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Personalized Sensing towards Building Energy Efficiency and Thermal Comfort

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Abstract—**The emergence of Information Technology (IT) based sensing has received increasing attention and acceptance in buildings due to its noninvasive nature and its ability in delivering real-time and potentially highly personalized feedback to building energy and comfort management. This study presents results of a pilot deployment experiment on such an IT-based sensing system – Personal Office Energy Monitor (POEM) developed by Intel Labs.**

The pilot study shows that with appropriate analytic methods the POEM sensor data could be transferred into valuable inputs to building management system (BMS). This study applies building science principle based models as the first step to calculate intermediate building performance indices based on raw measurement data. The intermediate performance indices are then further analyzed in order to reveal potential means to improve a building's operational energy efficiency and occupant comfort. Results demonstrate that POEM sensor data could lead to energy saving opportunities through localized comfort management, plug load sensing and scheduling, and occupancy based building control. As an IT platform-integrated and occupant centered sensing system, POEM provides a convenient, low-cost, and efficient sensing solution to the next generation of smart buildings, featured by its ability in assisting BMS to improve operational building energy efficiency without compromising occupants' thermal comfort and indoor environmental quality.

Keywords: building energy efficiency; sensor-enhanced IT; personal energy feedback; personal sensing architecture; data analytics; occupancy profile

I. INTRODUCTION

Today, buildings consume 40% of total energy and 73% of electricity in the United States [1]. Given the increasing demand on energy and the impact on the environment, it has become a critical task to improve building energy efficiency. For the first time California Energy Commission includes the energy savings from future energy efficiency plan into their power planning, relying on the clean energy efficiency to avoid the needs for any future unnecessary polluting power plant [2]. Better design tools (such as advanced building simulation tools) and design approach (such as integrated design approach) have been developed and implemented in practice over time, leading to more efficient building design. Advanced approaches in building commissioning and control (such as predictive control) are also being explored but there is a still large gap to make up for before we reach an efficiently operated building sector: the percentage of building energy consumption in the total energy consumption of all sectors has not changed much despite all the progress we have made in building design and control thus far.

The primary function of a building is to provide a healthy and comfortable indoor environment to occupants. This functionality is achieved together by building envelope and its mechanical system, i.e. heating, ventilation, and air conditioning (HVAC) system. Delivering this expected performance to occupants is challenging, especially when (1) ambient environment is changing constantly and (2) every occupant is unique and so is their own perception to the local environment.

Thermal comfort is defined as "the condition of mind that expresses satisfaction with the thermal environment [3]" and is a very subjective building performance. Being exposed to the exact same thermal environment, different individuals may differ widely in their satisfaction to the environment. Though environmental condition sensors (such as temperature and relative humidity sensors) are used in buildings for monitoring purpose, they are only installed in a few selected locations to provide overall performance monitoring and feedback to HVAC control. Therefore, it is extremely challenging, if not impossible, for HVAC system to respond and deliver an indoor environment where every occupant is satisfied to their local environment.

Efforts from multiple fields, including Information interfaces and presentation in human-computer interaction (HCI) field and sensor network, have been made to improve the interaction between occupants and the building (systems) and provide finer granularity in building performance monitoring. Wen and Agarwal discussed the importance of granular sensing in transferring a building to a smart building. They pointed out that software user interface and management policy are two challenges that must be addressed so that a smart building not only saves energy consumption but also improves the quality of life for occupants at the same time [4]. Murakami et al. discovered that by including occupants' request (for comfort) into control loop through computer user interface, an interactive HVAC system could save 20% more energy as compared to the conventional setpoint based control [5]. Attar et al. proposed a framework to instrument office furniture (cubical)

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with sensors to provide occupant-level building performance sensing and 3D data visualization for building operators [6] though occupants' experience in their cubicles is not actively collected and fed back to the HVAC control or building operators. In another user-centric HVAC control architecture proposed by Gomez-Otero and Martinez, HVAC control system was able to modulate indoor thermal environment by constantly evaluating building thermal performance through a comfort model coupled with sensor measurements of real-time temperature and relative humidity [7]. The comfort management is further customized by consistently adjusting the thermal comfort model against actual feedback from occupants in terms of how they feel. Instead of changing the entire building control architecture, smart phone applications are also explored in including occupants into control loop through the existing platform [8].

