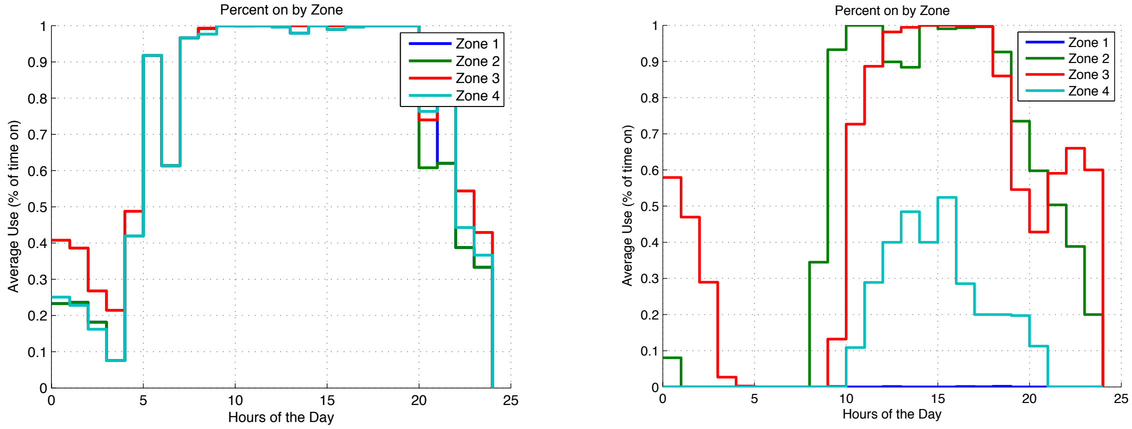


Figure 4. Lighting power of 4th floor and 7th floors showing a 47% reduction in energy use due to PLC.



(a) Average lighting use before personalized lighting controls.

(b) Average lighting use with personalized lighting controls.

Figure 5. 7th floor lighting use for each hour of the day averaged over three weeks, before and after installing PLC.

and vary primarily with holidays and occupant activity. Table 3 shows similar energy savings achieved on the 7th floor, demonstrating that PLC can be applied in other settings and works equally well with occupants that are not focusing on energy and climate issues.

Note that providing a relatively tight monitoring envelope around the subsystem under test is quite important. While the power savings of 1.6 kW per floor is significant it would be lost in the background of the other 825±25 kW of usage in the entire building. At the same time, finer grain monitoring allows us to isolate the factors contributing to the savings.

4.1 Source of Savings

To understand the source of energy savings we first explore the typical lighting use before the installation of personalized lighting controls. Figure 5(a) shows the fraction of time lights were on, on average, for each zone for each hour of the day taken over a three week period before the installation of the new personalized controls on the 7th floor. An automated schedule was used to keep all lighting zones on high brightness from 10am to 7pm. At other hours occupants used the override buttons to keep the lights on. Most zones are on at the same time suggesting that occupants used the whole floor switches rather than the per-zone switches. The 6am spike in lighting use is due to janitors regularly cleaning the floor at that time. When on, the light brightness settings were set to maximum 98% of the time.

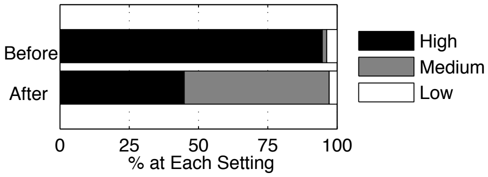


Figure 6. Brightness levels before and after PLC

We compare lighting use after installation of the personalized controls to this baseline to understand where the energy savings are coming from. Fundamentally, there are three sources of potential savings: part space (not illuminating all the zones when only some are needed), part time (allowing a zone to go off if unneeded), and part power (utilizing medium or even low brightness settings).

Figure 5(b) shows the lighting use after installation of PLC. Lights in zone 1, a meeting area near large windows, are now nearly always off, yielding large part space savings. In zones, 2 through 4, the lights are turned on later as occupants arrive at different times and turned off earlier in some cases. Zone 4 has only a few occupants so lights are often off even during working hours. Finally, brightness levels are set significantly lower than before as shown in Figure 6. The average brightness setting is medium yielding significant part power savings.

