

Toward Adaptive Comfort Management in Office Buildings Using Participatory Sensing for End User Driven Control

Farrokh Jazizadeh
Sony Astani Department of Civil and
Environmental Engineering
University of Southern California
jazizade@usc.edu

Burcin Becerik-Gerber
Sony Astani Department of Civil and
Environmental Engineering
University of Southern California
becerik@usc.edu

Abstract

Current building management systems (BMS) operate based on conservatively defined operational hours, maximum occupancy rates, and standardized occupant comfort set points. Despite the increasing building energy consumption rates, occupants are not usually satisfied with the indoor conditions in commercial buildings. This study proposes an intermediary communication platform, which enables occupants to communicate their preferences to the BMS. The objective is to facilitate the communication between humans and buildings toward adaptive end user comfort management and to compensate for high rate of discomfort in office buildings. The design process of the intermediary, as well as the participatory sensing approach for deploying it in a test bed is presented. The key element is the interpretation of occupants' preferences in the form of change in the HVAC system operations. The results are presented to investigate the correlation between sensed ambient conditions and the user preferences. The results show that although there is a weak to moderate correlation between ambient temperature, humidity, and occupants' preferences, the variation of correlation for different occupants is relatively high.

Categories and Subject Descriptors

H.1.2 [Models and Principles]: User/Machine Systems

General Terms

Human Factors

Keywords

Participatory sensing, occupant comfort, office buildings

1 Introduction

In the U.S., buildings consume about 40% of the energy, half of which is consumed by commercial buildings

[1]. Any reduction in energy consumption of commercial buildings can reduce the energy requirements and the environmental impact of energy generation. Making significant progress toward sustainable building energy usage requires a broad shift in how commercial buildings are used and operated. Occupant comfort is a dominant influence on building operations and a major criterion to evaluate the performance of building systems. Despite the increasing building energy consumption, occupants are usually not satisfied with indoor conditions in commercial buildings [2] - which can affect productivity and health of occupants. The paper introduces a vision of a human-building interaction framework that enables occupant driven control of building systems in commercial buildings to increase comfort and reduce energy consumption. As part of this framework, the paper focuses on the communication lines between humans and buildings, specifically, how occupants communicate their comfort preferences to the building systems. The paper describes the design of a mobile participatory sensing platform that not only enables occupants to communicate their preferences to the building systems but also intends to enable occupants to control buildings systems to meet their comfort requirements. The paper presents the initial comfort results by analyzing the data collected via the mobile participatory sensing platform in selected zones of an office building equipped with room level sensor systems and lays out the next steps for research.

2 Vision for Human-Building Interaction

The authors' vision is to develop a framework for ubiquitous and real-time interactions between buildings and humans to enable reduced energy use, increased comfort, and improved energy awareness and learning in commercial buildings. Building energy research community increasingly acknowledges the importance of human related information in building energy management. Recent work by [3], for example, incorporated dynamic modeling of occupancy load and simulated occupant energy use characteristics in buildings and proved that there is more than 25% variation in the energy use when dynamic occupancy parameters are used. In the envisioned human-building interaction (HBI) framework, buildings are not simply shelters; they are entities that connect with their users and adapt to their needs. Buildings are not only aware of and make use of its users' locations, processes, activities

Permission to make digital or hard copies of all or part of this work for personal or classroom use is granted without fee provided that copies are not made or distributed for profit or commercial advantage and that copies bear this notice and the full citation on the first page. To copy otherwise, to republish, to post on servers or to redistribute to lists, requires prior specific permission and/or a fee.

Buildsys'12, November 6, 2012, Toronto, ON, Canada.
Copyright © 2012 ACM 978-1-4503-1170-0 ...\$10.00

or preferences but they also learn and predict what is going to happen in the foreseeable future. Humans are decision makers in building operations, not just users of space. This HBI framework not only emulates human and building behavior but also facilitates learning, awareness and collaboration between humans and buildings. Currently, there are no means or methods for commercial building occupants to communicate their needs to their buildings besides infrequent complaints. There is a strong link between the degree of perceived communication and comfort [4]. At the same time, most occupants of commercial buildings are not aware of the impact of their individual activities and decisions on energy consumption [5]. In HBI framework, humans can communicate their needs to their buildings, buildings learn over time what occupants' needs are and act upon them. At the same time, buildings communicate directly with its users and delivers context aware, personalized and timely information for supporting decision-making, problem solving and learning. The HBI framework is supported through the use of mobile computing, and artificial intelligence, where the cyber, social and physical boundaries become less obvious.