This study introduces a sensor system that is able to provide occupant-level local environment sensing and that could also be deployed at the existing information technology (IT) platform: Personal Office Energy Monitor (POEM) developed by Intel Labs. The POEM system delivers occupant-level sensing, including local temperature, relative humidity, light level, and computer energy consumption, by deploying a set of sensors at each individual's work space. Through the POEM sensing system, a building management system (BMS) will gain access to granular information on local thermal comfort, power consumption, space usage, and occupancy status at the individual occupant level. The granular information essentially becomes invaluable for a building in considering and implementing future strategies to improve building operation efficiency, indoor thermal comfort, and space utilization. As an IT platform-integrated and occupant centered sensing system, the POEM system provides a convenient, low-cost, and efficient occupant-level sensing solution to the next generation of smart building applications.

The paper is organized as follows. Section II describes two key attributes of the POEM sensing system that are the foundation of the later realized occupant centric and personalized control. Section III describes methods used to analyze the granular personalized sensor data. Section IV discusses results from a pilot test, followed by conclusions in Section V.

II. Personal Office Energy Monitor

POEM is part of Intel's Eco-Sense Buildings (ESB) project [9] whose goal is to redefine the role of IT to maximize energy efficiency of buildings while improving occupant comfort. The objective of POEM is to do so by adding a pervasive sensing of local environment, energy and people, and using that input to drive coordinated power and occupant behaviors for building control systems.

A. *Platform-integrated sensors*

POEM provides noninvasive and yet very pervasive sensing in buildings through sets of IT platform-integrated sensors that are built into personal computing devices, such as laptops and desktops in this pilot study. The platform-integrated sensors offer many advantages over existing sensors, such as low cost, easy installation, operation and management, and personalization.

Currently the various control systems in buildings, such as IT and BMS, operate in isolation and without much coordination. In contrast, POEM sensing framework enables holistic building management through coordinating the behaviors of all control systems and therefore further improves performance of each individual system from being operated in isolation. Fig. 1 shows POEM's framework architecture. Each device or group of devices is monitored by a sensor agent, which can represent and abstract a hardware sensor or a software sensor. The architecture extends the notion of sensors to "people as sensors", which as an example provide personal comfort level readings. The agents report readings to a sensor database. The sensor database can be interfaced with an existing BMS database to exchange sensor information and control the devices for optimal building energy management.

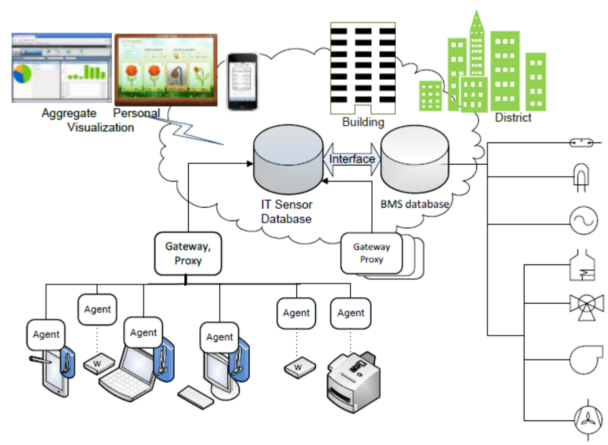

Fig. 1. IT-enhanced personal sensing of energy usage and ambient in smart buildings [10]

Fig. 1 is conceptual in that it depicts sensors in and around IT devices, such as laptops. In practice, we use a variety of sensors such as software and hardware sensors in laptops and other mobile devices, as well as stand-alone sensors such as power meters, embedded in the environment. POEM's system architecture and communication protocols are intentionally designed to accommodate sensors and aggregate data of interest to users across all relevant sensors.

POEM system is also carefully designed to utilize sensor metadata to associate the sensor data with users while accounting for static and dynamic sensor locations and intermittence of sensor data availability. In the initial prototype, design focus was enhancing IT infrastructure to measure personal energy consumption and personal ambient conditions, such as temperature, light, and humidity wherever the user (with the instrumented laptop) stays.

In general, buildings already have an IT infrastructure installed – such as PCs and LANs – and typically have a commercial BMS system. This makes an IT-centric sensing solution an incremental and cost effective add-on. In our prototype, all sensor and agent communication with the database occurs over the existing IT infrastructure, namely Ethernet and WiFi, thus simplifying provisioning.

