NSF Workshop on

Implications of Occupant Behavior for Building Operation and Design: Now and the Future

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Workshop Outcome Report

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1. Background

In commercial buildings, Heating, Ventilating, and Air-Conditioning (HVAC) systems consume nearly 45% of the total building energy consumption (DOE 2014). To design energy efficient buildings, U.S. Green Building Council (USGBC) and American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE) developed design standards and guidelines such as Leadership in Energy & Environmental Design (LEED) (USGBC 2014). However, according to the report by NBI (2008), most of the LEED buildings are under performance during operation stages and some are even below the national energy baseline. In addition, the expected performance of LEED certified buildings predicted from building energy simulation are greatly different from measured performance. One of reasons is because system did not operate as it should be which generates research topics such as performance monitoring and benchmarking, information visualization, controls, and fault detection and diagnostics (FDD). However, with the maturity of those technologies in building industry, it leads to a bottleneck that no more energy savings can be achieved beyond those technologies.

Building energy consumption is a systematic procedure comprehensively influenced by not only engineering technologies, but also cultural concept, occupant behavior and social equity, etc.. Occupancy behavior, to be discussed in this workshop, refers to occupancy presence and numbers in spaces or a building, and human building interactions, such as opening/closing windows, blinds, and turning on/off lighting, as well as occupant preferences, such as thermal and lighting comfort. Occupant behavior becomes one of the leading influencers of energy consumption in buildings. This is because the followings:

(a) Significant interactions between occupants and building systems. The occupants' expectation of comfort or satisfaction in the built environment drives the occupant to perform various controls, such as adjusting the thermostat in spaces, opening windows for ventilation, turning on lights, pulling down the window blinds, and consuming domestic hot water.
(b) Strong coupling between occupant behavior and building performance. Various occupancy behaviors have different impacts on built environment (e.g. indoor temperature, humidity level, lighting, CO_2, etc.) and energy end use. The building performance will also have economic,

physiological and psychological impacts on occupancy expectations. A recently study shows that with the identical building envelope in the same climate, the measured air-conditioning electricity consumptions of 25 apartments vary in a wide range, from nearly 0 to 14 kWh/m^2 with an average of 2.3 kWh/m^2 (Yan and Hong 2013).

The challenges to study occupancy behavior in buildings are: (a) occupancy behavior is stochastic and complex in nature; (b) privacy issues make data collection difficult; and (c) to monitoring occupancy behavior relies on various sensors with relatively high costs. The changes of built environment caused by occupancy behavior also affect occupants physiologically and psychologically. For example, studies show that a better comfort level through changing indoor temperature increases productivity in office buildings. There are several research studies that tried to understand and model occupancy behavior in buildings such as (1) occupancy presence (Wang et al. 2005; Page et al. 2008; Azar and Menassa 2011; Liao et al. 2012; Li et al. 2012; Stoppel and Leite, 2014), (2) occupancy number counting (Lam et al. 2009; Erickson et al. 2009; Dong et al. 2011; Yang and Becerik-Gerber 2014), (3) opening/closing window (Yun and Steemers 2008), (4) opening/closing window blinds (Foster and Oreszczyn 2001; Reinhart 2004; Gunay and O'Brien 2014), (5) turning on/off lighting (Yun and Kim 2012; Chang and Hong 2013) and (6) occupancy thermal and light comfort (Jazizadeh et al. 2014). These studies used various methods including statistical models, machine learning, and most recently immersive virtual environments to understand end user's preferences. To this date, potential energy savings from occupancy behavior based applications have been evaluated both by simulations and in field studies.

However, ***most current studies are individual and case-by-case, without* a *systematic and scalable approach*.** For example, almost every occupancy study has a different machine learning method applied such as Support Vector Machines (SVM), Artificial Neural Network, Hidden Markov Model, etc. There is an urgent need that all researchers in this area have a round table discussion and make an agreement on methodologies, not necessary a common one but an understanding of various methods under different conditions. In addition, ***existing building infrastructure impedes the development of occupancy behavior based industry products and applications***. One of the challenges to study occupancy behavior is that monitoring occupancy behavior relies on various sensors with relatively high costs. Most of existing buildings do not have required sensing and information infrastructure to support occupancy behavior based industry products. It is urgent to discuss and understand how research can help industry start-ups to overcome those challenges.