2.1 End User Driven Building Controls

Humans (end users of buildings) play an important role in both the issue of increasing energy consumption of commercial buildings and the proposed HBI vision. The bottom line for user-driven building controls is the occupant satisfaction, which includes thermal comfort. Previous research has proven that reducing building energy consumption and increasing occupant comfort could be achieved concurrently [6]. However, without any direct feedback other than infrequent complaints, facility managers are forced to 'play it safe', resulting in sub-optimal operations. There is no feedback about the energy used per building area, or about the occupants' comfort levels. Currently, most building management systems (BMS) rely on industry standards such as ASHRAE, using the predicted mean vote (PMV) thermal comfort index, to ensure and assess satisfactory environmental conditions during occupancy. PMV is estimated based on a combination of parameters in indoor environments including air temperature, radiant air temperature, humidity, air speed, clothing insulation and metabolic rate. The PMV-PPD (predicted percentage dissatisfied) model, which is used as a design criterion to calculate percentage of dissatisfied occupants (e.g., 20% of the building occupants based on ASHRAE standards), has been developed based on controlled experiments and a set of assumptions. Recent studies [7] have shown weak and context dependent correlations between standard-defined comfort ranges and occupant-reported comfort ranges. Often times, occupant comfort ranges are found to be larger and more forgiving than predicted ranges implying a potential for reduced building energy consumption by allowing more flexible and adaptive control of system set

points [8]. This study argues that operation strategies for buildings should integrate occupant feedback into the operational logic and control of building systems. The study proposes an intermediary that is built on participatory sensing principles. This intermediary enables commercial building occupants to provide continuous and real time feedback about their environmental conditions to the BMS.

3 Intermediary Design

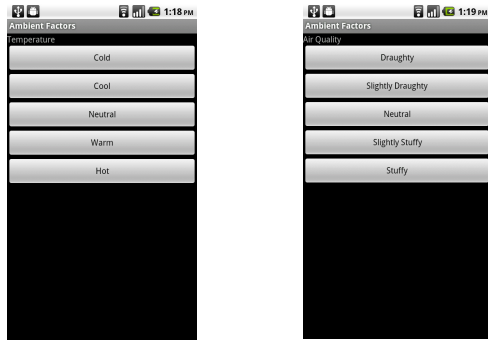
The PMV-PPD model is a standard that is used for the design of HVAC systems in commercial buildings. The PMV index aggregates the effect of multiple ambient condition parameters into one index. The majority of the occupant comfort studies have tried to improve the comfort by either introducing an improved PMV model or by using sensor systems to estimate real time and individual comfort indices. These comfort models are developed based on experiments in controlled test beds (mock-up or real) or based on generalized assumptions for metabolic rates and clothing values. In general, these studies are highly dependent on the context of the experimental set up and the opinions of the human subjects in the experiment.

Our HBI framework adopts participatory sensing principles as a complementary approach to the PMV-PPD for improving comfort in commercial buildings. Participatory sensing provides an opportunity to track and act on information while enabling mapping and sharing of local knowledge at the personal scale [9]. Participants use smart sensing devices and interact with their environments, they are the construct upon which sensor nodes reside. This relationship allows the mobility of nodes without extra costs to the nodes (e.g., bother cost). A participatory sensing application as an intermediary was designed for both smartphones and web applications. According to the recent statistics, by March 2012, 50.4% of mobile consumers had smartphones [10]. The objective was designing and testing an application that contains a few focused questions to encourage fast and frequent input. The focus of the participatory sensing application was to inquire about comfort levels for three influential factors on comfort -- temperature, light intensity, and air quality-- that have the greatest impact on building energy consumption and occupant comfort [11].