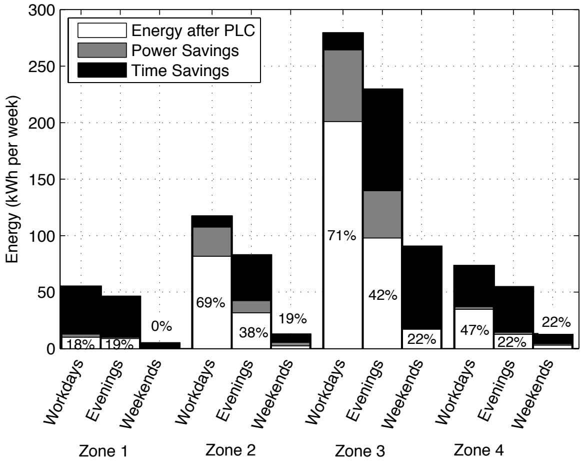


Figure 7. Breakdown of energy use and savings. Full bars represent the baseline weekly energy use before PLC. Shaded regions show sources of energy savings. The white bars show weekly energy consumption after PLC, labeled with the percent of baseline energy.

Figure 7 shows the breakdown of energy use before and after PLC. Energy is broken down by time: working hours (9am to 6pm), non-working hours (labeled evenings), weekends and by zone. For each zone and time, the full bar represent average weekly energy use before PLC implementation and the white bar represents the energy use after implementation. The difference, energy savings, is shaded indicating part power and part time savings. Overall, the majority of energy is saved from keeping lights on part time rather than on lower brightness levels. However, during working hours in the cubicle zones brightness settings make up most of the savings. The meeting area in zone 1 is kept off most of the time, however, those energy savings are dwarfed by turning off the large cubicle zone 3 slightly earlier in the evenings and on slightly later in mornings.

5 Enabling Extensions

Within one week of enabling PLC we observed that building occupants were independently creating applications on top of it. One student wrote a short Linux script to automatically extend the lighting control timer only when he was actively using his laptop and connected to one of the wireless access points on his floor. We encouraged this type of rapid development by providing an easy to use web service API.

We subsequently extended this idea by developing a cross-platform application with a graphical user interface. Occupants can now optionally download this alternative interface to the PLC on their laptops. The program asks users to input their typical seating zone and brightness preference. It then uses a combination of activity detection and coarse-grained WiFi localization, based on per-floor BSSID fingerprints, to determine when the lights should be kept on.

Alternative occupancy detection techniques could just as easily be programmed to control the lights using this simple web interface, enabling support for buildings with or without occupancy sensing hardware.

6 Conclusions

We show, through an experimental case study of personalized lighting controls implemented on top of our information infrastructure for developing building applications, that it is possible to enable rapid development of innovative building applications, and that a simple, principled approach can yield large savings. Personalized controls were deployed in a large building on campus utilizing the existing lighting automation system, but presented as a web service. The PLC presents a web and smartphone interface with a shared timer and brightness slider to control the lights.

Over the last 12 weeks of the ongoing deployment, we saw a reduction of 50% to 75% of the lighting power consumption on both floors with personal lighting controls. Energy savings came in a variety of forms, seemingly unpredictable intervals of time during working hours when lights turn off, due to meetings, lunches, etc., turning down the lights due to an abundance of daylight, or turning off the peripheral meeting zones which are unused most of the day. The biggest impacting factor of the energy savings came from turning zones on independently as occupants arrived at varying times in the morning. Fine-grained monitoring and tracking is key to isolating the cause of the savings. We are now expanding this approach to other floors and other buildings, and certainly hope to see it move toward broad innovation of building systems applications.

Acknowledgments

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7 References

[1] ASHRAE. Ansi/ashrae standard 135-1995, bacnet, 1995.

[2] S. Dawson-Haggerty, X. Jiang, G. Tolle, J. Ortiz, and D. Culler. smap: a simple measurement and actuation profile for physical information. In *Proceedings of the 8th ACM Conference on Embedded Networked Sensor Systems*, SenSys '10, pages 197–210, New York, NY, USA, 2010. ACM.

[3] Django Software Foundation. `www.djangoproject.com`.

[4] R. T. Fielding. *REST: Architectural Styles and the Design of Network-based Software Architectures*. Doctoral dissertation, University of California, Irvine, 2000.

[5] A. D. Galasiu and G. R. Newsham. Energy savings due to occupancy sensors and personal controls: A pilot field study. In *Proceedings of Lux Europa 2009*, 2009.

[6] Y. jung Wen, J. Bonnell, and A. M. Agogino. Energy conservation utilizing wireless dimmable lighting control in a shared-space office. 2008.

[7] T. Moore, D. Carter, and A. Slater. A qualitative study of occupant controlled office lighting, 2003.

[8] G. Newsham, J. Vietch, C. Aresnault, and C. Duval. Effect of dimming control on office worker satisfaction and performance. In *Proceedings of: IESNA Conference 2004*, 2004.

[9] J. S. Sandhu, A. M. Agogino, and A. K. Agogino. Wireless sensor networks for commercial lighting control: Decision making with multi-agent systems. In *In AAAI Workshop on Sensor Networks*, pages 131–140, 2004.

[10] WattStopper Lighting Integrator. `www.wattstopper.com`.