B. Occupant centered sensors

One of the best features POEM provides to smart building applications is its ability of bringing end users (i.e. occupants) into building control and management loop. Although the primary function of a building is to provide a desirable indoor environment to occupants, an individual occupant's need is only taken into account in building design and operation in a collective sense at best: buildings are only designed and operated to meet the needs of a majority of occupants in buildings.

Built on its IT platform-integrated nature, POEM system can be conveniently deployed at individual's level. In fact, POEM system targets to measure indoor environment conditions and energy consumption at each individual occupant's level. POEM's effort of bringing occupants into building control and management applications are two folded:

- POEM has implemented a user-centric visualization interface that provides energy feedback in hope to raise community awareness. In addition to providing energy usage feedback, this user interface also collects occupants' feedback in terms of the perceived thermal comfort to their local environment. Occupants have the choice to report how they feel about their local environment whenever they like. Currently the ASHRAE 7-point thermal sensation voting scale [3] is used in POEM. The 7-point thermal sensation scale asks people to rate their perceived comfort to the local environment. The rating ranges from -3 to +3 with -3 being "cold", +3 being "hot", and 0 being "neutral". The feedbacks on thermal comfort of local environment are collected and aggregated before being passed to the building managers. In this way, an individual's preference to local comfort could be taken into account into building operation, which further improves occupants' satisfaction to their work environment. More details on the user experience regarding the visualization interface can be found in [11].
- POEM comes with a set of physical sensors deployed at individual work station. The physical sensors measure temperature, relative humidity, lighting level at the users' location, and power consumption of office equipment (such as printers). Besides the physical sensor, the POEM sensor set also includes software sensors that are deployed at every desktop/laptop. The software sensors measure power consumption of each individual from their laptop/computer. As every sensor set is associated with a specific work space, it allows us to associate sensor readings with specific time and place of the capture. This feature enables future development opportunities for any 3rd party to design their specific application and provide highly personalized satisfaction to individual customers if desired.

C. Pilot experiments

POEM sensors were deployed in two pilot office buildings at the initial prototyping stage in 2012: one in France and the other one in Japan [11]. This study will only discuss results from France pilot site in Section IV but the analysis methods presented in Section III could be readily applied to the other pilot site as well.

The pilot site in France represents a typical office work environment where employees have a routine work schedule and stay in the office mostly during the typical work hours (such as 8AM-5PM or 9AM-6PM). The experiment spanned across five floors of a 2522 m^2 office building, which is mainly open plan office space. A random sample of 23 occupants participated the pilot study, coming across from different floors, different business departments, and different professions. POEM sensors were deployed at each participant's work space and his/her computer. Fig. 2 shows the POEM sensor deployment in part of a floor in the pilot building. The experiment lasted approximately 3 months, from Mid-June 2012 to Mid-September 2012.

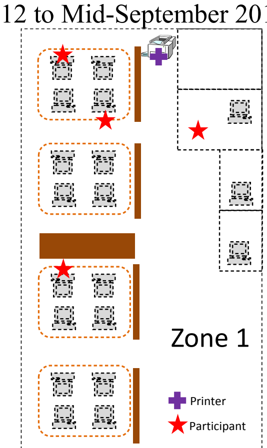

Fig. 2. Floor layout of a sample zone in a pilot testing site

III. ANALYSIS METHODS

POEM system collects a categories of data: (1) local indoor environmental conditions, including temperatures, relative humidity, and light levels; (2) power consumption data from personal computer desktop (or laptop depending on the users' setup) and from printers; (3) the perceived comfort responses from individuals at their discretion. The primary objective of data analysis in POEM pilot study is to identify appropriate analytic method(s) and transfer the raw measurements into actionable information that BMS could use to improve operational building energy efficiency and personalized comfort for occupants (Fig. 3).