The initial interface was designed using the ASHRAE sensational scale. This scale for thermal comfort includes seven degrees from -3 to +3 (Hot, Warm, Slightly Warm, Neutral, Slightly Cool, Cool, and Cold). The three middle degrees (-1, 0, 1) are considered as satisfactory; consequently, five levels (Cold, Cool, Neutral, Warm, Hot) were incorporated in the design of the interface (Figure 1).

The design verification tests showed that the occupants are still satisfied even if they indicate they are warm or cool. A series of prototypes were prepared and tested in multiple phases. In these prototypes, the design has

changed and included sliders for which the center was considered as neutral (satisfactory). By moving the slider to the left or right, occupants could determine their preferences (Figure 2). Alternatives of this design including sliders with temperature increments plotted on scales, and sliders with graduated scales and a memory of the last adjusted scale location were also developed and tested. The two extreme values on the slider are ± 50 .



a) Thermal comfort scale b) Air quality scale

Figure 1. Screenshots of the initial interface design using a scale similar to the ASHRAE sensational scale

Although in the PMV model, six factors are the influencing factors on the thermal comfort index, the only tangible index for occupants to express their preferences regarding the thermal comfort is the temperature. In an analogy to PMV model and individual control systems, this interface uses occupants’ temperature preferences as an index that aggregates all of the influencing factors into one parameter. This is due to the fact that occupants provide real time feedback about their contextualized comfort for the environment that they are in, incorporating their metabolic rate, clothing levels, activity levels and so on.

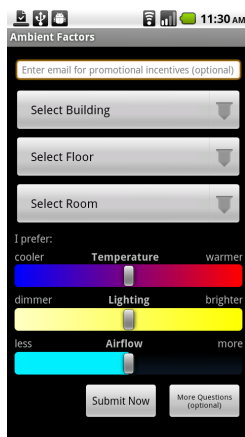


Figure 2. A screenshot of the final interface design

Location and time of participation are the two context parameters that are also collected. The location-sensing

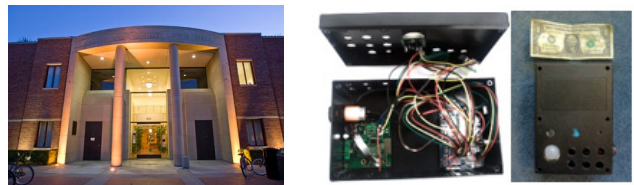
module of the application for smartphones runs as a service to record the last GPS based location algorithm, which measures the distance between the user’s location and the buildings’ footprint, provides the list of five nearest buildings to participant’s location and facilitates their input by navigating and scrolling through the floors and rooms of their buildings. Reducing manual data entry facilitates sustained contribution and also reduces the entry of faulty data. Location-sensing module and comfort index sliders are integrated into one page of application to address the requirement for ease of use.

The interface was developed for both Android and iPhone and as a web application the application, AmbientFactors, is available via the iTunes and Android market and could be downloaded at user’s discretion. Occupants’ feedback is stored in a central server, which interprets and provides information for actuation to the BMS through a web service. Once the feedback is sent to the server, the actuating agent on the server interprets each occupant’s thermal comfort range (based on an online learning algorithm) and then commands the HVAC controller. Although they are important components of the HBI vision, the interpretation and actuating agents are not reported in this paper.

4 Test Bed Building

To implement the proof of concept and test it, an office building on the University of Southern California campus, is chosen. The test bed building houses classrooms, conference rooms and offices on the USC campus. The building hosts around 60 permanent residents (staff, faculty, grad students) and more than 2000 temporary residents (undergrad and grad students) per semester.

The building was chosen (Figure 3-a) as a representative test bed due to its sufficient size and activity for research, its unique indoor system of sensors, actuators and its state-of-the-art BMS developed by the Building Level Energy Management (BLEMS) project. BLEMS aims to bring together ad-hoc legacy BMS configurations under a single unified framework that makes them interoperable. BLEMS is an occupant and building behavior-driven BMS that attempts to meet occupant preferences while simultaneously meeting specific energy usage goals.



a) Test bed building b) Sensor box

Figure 3. a) Test bed building; b) Moveable sensor boxes deployed in the test bed building