2. Objectives and Topics

The ultimate goal of occupancy behavior research is to improve building design and operation in a homogeneous way for next generation energy efficient buildings. The objective of this workshop is to identify the research gaps in existing occupancy behavior research including what the obstacles are and what is needed from both NSF and industry, and the identification of future research directions. The list of topics were discussed include:

(1) Panel 1: Human building interactions

In this panel, we presented and discussed (a) how to evaluate impacts on energy consumption due to interactions; (b) what are future possible methods to evaluate interactions.

(2) Panel 2: Modeling and simulation of occupancy presence in buildings

In this topic, we presented and discussed (a) existing methods for occupancy presence modeling; (b) what specific challenges are; (c) how to improve method itself or process in the future.

(3) Panel 3: Occupancy behavior based applications in industry

In this topic, we presented and discussed (a) latest occupancy behavior oriented industry products; (b) what the obstacles are for large-scale deployment; (c) what research needs are based on existing infrastructure; (d) how to improve building design and operation through occupancy behavior research in a homogeneous way.

3. Workshop Summary

Panel 1 Human Building Interactions

By Drs. Jin Wen and Khee Poh Lam

- **Panel presentation summary:**

This panel consists of four presentations themed on understanding and promoting human and building interactions:

Dr. Becerik-Gerber's presentation "*End of the Discrete: Towards Continuous Human-Building Interactions*" presented the significance and urgency to have a bi-directional and continuous dialogue between a building (including its systems) and the occupants. She emphasized that a building should listen to its users to maximize its efficiency subject to user constraints and a building should also speak to its users with the hope that occupants would accommodate to a building's constraints. A study to understand how to give buildings a "Human Like" persona was introduced in the presentation. Issues such as how to incorporate relational features (e.g., rapport-building tactics); how the interaction should be framed to building users; why people would form social connections with technology; and what were the cost and benefits of this tendency were investigated in the study.

Ms. Erin Griffiths's "*Occupant-oriented Sensing and Control in Homes*" discussed potential sensors and strategies that can be used to understand the occupancy pattern in a residential setting without compromising occupants' privacy or convenience. A case study was also presented to demonstrate the potential energy saving that could be achieved by operating the water heater based on the learned occupancy pattern.

In Dr. Panagiota Karava's presentation "*Occupant Interactions with Visual and Thermal Comfort Delivery Systems in Perimeter Building Zones*", the focus turned to commercial building setting to understand what occupants' behavior pattern would be when interacting with a building's thermal and lighting systems in a premier zone. A testbed and a series of survey and experimental studies were designed and employed to identify the recruited occupants' behavior, attitude, and satisfaction toward their thermal and lighting systems.

The attention switched to whether peer network and more targeted information delivery would result in better occupant energy behaviors in Dr. John Taylor's presentation "Building-Occupant Network Dynamics Pursuing Sustained Energy Efficiency through Feedback, Interaction and Prediction". His field and survey studies on both a multifamily residential and a commercial building confirmed that peer network (in residential building) and organizational network (in commercial building) sharing of eco-feedback induced statistically significant energy consumption reductions. He further showcased the potential of expanding building and occupant dynamical interactions to be at a neighborhood scale and at a city scale.

- **Panel discussion summary:**

The panel discussion centered around seven topics:

Topic 1: How much can building-occupant study be benefited from the development of other technologies and research areas.

Many existing building-occupant projects have benefited from the development of other technologies, such as robotics, system network, cyber-physical system etc. The panelists believed that we should tap into the findings and funding from these relevant areas. However, although there are many similarities between building systems and other dynamic systems, and between occupant behaviors and other human behaviors, there are often significant and fundamental differences between building-occupant systems and other systems. At this time, we need building-oriented and building-specific funding and projects to focus on the unique challenges and to identify fundamental theorems within the building-occupant domain. This kind of research should be conduct in a multi-disciplinary environment to ensure that specialist in other areas (such as sensor, robotics, etc.) understand the specific issues in the building field. The findings and solutions need to be scalable to have a real impact on the building industry and market.

Topic 2: What is the proper sample size for building-occupant system study.

In many other human subject studies, human sample size is often at the hundreds, if not at the thousands level. Compared to those studies, the sample sizes in the building-occupant area are much smaller, often due to the funding size limitation. Unlike those established human-subject areas, such as pharmaceutical area, many are unknown in the building-occupant area. Controlled tests, such as those performed in the pharmaceutical studies, are difficult to perform in the building-occupant area due to the complicated interactions and the large varieties.

The panelists therefore argued that, although we could utilize some existing theorems/rules from other areas, we needed to conduct more fundamental, large-scale, and long-term studies in the building-occupant area to establish data collection standards, to understand data uncertainty, to identify how variables, such as building type, size, etc. affect the data quality and scalability.

