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DISCOVERING THE VALUES OF RESIDENTIAL BUILDING OCCUPANTS FOR VALUE-SENSITIVE IMPROVEMENT OF BUILDING ENERGY EFFICIENCY

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Abstract: Improving building energy efficiency is one of the best strategies to reduce building energy consumption. Recent studies emphasized the importance of occupant behavior as key means of enhancing building energy efficiency. It is critical that while we strive to improve the energy efficiency of buildings through the understanding of energy use behavior that we also understand the values (such as thermal comfort, indoor air quality, productivity) of building occupants, how these values may impact energy use behavior, and how we can improve energy efficiency without negatively impacting these values (i.e., while maintaining the satisfaction levels with these values). This paper focuses on presenting the authors work in (1) identifying potential occupant values that may impact energy use behavior and energy consumption in residential buildings, (2) discovering actual building occupant values and the importance levels of these values to residential building occupants, and (3) discovering the current satisfaction levels of residential building occupants with these values. The discovery of actual occupant values and current satisfaction levels was conducted using an online survey. A randomly selected set of 310 residential building occupants in Arizona (AZ), Illinois (IL), and Pennsylvania (PA) were surveyed using an online questionnaire. The paper discusses the value discovery, questionnaire design, survey results, results analysis, and conclusions. The results showed similarities and differences across occupants in AZ, IL, and PA in terms of what they value in buildings as well as their current satisfaction levels with these values.

1 INTRODUCTION

Residential and commercial buildings consume 40% of the primary energy and contribute 30% of the annual greenhouse gas emissions. The production and consumption of non-renewable energy, including oil and natural gas, pose adverse environmental impacts on the ecosystem in terms of air pollution and global warming. Enhancing building energy efficiency is one of the most effective ways of reducing both energy consumption and CO_2 emissions (Becerik-Gerber et al. 2013).

Recent studies emphasized the importance of occupant behavior as key means of enhancing building energy efficiency. For instance, a two week study revealed that dormitory occupants reduced their consumption by 31% when they received weekly energy consumption data and by 55% when they received real time energy consumption data (Petersen et al. 2007). Similarly, a short-term study compared the energy consumption of four groups: (1) control group, (2) a group of occupants that had access to their past and present individual energy consumption data, (3) a group of occupants that had access to their past and present individual energy consumption data, in addition to average energy consumption data of all occupants in the building, and (4) a group of occupants that had access to their past and present individual energy consumption data, average energy consumption data of all occupants, and individual energy consumption data of other occupants. The results showed that the fourth group made the most significant saving (Peschiera et al. 2010).

It is critical that while we strive to improve the energy efficiency of buildings through the understanding of energy use behavior that we also understand the values (such as thermal comfort, indoor air quality, productivity) of building occupants, how these values may impact energy use behavior, and how we can improve energy efficiency without negatively impacting these values (i.e., while maintaining the satisfaction levels with these values). On one hand, values impact energy use behavior. “Values influence behavior because people emulate the conduct they hold valuable” (Boundless 2014). On the other hand, people spend the majority of their time in buildings, and therefore it is essential that while we aim to reduce building energy consumption that we also satisfy their values (Frontczak and Wargocki 2011). A number of important research efforts (e.g., Klein et al. 2012; Yang and Becerik-Gerber 2014; Gao and Whitehouse 2009; Dong et al. 2011; Agarwal et al. 2010; Mohammadi et al. 2007) primarily focused on reducing energy consumption of buildings by utilizing occupancy information. More focus is needed on understanding the interdependency between occupant values and energy consumption.

In this paper, the authors focus on (1) identifying potential occupant values that may impact energy use behavior and energy consumption in residential buildings, (2) discovering actual building occupant values and the importance levels of these values to residential building occupants, and (3) discovering the current satisfaction levels of residential building occupant with these values. The paper also compares importance ratings of values and satisfaction levels with the values across occupants in AZ, IL, and PA.

2 OCCUPANT VALUE DISCOVERY

In the context of building energy efficiency, a comprehensive literature review was conducted to identify all potential values that could be related to energy use behavior and energy consumption. As a result, three main categories of values were identified: (1) values that may impact energy use behavior and energy consumption level (thermal comfort, lighting/visual comfort, and indoor air quality), (2) values that may be impacted by the set of values in the first category (health and personal productivity), and (3) values that may motivate enhanced energy use behavior towards reduced energy consumption (environmental protection and energy cost saving).