Communication networks are implemented in the building to transmit sensor data to a centralized control system, which in response, sends and controls information to system actuators. In addition to the 64-wired sensors that are part of the BMS, 500+ WiFi-based wireless sensors (i.e. temperature, humidity, light, CO₂, sound, magnetic, infrared, and motion) are deployed in 50 moveable sensor boxes (Figure 3-b), as well as 100+ actuators and several cameras in offices and sub-meters. To control the building systems and devices, requests are sent to the building's BMS via the centralized BLEMS system. Figure 4 shows various key wired and wireless communication links. The link A indicates the links between the wireless devices and the server; link B is the link between the static sensors and a backend server, where all information is logged; link C is a link enabled via the Internet to communicate real-time sensor readings and control preferences to the BMS; and link D is the existing link from the BMS to various actuators in the building.

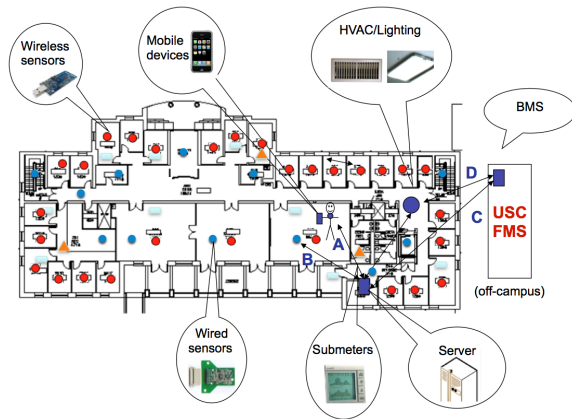


Figure 4. A representation of various elements of the test bed

5 Data Collection Process

In participatory sensing, sustainable contribution is a major factor in the success of the study. Hence, sensing campaigns organize individuals to cooperatively contribute and sense data. In addition to software and hardware design, there are research challenges that should be taken into account prior to data collection campaigns. One of the main challenges in all participatory sensing studies is the motivation for participation. Various types of incentives, including different forms of monetary incentives, could be used to increase the quality of the data collection.

In general, participants tend to contribute more to the studies that are related to their communities [12]. Since this study addresses comfort and there is a potential to benefit from it, occupants are expected to be motivated to participate. The results of a survey that is conducted in the

test bed prior to the intervention showed that more than one third of the occupants were dissatisfied with the indoor environmental conditions in the building (34% dissatisfied with temperature, 9% dissatisfied with lighting, 22% dissatisfied with airflow). The first stage of data collection was carried out in the test bed building. An email was sent to all of the occupants in the building with the goal and objectives of the BLEMS study (a multi-objective optimization of energy/comfort trade-off not addressed in this paper). Occupants were asked to provide their feedback during the day for at least four times, especially when they are feeling uncomfortable. In the message, the guidelines for using the interface were provided. The data collection process continued for two weeks with regular reminder emails. An iPad was given to a participating occupant each week through a raffle.

As the intermediary was not actuating the HVAC system in the building during the data collection period and therefore it did not change the indoor environmental conditions, a low response rate was experienced (low added value for participants in short term). Procedure development for recruitment is an approach for increasing the high quality and frequent responses [13]. Profiles of individuals including when/where the user is likely to contribute to the campaign and the performance information including the performance (in terms of quality and frequency) of individuals in previous campaigns, their commitment, consistency, and responsiveness to the data collection requests are analyzed. Following this approach, a set of eight participants was selected based on the above criteria in the first stage data collection and the thermal zoning of the building. A total of 4 thermal zones were selected. At least two offices shared one VAV box. The second stage data collection started at April the 24th and ended at the end of May 2012. An iPad per participant was given as an incentive to participate for a period of one month. The recruited participants in this study were administrative staff and faculty members, who had their own offices or shared them with another person. All of the occupants were asked to submit their preferences of the indoor environmental conditions at different times of the day to cover the entire work day with equal intervals to provide at least four to five data points per day. Participants were also asked to submit their feedback even if they feel comfortable with their environment in order to avoid biases by submitting feedback only for discomfort. By capturing the satisfaction conditions as control points, the interpretation of discomfort is facilitated.