Topic 3: Existing building vs. new building.

The topic of whether the research should focus on patching existing buildings or identifying new solutions/designs was discussed next. The panelists recognized the needs and significance to find solutions that would consider the limitations often posed by an existing building, considering that the number of existing buildings greatly outline new construction in the U.S. However, the panelists also emphasized on the importance of developing innovative new designs that could transform existing building design practices to revolutionize buildings' performances and building-occupant interactions. In order to achieve this goal, the panelists recommended that we should a) emphasize on overall building quality (not just a specific criteria or system), b) consider and integrate many perspectives of a building, including building systems, building envelope, occupant behaviors, and other perspectives during a building's design and also operation stages; c) take advantage of new concepts and technologies and apply them in building design and operation; and d) understand occupant behavior and building-occupant integration so we could change certain behaviors.

Topic 4: When performing an occupant study, which is a better mechanism: controlled experiments or field-testing?

Both well-control experiments (often engaging paid occupant samples) and field tests (with many real-world complexities) were reported in the literature for occupant studies. The panelists discussed the pros and cons of both mechanisms. It was stressed that the adoption of a testing mechanism (controlled test vs. field test) should be determined by the hypothesis and modeling mechanism. For example, when developing a stochastic occupant behavior model, field-testing would be a better method than controlled experiments. But if the objective were to understand how a specific driving force would affect the behavior, then controlled experiments would serve the purpose better. Several panelists stressed on the significance of considering future data sharing and multiple usages of a dataset, when designing an experiment.

Topic 5: The potential and barrier of engaging social media in occupant research

The panelists expressed a mixed feeling about the potential of using social media in occupant research. Although social media seem to contain large quantity of data, very limited information often can be obtained from this "big data" that can help understanding building-occupant interactions. The limitation of the data, such as that the data might only represent certain population and not the general population, needed to be observed. However, social media did present new ways to recruit and communicate with occupants, which should be utilized to open up more innovative data collection methods. One example given in the discussion was smart-phone based apps for occupants' communication.

Topic 6: The challenge of multi-disciplinary research - collaboration among engineers, architects, social scientists, economists…

Many of the building-occupant research were conduct in a multi-disciplinary environment that often engaged researchers from engineering, architecture, social science, and even economy. The panelists shared their experiences working with other researchers who had very different backgrounds. The panelists recognized that 1) when a researcher had a multi-disciplinary background himself/herself, he/she tended to collaborate better with other researchers who had very different backgrounds; 2) different disciplines often had very different terminologies, which needed to be understood before a successful multi-disciplinary collaboration; and 3) common interests needed to be identified among the multi-disciplinary teams. Although there were challenges for multi-disciplinary collaboration, it was considered as a "must-have" for a successful building-occupant research. The role of architects in understanding and improving building-occupant interactions was emphasized since they were often the decision-makers and integrators. Architects should participate in and take leadership in building-occupant research.

Topic 7: Building energy data

A major limitation of existing buildings is the scarcity of energy measurements, especially on the subsystems. It is well-recognized that much more effective information could be generated and delivered to the occupants/facility if sub-metering data are available. The panelists strongly emphasized the needs for more energy measurements, more diversity in energy measurements and better data quality. Beyond data, the panelists also advocated for more in-depth building information, such as building performance monitoring, fault diagnosis, energy analysis etc. Analysis of building energy data at different scales, from sub-systems, to individual buildings, neighborhood buildings, and at city or regional levels, were discussed. Higher scale energy data analysis was typically of interest to economists. The panelists advocated for collaborative research between building researchers and economists to understand the connections between different scales and populational energy behaviors.

- **Future research directions:**

The panel concluded with the following recommendations for future research in the building-occupant interaction area:

- More large scale and long term experimental study (controlled and field) to develop more in-depth understanding of building-occupant interactions, and occupant behaviors; and to utilize this knowledge to improve building performances, to change occupants' behavior, and to develop more innovative building designs;
- Develop high quality buildings in an integrated manner, not just focusing on one component, one system, or one criteria;
- Develop standards for data collection, sharing, storage, and updating in building-occupant study areas;
- Encourage multi-disciplinary research, especially those engaging architects, social scientists, and economists to work with engineers.