Thermal comfort is “that condition of mind that expresses satisfaction with the thermal environment” (ASHRAE 2010). There are six primary factors that determine thermal comfort conditions: metabolic rate, clothing insulation, air temperature, radiant temperature, air speed, and humidity (ASHRAE 2010). Among these factors, metabolic rate depends on a number of subfactors such as activity level, gender, and health conditions (Maiti 2014). Clothing insulation varies by occupant clothing type. Air temperature, radiant temperature, air speed, and humidity, on the other hand, are highly dependent on the settings and parameters of the HVAC system of buildings, which in turn may impact energy consumption.

Visual comfort is defined as “a subjective condition of visual well-being induced by the visual environment” (EN 2002). Visual comfort or discomfort is impacted by luminance distribution, illuminance and its uniformity, glare, color of light, color rendering, flicker rate, and amount of daylight (EN 2002). Illuminance is the factor which associates visual comfort with energy consumption.

Indoor air quality (IAQ) is “a term referring to the air quality within and around buildings and structures” (EPA 2014). The amounts of indoor pollutants and of ventilation are the major factors that impact IAQ. Building materials, combustion sources (wood, coal, oil etc.), cleaning products, tobacco, and air pollutants entering from outdoor space are main causes of indoor pollutants (EPA 2014). On the other hand, the amount of ventilation is determined by the amount of air that enters the building. Poor IAQ is seen as the primary environmental health risk by EPA (2014). In order to maintain good IAQ to building occupants, the amount of pollutants should be controlled and a proper amount of ventilation should be provided (EPA 2014). While controlling the amount of pollutants can be achieved by improving occupant behavior and eliminating the causes of pollutants, the amount of ventilation is highly dependent on the building ventilation system which may consume energy.

Health and personal productivity are the values that may be impacted by the set of values in the first category. With the majority of people spending about 90% of their time indoors, the impact of thermal comfort, visual comfort, and IAQ on occupant health and productivity has been emphasized in recent years (EPA 2014). Good thermal comfort, visual comfort, and IAQ are linked to decreased number of illnesses and sick building syndrome symptoms and enhanced productivity.

Environmental protection and energy cost saving are values that may motivate enhanced energy use behavior towards reduced energy consumption. Energy consumption is associated with both environmental impacts and cost. Residential buildings account for 20.8% of the US total CO_2 emissions (EPA 2009) and residential building occupants spent 2.7% of their household income for home energy bills in 2012 (EIA 2013). The role of energy consumption behavior in reducing energy consumption, and in turn environmental protection and energy cost saving, is vital. EIA estimates a 50% increase in energy demand caused primarily by buildings by 2050, and highlights that this increase can be capped to 10% without any sacrifice in the comfort of building occupants, if necessary improvements in energy use behavior and energy efficiency can be achieved (2013).

3 RESEARCH METHODOLOGY

A questionnaire survey was conducted to solicit the input of a randomly selected set of residential building occupants in Arizona (AZ), Illinois (IL), and Pennsylvania (PA) on (1) the importance levels of occupant values and (2) the current satisfaction levels with these values. The scope of the energy studies are focused on IL and PA. AZ was additionally selected to capture potential variability in responses as a result of a different climate, which provides an opportunity of investigating the impact of climate on occupant values and satisfaction levels with the values. According to the Köppen-Geiger climate classification, IL and PA have a humid continental (warm summer) climate (Dfa), whereas AZ has a dessert climate (Bwh). The research methodology was composed of four main research tasks: (1) questionnaire design, (2) questionnaire validation, (3) survey implementation, and (4) survey results analysis. Further details on the research methodology is provided in the following section.