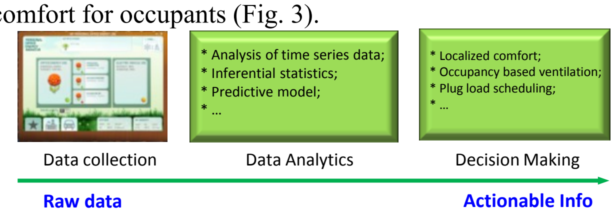

Fig. 3. The framework of data analysis approach around POEM

The specific analytic approach may vary from one decision making domain to another. Such approach include time series data analysis, predictive model, and inferential statistics. This study focuses on analyzing POEM sensor data through fundamental building science principles instead of data mining technique at a higher level (from "raw data" to "intermediate indices" as shown in Fig. 4). Performance indices are sought in three application aspects in this study: (1) occupant based localized comfort management, (2) plug load scheduling, and (3) occupancy based ventilation (i.e. demand controlled ventilation). It is our hope that building science principle based models will serve as an invaluable intermediate step. And other more advanced data mining technique could be explored and exploited on top of the calculated performance indices to further enhance the balance between building energy efficiency and occupant comfort.

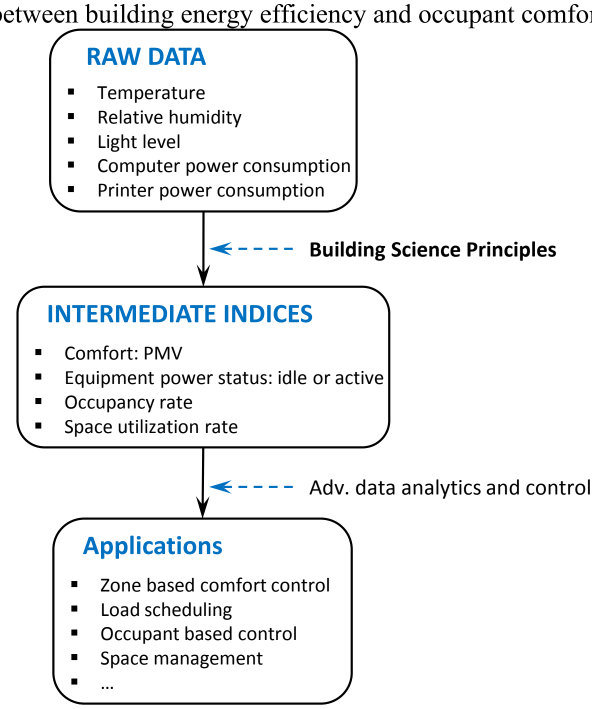

Fig. 4. Framework of the overall analytical strategy for POEM pilot data: a number of intermediate building performance indices are calculated based on fundamental building science principles

A. *Thermal comfort model*

Despite the fact that thermal comfort is the subjective building performance measure, researchers have developed thermal comfort models that associate resulting thermal comfort with a few key factors, including two physiological factors (clothing level and metabolic rate) and four environmental factors (air temperature, humidity, velocity, mean radiant temperature) [12]. The thermal comfort analytic module adopts the classic thermal comfort calculation algorithm (as shown in (1)) as provided by ASHRAE thermal comfort standard – standard 55 [3]. The basic comfort model provides an objective assessment of thermal comfort in each work space.

There are two common objective thermal comfort outputs from the thermal comfort model: PMV (predicted mean vote) and PPD (predicted percentage of dissatisfied), as defined in ASHRAE standard 55. The PMV predicts the mean value of the thermal sensation votes for a large group of people subjected to the same environmental conditions. The PPD predicts the percentage of people who are dissatisfied with the thermal environment. These two indices are inter-related through the comfort model. ASHRAE recommends the PMV value to be within the range of between -0.5 and +0.5 in order to make at least 90% of the people who are exposed to that environment feel satisfied to the overall thermal comfort. We will only discuss the thermal comfort results using PMV in this study.

$$PMV = 3.155[0.303\exp(-0.114M) + 0.028] \times L \tag{1}$$

Where, PMV is the predicted mean vote, M is the metabolic rate, and L is the thermal load on the body, defined as the difference between internal heat production and heat loss to the actual environment for a person hypothetically kept at comfort at the actual activity level.

This objective assessment evaluates thermal comfort of local environment assuming that a male adult with average weight, height and metabolism rate stays in the work space. By cross-referencing this objective assessment with the feedback provided from each individual in terms of their perceived thermal comfort, the comfort analysis module will be able to infer on each individual's preference to their local thermal environment. Since each sensor set is associated with a specific location, the objective assessments could be aggregated to provide resulting thermal comfort at zonal levels for building operators. Real-time monitoring thermal comfort in buildings at this aggregated level could be valuable in help spotting potential system malfunction at its earliest existence.