Panel 2 Modeling and evaluation of occupancy behavior

By Dr. Panagiota Karava

Summary

The discussion in this session was organized around a set of key questions. Initially it was focused on the importance of occupant behavior (OB) modeling and evaluation. The panelists presented their view points and it was concluded that incorporation of OB modeling during the design phase may improve robustness while research on policy can reveal the cost and performance of various interventions which is important in decision making by investors, buildings owners, property managements, etc. The need for large scale experimental campaigns was highlighted due to heterogeneity in occupant behavior and lack of knowledge on energy efficiency measures and interventions that would be accepted from different occupants. It was mentioned that lessons can be learned from the insurance industry which has a risk policy. With regards to the use of data from smart meters to provide feedback to the users it was highlighted that such technology would be more compatible with personalized rather than large centralized systems. It was agreed that the potential of such systems needs to be systematically examined and evaluated using experimental as well as simulation studies.

The second part of the discussion focused on the main challenges in understanding occupant behavior. For example the panelists discussed how we can solve the problem without collecting infinite data and it was mentioned that utility functions as well as statistical/econometric methods would be used to addressed such questions. Other suggestions were related to the development of new sensors or devices that can improve our understanding on differences in occupant behavior. For example, occupant feedback on comfort and wearable technology to measure skin temperature or heart rate could provide information on why people have different preferences. Other possibilities could be learning from existing data with the use of advanced algorithms. Potential measures that could improve our understanding of behavior could be the development of energy policy per person or per household instead of floor area in the case of residential buildings.

All panelists agreed that doing research at scale is critical and such efforts should send the right message in terms of the consequences of behavior and its impact on future availability of energy. The importance of identifying what kind of data are needed and how they will be used was discussed extensively. It was admitted that present studies are based on small numbers of buildings or in cases that studies include several buildings, the number of data points is small so research is needed to determine how we can bring the different data scales together. Other suggestions focused on the characterization of people based on their lifestyles, i.e. each life style should include all aspects of energy consumption from occupants.

Other questions were raised aiming to identify the main research gaps in occupant behavior research; for example, we need to determine if this is a technology or information issue or related to policy. It was concluded that is a complex problem and one solution would not be enough. Different pathways should be explored; as a potential example, the use of social media to encourage energy efficient behaviors may result in relatively small savings but the cost is zero so it could be leveraged together with other more expensive solutions. The importance of education and training was also highlighted.

All panelists agreed that interdisciplinary research is needed to move forward. This could potentially include international collaborations to leverage technological solutions that could be adopted in different countries.

Panel 3: Occupancy behavior based applications in industry

By Erin Griffiths

This section focused on occupant behavior in buildings as it relates to current industry. Both panelists are members of companies that provided energy and comfort related services to building owners and managers based on occupant usage.

Panel Summary:

The panelists discussed how occupant behavior is used in industry and the challenges associated with incorporating this technology into the market. Particularly, one main challenge to adapting these technologies to industry is determining how to make the technology valuable to the end user. Focusing on short term engagement or requiring the user to act will prevent this technology from being widely adopted. One suggestion is to focus on technologies where energy is saved when people do not act, rather than requiring them to act on given information from the technology to save energy.

Both panelists predict that we will see many more companies in the future that focus on occupant behavior. Many of these companies may have energy savings as a secondary value in their product, focusing on comfort or another value in the final product. On the other hand, as access to buildings and building control becomes easier and potentially on mass from the cloud, occupant comfort may become a victim from this energy saving control. Another type of company that may appear are third parties to the utility market, often focusing on demand response. Additionally, there is the potential for remote or software controlled building control to allow for a market of third party apps. These apps might act the same as iPhone apps do today, but for control of buildings and homes.

While these companies collect large amounts of data that may provide insights for researchers, both panelists stated that sharing their data would be difficult. Some data is shared in collaborative research projects, but sharing data collected outside of these collaborations for publishable research is not possible. However, companies could potentially add an opt-in feature to share data with researchers if customers agree.

Panelists stated that technology needed for using occupant behavior consisted mainly of cheap, retrofitting, easily deployable tech that lets companies manipulate the physical environment. Additionally, a slow introduction of the technology, insights, and analytics that begins to scale up has the greatest chance of adoption. If building controls were a legible as car controls, the industry would be doing a lot better.

One question was directed specifically at Lindsay about her company Comfy: how do you deal with buildings where the hardware is not ideal for your technology? She stated that in this case they can’t support some of these buildings (such as those with only one zone per floor), but that in other cases they allow large people zones (up to 40-50 occupants). They sometimes add supplemental requirements to these system, such as requiring another occupant’s agreement to change the temperature. Additionally, in these large spaces occupants may respond more to the placebo affect rather than actual temperature changes.