Post-campaign feedback, visualization of daily contribution summaries and in situ reminders are factors that could increase participation [13]. Keeping participants active in the feedback loop, specially giving them access to the results of the study is a motivating factor that could prevent the loss of interest [14]. Based on the previous studies and the requests of the participants, participant contribution was

monitored on a daily basis and the contribution rate of each participant was reported back to them when it has decreased for more than two days in a row (Figure 5). Each occupant has received only his/her own rate of participation. Tracking of the results show that the provision participation graphs is more effective in increasing the number of responses in comparison to text based reminders.

6 Data Analysis and Results

Total of 529 data points were collected from eight occupants in seven rooms (one room had two occupants).

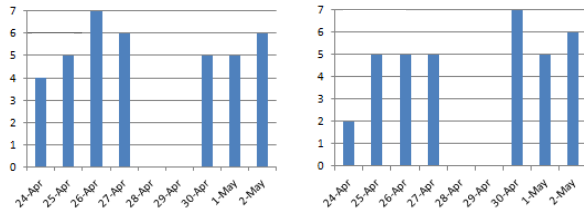


Figure 5. Samples of the participation rate graphs sent to two participants when participation has dropped

Data types included room number, preference time stamp, temperature preference, lighting preference, and airflow preference. In parallel, environmental condition data was gathered from the sensor boxes in the rooms and recorded in a centralized database. There were eight different sensors in each sensor box, which provided 12 features. The features can be categorized into three types of variables: (1) instant variables that show the instant output of a sensor at the time the data is queried (light, sound, motion, CO₂ concentration, sensed temperature, humidity, PIR, door status and current time); (2) count variables that sum the number of times a sensor's output changes in the last minute, (motion count net, PIR count net, and door count net); (3) average variables that show the average value of a sensor's output over a certain period of time (sound average - every 5 seconds). The data is automatically queried every one minute, time stamped, and stored in an SQL database. The preference data was fused with the available sensor data for analysis. Temperature, humidity, lighting (as a measure of variation of the natural light intensity in rooms), and CO₂ concentration were used.

6.1 Visual Comfort

Visual comfort is measured by the satisfaction of the occupants with the lighting conditions in their rooms. In case of the lighting data, out of seven rooms in the study, two occupants preferred changes in the lighting conditions occasionally. Fifty-one of the preference data points, out of 529, which is equal to less than 10%, showed a value different than zero on the slider. In the cases that occupants asked for a change in the lighting conditions, the preferred value was set at around +10 out of +50 for both occupants

almost in all cases. The distribution of the preferences for brighter lighting over time shows that the majority of change requests were sent either early morning (7:30 to 9:30 am) or in the afternoon (around 2 to 7 pm). In general, the results show that occupants are satisfied with the lighting conditions in their rooms. All of the rooms in the test bed building are both naturally and artificially lit. The lighting condition could potentially be used by facility managers to determine the spaces that need improvements in the lighting system. The satisfaction rate with the lighting condition could point to a potential for reducing energy consumption by modifying energy related behaviors through negotiations with occupants.

6.2 Thermal Comfort

6.2.1 Air Flow Preference

In 32% of the data points, participants were satisfied with the air flow in their rooms. However, 311 data points (59%) showed that occupants preferred more air flow. Among the feedback where participants preferred more air flow, 70% asked for more air flow between +20 to +42 and 30% asked for more air flow between +5 to +20. In the remaining 9%, participants asked for less air flow, which were uniformly distributed between -5 to -45.

Previous studies suggested that there could be a relationship between thermal comfort and airflow [11]. The preference data for three different occupants, as examples, are illustrated in Figure 6. There is a negative correlation between temperature and airflow preferences. An interesting observation is that while participants asked for warmer indoor conditions they also requested for more airflow. To examine this correlation statistically, Table 1 shows the spearman correlation between the temperature preferences and the airflow preferences for all of the rooms. In these cases the correlations are significant at level 0.01. As it could be seen there is a moderate to strong negative correlation between the occupants' perception of the temperature and the airflow.

Table 1. Correlation between temperature preferences and air flow preferences for all participants

Room Number	A	B	C	D
Corr.	-0.664	-0.923	-0.693	-0.54
Room Number	E	F	G1	G2
Corr.	-0.811	-0.385	0.243	0.376

The variation of the correlation coefficients for different participants is an indication of the need for the proposed intermediary. In this case, there is a correlation between preference values, but the correlation is weak to moderate.