B. *Energy consumption analysis*

There are two types of energy sensors deployed through POEM sensing architecture: (1) software sensor installed in the desktop/laptop of individual's work space and (2) commercial power meters installed at each printer in the work space. The primary objective of analyzing the time series of energy consumption data is to identify the corresponding device's power state (and user activity) based on the measured energy consumption at any given time. One can then examine the statistics of power states of all devices within an organization and decide whether it would have been an economic measure to implement certain energy efficiency measure such as load scheduling.

Since the software sensor is associated with specific work space and thus associated with specific organizational department/discipline, energy consumption analysis could be further aggregated to departmental or disciplinal levels for organization wide resource management.

C. *Occupancy profile Estimate*

The occupancy rate refers to the percentage of total expected employees in an organization that are actually present in work space at a given time. The number of occupants determine the amount of ventilation a building system needs to provide. Knowing the actual occupancy rate in real time is essential in reducing ventilation load in operation that would have been otherwise provided based assumed maximum occupancy.

As introduced in previous sections, POEM has two types of sensors: (1) physical sensors that are deployed in individual work spaces, measuring local environmental conditions; and (2) software sensors that are installed in individual desktop/laptop, measuring computer power consumption. Measurements of physical sensors are only recorded into the IT sensor database when someone logs into his/her desktop or docks his/her laptop into a dock station (located in individual work space). And measurements of software sensors are only recorded into the IT sensor database if the computer is turned on. The unique mechanism of data recording of the POEM sensor set provides an opportunity for us to derive a real-time occupancy rate profile in buildings. Details of the occupancy profile estimate algorithm and some preliminary results have been reported in [13] and [14].

IV. Results

A. Thermal comfort

Fig. 5 shows the calculated PMV for one randomly selected work space, based on the measured temperature and relative humidity from POEM physical sensors, during the entire experimental period. This calculated PMV for this work space falls into the comfortable range for 92% of the time when there are physical measurements recorded. And for 98% of the time, the calculated PMV falls below zero which indicates that the thermal environment is on the cool or cold side. The results indicate this randomly selected occupant happens to sit in an area where the space is relatively overcooled than necessary. Fig. 6 shows a boxplot of calculated PMV values but categorized at zonal level for the pilot testing site. Apparent difference can be observed: zone 25 is the warmest zone while zone 32 is the coldest zone. Zone 29 experiences the widest comfort variation throughout the experiment period while Zone 32 experiences the least variation in its thermal environment. POEM sensor set presents the opportunity to assess thermal comfort at both individual space level and the aggregated zone level. This granularity of information provides building operators and manager a long-missing opportunity: to control the building HVAC system and deliver occupant based and zone based comfort. Together with the occupant feedback through end user visualization interface, the HVAC will be able to deliver thermally comfortable environment based on the actual occupants' need and in the meantime seek opportunity of energy savings by adjusting indoor temperature/humidity settings without compromising comfort needs.

B. Energy consumption characterization

Plug loads account for a significant part of the electricity consumption in office buildings, ranging from 21% to 50%, depending on building usage and design [15]. Schedule timer and load-sensing are two effective plug load reduction control strategies in practice. The schedule timer de-energized devices according to the preset schedule such as weekends and holidays. The Load-sensing controller monitors the power state of a device and de-energized it when it's not in use. The POEM sensor set shows a great potential for building operators to implement the load-sensing strategy conveniently and effectively:

- For desktop users, there will only be a power consumption measurement recorded when occupant logs into the company system. Therefore, all desktops that do not have a corresponding power measurement at any given time could be de-energized.
- For laptop users, software sensors monitor power consumption levels whenever the laptop is on. The laptop power state, such as short idle (i.e. active use), long idle, and sleep modes, could be identified. Extra control strategies could be implemented to de-energize laptops whenever they are in long idle mode.
- For printers, external power meters are installed to monitor their power consumption levels. The standby mode could be easily identified based on the energy consumption level. Additional control strategies could be implemented to either de-energize those printers in long standby mode or re-consolidate the printer resource across the office in situations where there are multiple printers and some of them are never in sufficient use for a considerable amount of time.