Panelists reported that every building management system is different and interfacing with each system takes a large amount of time and effort. Comfy took 2-3 years to finalize how they could interface with the buildings they service. However, the companies that building these management system do not seem to need/want the technology that provides these energy savings. The companies need have a problem with their current system or need to have the efficacy of this new technology proven to them before they consider occupancy based system to be important. Additionally, some people don't believe that they need something this "high-tech" in buildings. Overall, industry isn't competitive in this space yet.

Workshop Wrap-up Session

By Dr. Yue Ming Qiu

In the summary session, three important topics were discussed: the need for establishing data sharing protocol, the importance of sharing case studies with the industry, and the need for future workshops.

Data sharing protocol:

Data is valuable and important for occupant behavior research in order to generalize the results to a larger scale. Currently, most occupant behavior research projects are focused on only a few buildings for each project, making it difficult to generalize the conclusions to more general buildings. Thus, data sharing among occupant behavior researchers is valuable to cross-checking the validity of the research as well as generalization of the results. Currently in the U.S., there is very limited sharing of occupant behavior data. For example, in the U.S. DOE Open EI project, there are only two academic datasets related to occupant behavior research available to the research community. More datasets related to occupant behavior research need to be shared among the research community.

However, one major challenge of data sharing is the lack of a standard data sharing protocol which can make the use of other datasets difficult for researchers. Dr. David Shipworth from UCL-Energy Institute introduced the Nature Scientific Data (N:SD, http://www.nature.com/sdata/) to the workshop participants. The N:SD is “a peer-reviewed, open-access journal for descriptions of research datasets. It aims to promote wider data sharing and reuse, and to credit those that share”. Either major consortiums or single research groups can submit descriptions of big or small datasets. Scientific Data “primarily publishes Data Descriptors, a new type of publication that focuses on helping others reuse data – rather than testing hypotheses or presenting new interpretations”. The Data Descriptors are peer reviewed.

The building occupant behavior research community agrees that it is important to have a common Data Descriptor format for the N:SD submission, based on an agreed data ontology developed by Dr. Ardeshir Mahdavi. Dr. Shipworth invited Annex 66 participants to submit to a Scientific Data Collection on occupant behaviour in buildings. He mentioned the necessary sections of the Data Descriptor such as methods, data records, technical validation and data citations. The workshop participants mentioned that in addition to N:SD, IEEE also has a journal on human behavior which can be a potential outlet to publish such data descriptors.

Dr. Shipworth also presented an online data sharing platform – Metadata software support on GitHub (https://github.com/nilmtk/nilm_metadata). The software is called Non-Instrusive Load Monitoring (NILM) Metadata, which is used for describing appliances, meters, measurements, buildings and datasets. The U.S. building occupant behavior research community might find this data sharing framework useful in their research.

Sharing case studies with the industry

It is important to share the results and implications of occupant behavior research with the industry. The industry involves many key processes such as design, construction, commissioning, and operation. Evaluation, measurement and verification are also important throughout these processes. Codes and standards are needed for all these processes. Sharing case studies related to these processes is helpful for the industry to better improve these different building processes.

Dr. Khee Poh Lam from CMU discussed an opportunity to share case studies on building occupant behaviors with industry people such as design and construction companies. Dr. Lam, together with Dr. Clint Andrews, and Cary Chan are preparing an Annex 66 report on case studies, which will be published and shared with the industry. Building occupant behavior researchers can submit a three-pager of case studies to him. Currently there are16 case studies from different countries and more studies are needed.

<u>Need for future workshops</u>

Workshop participants expressed the need for future similar workshops to discuss the recent progress on occupant behavior research and to identify gaps for research and funding. The frequency could be once or twice a year, right after major conferences such as American Council for an Energy-Efficient Economy conference, ACM International Conference (http://buildsys.acm.org/2016/), and the International High Performance Buildings Conference organized by Purdue University.

The project itself is a workshop. The workshop has attendants from both university including faculties and students and industry professionals. During this workshop, knowledge of occupancy behavior, latest modeling technologies and industry applications has been successfully disseminated. The workshop itself is a great opportunity for training and professional development.

The results from this workshop include: (a) All presentations from speakers in the format of .ppt or .pdf; (b) Panel summaries from panel chairs. This summary includes all questions, discussions and suggestions for specific occupancy behavior research during panel discussion. All results are be available online through the workshop website: http://obworkshop.com/, and will be kept for next five years.

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