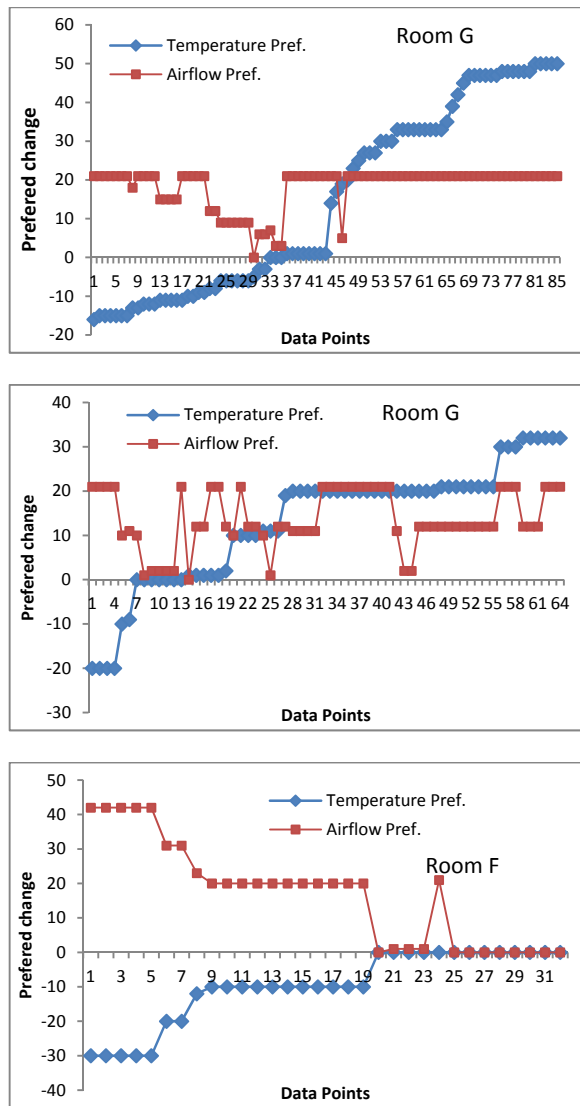


Figure 6. Comparison of the preferred temperature versus airflow in two rooms of three occupants (Room G is shared by two occupants)

6.2.2 Temperature Preference

The analysis of the temperature preferences showed that out of 529 data points, 217 were preferences for cooler room temperatures, 160 were preferences for warmer, room temperatures and 152 were neutral. Taking into account a tolerance for slider locations, the preferences between -5 to +5 can be considered as neutral, which is equivalent to the satisfaction point. Even then, only 30% of the time, participants were satisfied with the temperature in their rooms. In 41% of the data points, participants preferred cooler indoor conditions with 18% of the data points preferring in the range of -40 to -50, 27% of the data points between -20 to -40, and 55% of the data points between -5 to -20. In 29% of the data points, participants preferred warmer indoor conditions with 12% of the data points

preferring in the range of +40 to +50, 55% of the data points between +20 to +40, and 33% of the data points between +5 to +20. The preferences for the temperature are distributed to different hours of day.

Table 2. Correlation between temperature preferences and ambient condition features

Occupant	Temp.	Light.	Humidity	CO ₂
A	0.031	0.071	-0.06	-0.116
B	-0.41	0.204	-0.365	-0.162
C	-0.351	0.101	-0.161	0.163
D	-0.013	-0.029	0.329	0.107
E	-0.147	-0.16	-0.3	0.131
F	-0.764	-0.351	0.712	-0.531
G1	-0.467	-0.219	0.592	-0.006
G2	-0.538	-0.24	0.32	-0.267

In buildings where occupants can control the set points, thermostats are the only means of providing feedback to building management systems by adjusting the temperature. The effect of the ambient conditions in each room on occupants' temperature preferences, which simulates the thermostat action, was assessed. An analysis is performed to find out if it is feasible to correlate the participants' temperature preferences to four ambient factors (temperature, humidity, CO₂, and lighting). The key element in controlling the HVAC systems using the intermediary is the relationship between indoor environmental conditions and each occupant's preferences. Although the ambient conditions are highly effective in determining the comfort sensation of occupants, other factors including metabolic rates, clothing values, occupants' historical thermal experience, and psychological conditions (which are very difficult to be sensed) could overrule in deriving dynamic comfort sensations. Therefore, an HBI intermediary interface is important for improving the individual comfort satisfaction levels. The results of correlations between temperature preferences and ambient condition features are presented in Table 2.