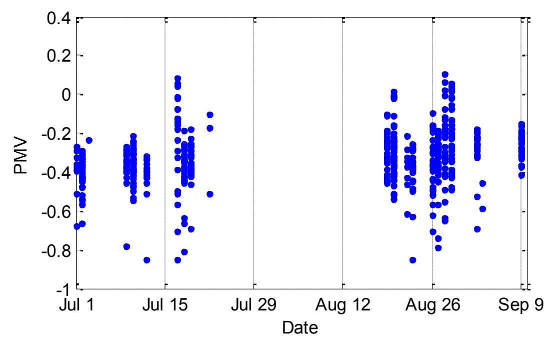

Fig. 5. The calculated PMV of one participant in the pilot site throughout the entire experiment period

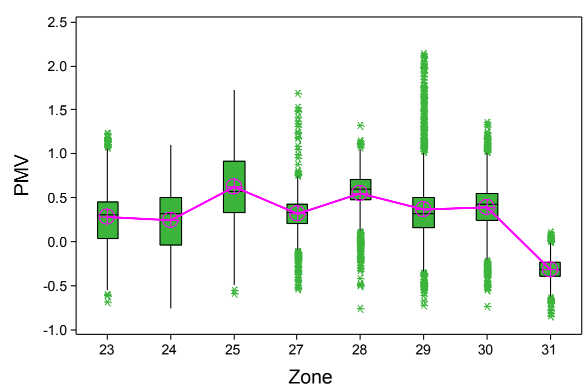

Fig. 6. The box plot of calculated PMV but aggregated at zonal level in the pilot site (the pink cross circle represents the mean value of calculated PMV of the each zone)

Fig. 7 shows a sample usage statistic of all computers (mostly laptops in the case study) during the pilot experiment. The computers in this pilot site spend an average of 16% of their daily time in long idle mode which contributes to about 15% of the total daily computer energy consumption. Fig. 8 shows a sample usage statistic of all printers. There are 8 printers onsite and apparently printer 4 has been mostly in standby mode and barely used. The printers consume about 30% their daily energy consumption on average while in standby mode during the pilot experiment period.

The computer energy usage could also be aggregated across different department, discipline, or any other classification method an organization favors for management purposes. Fig. 9 compares daily computer energy consumption per user among different departments within the participating organization. Combining periodic reports of daily energy consumption per user with departmental function, building managers can identify departments that use abnormally high amount of energy at a certain time. A friendly energy saving competition among departmental units could also help promote energy conservation awareness within the organization.

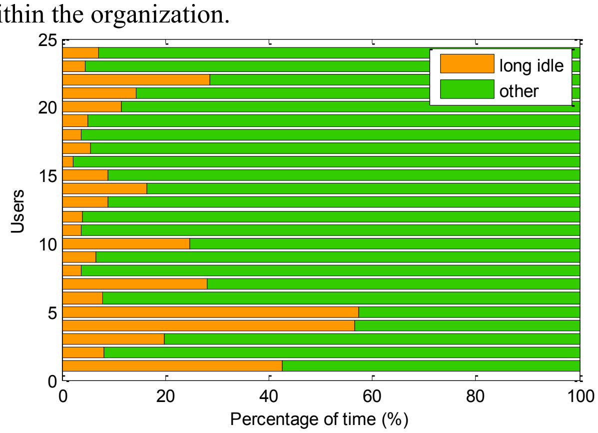

Fig. 7. The percentage of time computers in long idle modes per user

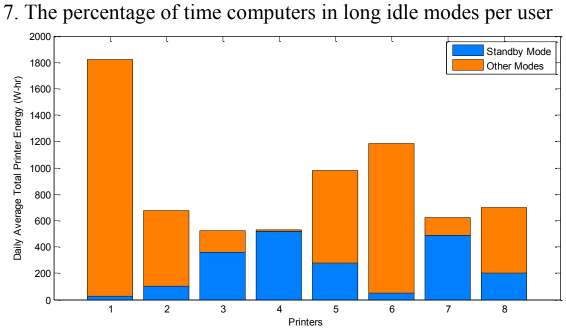

Fig. 8. The comparison of printers' daily energy consumption between in standby mode and in non-standby mode