There is a weak correlation between the features and the temperature preferences in five of the rooms. Most of the calculated correlation coefficients for these rooms are not statistically significant. The correlations for the last three rooms in Table 2 are significant at the levels of 0.05 or 0.01. For these participants, temperature and humidity are moderately correlated to the temperature preferences.

The negative correlation for temperature is due to the fact that the participants provided "their preferences" via the intermediary. In other words, when the temperature was high, participants asked for cooler temperatures, which were represented by negative number on the slider. Although there is a correlation between the humidity, temperature and temperature preferences, the degree of

correlation varies for different participants and the correlations are moderate.

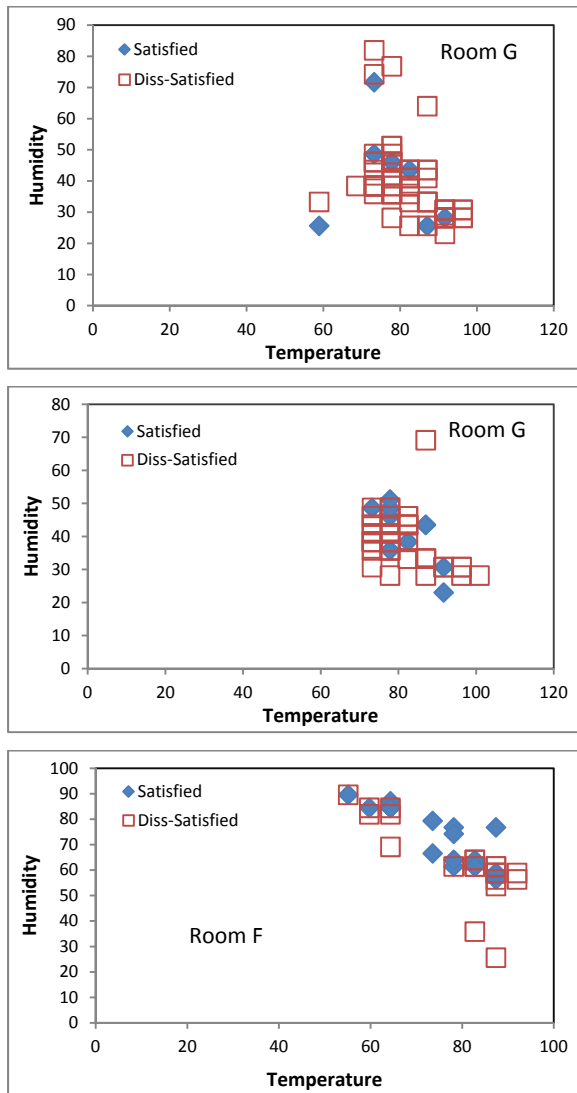


Figure 7. Satisfaction versus dissatisfaction for different ambient conditions for three occupants

Taking temperature and humidity into account, the occupants’ satisfaction versus dissatisfaction for three rooms, as examples, have been illustrated in Figure 7. The clusters of satisfaction and dissatisfaction have almost a complete overlap for room G and there is a substantial overlap for room F. This is another indicator of subjectivity of the occupants’ perceptions of indoor environmental conditions. The introduced intermediary addresses these observed variations in occupants’ perceptions.

7 Conclusion and Future Work

Based on the results of the surveys conducted in university campus buildings, a considerable fraction of occupants in buildings are not satisfied with the ambient

conditions. This issue mainly stems from the fact that building systems are designed and operated based on standard set points and do not take into account the dynamism in the occupants behavior. In the context of the authors’ human computer interaction vision, a tool is proposed to compensate for the missing communication between humans and buildings. Adopting a participatory sensing approach, an intermediary interface has been incrementally developed which provides the communicating channel from occupants to BMS. The ultimate objective of the framework is to enable occupants to drive HVAC operations with the objective of comfort improvement without compromising the energy consumption. The key element in this loop is the translation of the individual occupant preferences to HVAC control commands. This interpretation requires the relationship to be defined between different variables. Analyses of the collected data in a test bed showed that there are correlations between occupants’ temperature and air flow satisfaction, ambient temperature and relative humidity. However, the correlations are weak to moderate and show variations for different occupants, which supports the necessity for the intermediary. In future research, to address these issues, an online learning approach based on fuzzy rule extractions will be adopted to learn from occupants and control the BMS in order to address local discomfort as well as assessment of the trade-off between comfort and energy consumptions in office buildings.

8 Acknowledgements

This material is based upon work supported by the Department of Energy under grant # DE- EE0004019 and the National Science Foundation under grant #1201198. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation. Authors would like to acknowledge the support of USC Integrated Media System Center (IMSC).

9 References

- [1] Y. Zhu, T. Batten, H. Noboa, D.E. Claridge, W.D. Turner, M. Liu, J. Zhou, C. Cameron, D. Keeble, R. Hirschak, Optimization Control Strategies for HVAC Terminal Boxes. *12th Symposium on Improving Building Systems in Hot and Humid Climates. Energy Systems Laboratory*, 2000.
- [2] F. Jazizadeh, G. Kavulya, L. Klein, B. Becerik-Gerber, Continuous sensing of occupant perception of indoor ambient factors. *Int. Workshop on Computing in Civil Engineering*. June 2011, 161-168, 2011.
- [3] E. Azar, C.C. Menassa, Agent-based modeling of occupants’ impact on energy use in commercial buildings. *J. Comput. Civ. Eng.* 26:4, 506-518, 2012.
- [4] H. Zhang, E. Arens, D. Kim, E. Buchberger, F. Bauman, C. Huizenga, Comfort, perceived air quality, and work performance in a low-power task-ambient conditioning system. *Build. Environ.* 45, 29-39, 2010.

- [5] J. Pierce, W. Odom, E. Blevis, Energy aware dwelling: a critical survey of interaction design for eco-visualizations, Proceedings of the 20th Australasian Conference on Computer-Human Interaction: Designing for Habitus and Habitat, 1-8, 2008.
- [6] L. Klein, J. Kwak, G. Kavulya, F. Jazizadeh, B. Becerik-Gerber, M. Tambe, Coordinating occupant behavior for building energy and comfort management using multi-agent system, *Autom. Constr.* 22, 525-536, 2012.
- [7] S. Barlow, D. Fiala, Occupant comfort in UK offices - How adaptive comfort theories might influence future low energy office refurbishment strategies, *Energy. Build.* 39, 837-846, 2007.
- [8] J.F. Nicol, M.A. Humphreys. New standards for comfort and energy use in buildings, *Building Research and Information.* 37, 68-73, 2009.
- [9] K. Shilton, N. Ramanathan, S. Reddy, V. Samanta, , J.A. Burke, D. Estrin, M. Hansen, M. Srivastava, Participatory design of sensing networks: strengths and challenges. Proceedings of Participatory Design Conference, CPSR/ACM, 2008.
- [10] Nielsonwire. America's new mobile majority: a look at smartphone owners in the U.S. <http://blog.nielsen.com/nielsenwire/online_mobile/who-owns-smartphones-in-the-us/>, 07/29, 2012.
- [11] H. Zhang, E. Arens, W. Pasut, Air temperature thresholds for indoor comfort and perceived air quality. *Building Research and Information*, 39(2), 134-144, 2011.
- [12] S. Kuznetsov, E. Paulos, Participatory sensing in public spaces: activating urban surfaces with sensor probes, Proceedings of the 8th ACM Conference on Designing Interactive Systems, 21-30, 2010.
- [13] S. Reddy, D. Estrin, M. Srivastava, Recruitment framework for participatory sensing data collections, Proceedings of the 8th international conference on Pervasive Computing, 138-155, 2010.
- [14] M.V. Kaenel, P. Sommer, R. Wattenhofer, Ikarus: Large-Scale Participatory Sensing at High Altitudes, Proceedings of the 12th Workshop on Mobile Computing Systems and Applications, 63-68, 2011.