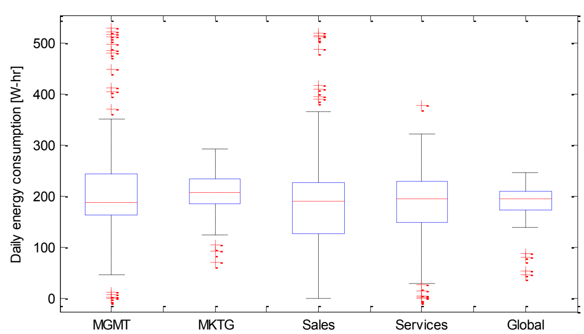

Fig. 9. A boxplot of daily computer energy consumption per user among 5 departments in the pilot site

C. *Occupancy rate profile*

Occupancy rate, also referred as occupancy schedule in building research community, measures the actual number of people present in a building at a given time as compared to the peak headcount at full occupancy. Because of flexible work schedules and the dynamic life styles we have these days, work space is rarely fully occupied. And yet often that information is not fed back to the HVAC system controller. Thus building HVAC systems still operate as if every occupant is in the building as expected. This lack of feedback could make a building miss energy saving opportunities such as those which are resulted from demand control ventilation (a control strategy where the mechanical ventilation system only delivers enough outdoor air for the actual number of occupants in the building).

As important as it is to feed the real-time occupancy rate to building control system, it is often challenging and expensive to measure occupancy rate in real time. The well-known occupancy sensors are only able to detect presence of occupants, not the number of people present in a space. Current practices use carbon dioxide as an indicator and estimate the overall occupancy by solving the steady-state mass balance equation. The drawback is that it is often too costly to install a carbon dioxide sensor in every single space, not including the continuous maintenance that is required to keep all sensors calibrated and accurate throughout their lifetime. The POEM sensor provides an economic and convenient way to measure real-time occupancy rate per space. Coupling POEM based estimates of real-time occupancy with existing carbon dioxide sensors, the BMS will be able to execute demand control ventilation more effectively without compromising the indoor air quality.

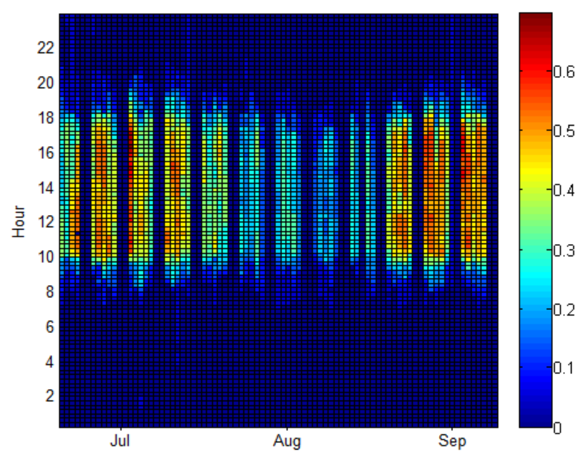

Fig. 10. The organizational wide occupancy rate in the pilot site during the experiment period: the peak occupancy rate is around 70%; and the average occupancy rate during normal work hours in a typical week is only 41%.

Fig. 10 shows the estimated overall occupancy rate throughout the experiment period in the participating organization in the pilot study. One can easily spot the period of time people take vacations which lead to considerably lower occupancy as compared to that in typical weeks. The participating organization has a peak occupancy rate at 70% during the experiment period. The typical week has an average occupancy rate of only 41% during the normal work hours. Since the POEM sensor set is associated with specific end user and location, the occupancy rate could also be calculated with respect to organizational departments, floors, disciplines, and etc. for other management purposes. One shall note that the resulting occupancy rate in the test site is considerably lower than the full occupancy which presents great opportunity for energy savings through implementing occupant based control.

V. Conclusions

This study presents an IT platform-integrated and occupant centric sensor system, POEM, that provides convenient, low cost, and end user specific monitoring of local environmental conditions and energy consumption. Current stage of the project focuses on exploratory analysis, aiming to transfer raw data into actionable information for future smart building applications.

Several building science principle based models have been explored and applied to analyze the massive raw sensor data. Results reveal that building science principle based models can be critical in uncovering the relationship between building performance and measured local environmental conditions. These building science principles are able to turn raw data into meaningful intermediate building performance indices for further data mining. This study demonstrates the great value this type of personalized sensing could bring to the next generation of smart buildings, especially in its ability in assisting BMS to improve operational building energy efficiency without compromising occupants' thermal comfort and indoor environmental quality.

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