4 SURVEY OF ENERGY-RELATED VALUES AND SATISFACTION LEVELS

4.1 Questionnaire Design, Validation, and Implementation

The questionnaire was composed of four sections. Section 1 included two filtering questions that were asked to verify eligibility of participation in terms of occupancy type and residency state (i.e., occupancy of a residential building and residency in AZ, IL, or PA). Responses which failed to pass Section 1 were disregarded. In Section 2, respondents were asked to rate the importance levels of occupant values to them on a 6-point Likert scale (very unimportant, unimportant, moderately unimportant, moderately important, important, very important). Section 3 was composed of three questions, all which aimed at soliciting the satisfaction levels with the values. Question 1 directly asked respondents to rate their satisfaction levels with the following values on a scale of 1 to 6 (very dissatisfied, dissatisfied, moderately dissatisfied, moderately satisfied, satisfied, very satisfied): thermal comfort in winter, thermal comfort in summer, visual comfort, IAQ, energy cost saving, and environmental protection. Because both productivity and health are values which may be impacted by the values in the first category (i.e., thermal comfort, visual comfort, IAQ), Question 2 and 3 aimed at assessing satisfaction levels with productivity and health through quantifying the changes in productivity and health caused by the values in the first category. Using a 9-point scale (40% or more, 30%, 20%, 10% decrease, no effect, 10%, 20%, 30%, 40% or more increase), Question 2 asked respondents to rate how they think their personal productivity or level of activity at home is decreased or increased by the current indoor environmental conditions (temperature, lighting, IAQ) at home. Using the same 9-point scale, Question 3 asked respondents to rate how they think their perceived health is decreased or increased by the current IAQ at home. Section 4, included a set of background questions about the characteristics of the occupants, the frequency of experiencing some health symptoms such as headaches, the characteristics of the building including energy efficiency features and level of occupant control of the building system, the level of energy cost and consumption data given to occupants, and the behavior of occupants to control the indoor environmental conditions such as opening windows.

Prior to launching the survey, a pilot study on fifteen building occupants was conducted to test the effectiveness and clarity of the questionnaire. Participants were requested to complete the survey and, then, to provide feedback on the format and content of the questionnaire. Feedback was solicited on different aspects of the questionnaire, such as question wording, response options and evaluation scale, instructions to respondents, visual appearance, and clarity of value concepts. The questionnaire was revised based on the feedback. For instance, the scale of some questions were modified in order to improve clarity.

The survey was conducted from October to November 2014. Potential respondents were recruited by Qualtrics, a provider of online panels (potential respondents). Panels were generated using samples from various database and were verified to prevent any fraudulent or duplicate respondents (ESOMAR 2014). Qualtrics hosted the survey and sent emails to potential respondents inviting them to complete the survey, for research purposes, in return for incentives. Two response quality filters were used: (1) an attention filter question and (2) a minimum survey completion time of two minutes. Responses that failed to pass these two filters were disregarded.

4.2 Survey Results and Analysis

The analysis of the survey results aimed at answering the following research questions:

- What are the ratings of the values by residential building occupants in AZ, IL, and PA?
- What are the rankings of the values by residential building occupants in AZ, IL, and PA?
- What are the satisfaction levels of residential building occupants with the values in AZ, IL, and PA?

Three statistical analysis methods were utilized to address the above research questions: (1) mean indexing, (2) Kendall's coefficient of concordance, and (3) Kruskal-Wallis H Test. Mean indexing was used to determine the mean ratings of values. Kendall's coefficient of concordance was computed to examine whether there was a significant agreement in the ranking among occupants across the three states. Kruskal-Wallies H test was conducted to identify whether specific values were rated differently across occupants in the three states. The Statistical Package for Social Sciences (SPSS) version 20.0 was used to conduct these statistical analyses.

4.2.1 Classification of Respondents

A total of 310 valid responses were collected. Qualtrics identified approximately 4,800 potential respondents and invited them via email. A total of 381 responses (including invalid responses) were received, representing a response rate of 8%. This is consistent with the reported response rates for online panels (Neslin et al. 2009). This sample size is statistically significant with 95% confidence level and 10 confidence interval. Responses were classified into three subgroups by state: AZ, IL, and PA. The descriptive statistics of the three subgroups are shown in Table 1.

Table 1: Descriptive statistics of responses

Arizona		Illinois		Pennsylvania		Total		
Number of Participants	Number of Valid Responses	Number of Participants	Number of Valid Responses	Number of Participants	Number of Valid Responses	Number of Participants	Number of Valid Responses	Response Rate
123	104	119	102	129	104	371	310	8%

4.2.2 Reliability of Survey Questions

In order to validate the internal consistency of the data, prior to data analysis, a Cronbach's alpha reliability analysis was conducted. Internal consistency indicates the extent to which all the items in a test measure the same concept. Alpha values greater than 0.7 indicate adequacy of internal consistency (Tavakol and Dennick 2011). The overall Cronbach's alpha values for the survey is 0.883, which indicates a high level of reliability.

4.2.3 Occupant Ratings and Rankings of Values

The rating frequencies of the values by occupants is shown in Figure 1. Overall and across the three states the majority of occupants rated the seven values as "moderately important" or higher. Health is the most important value; 93.9% of the occupants rated health moderately important or higher. Indoor air quality, energy cost saving, personal productivity, thermal comfort, visual comfort, and environmental protection, respectively, are at least moderately important to 92%, 91.6%, 91,6, 90%, 89.7%, and 85.8% of the occupants.

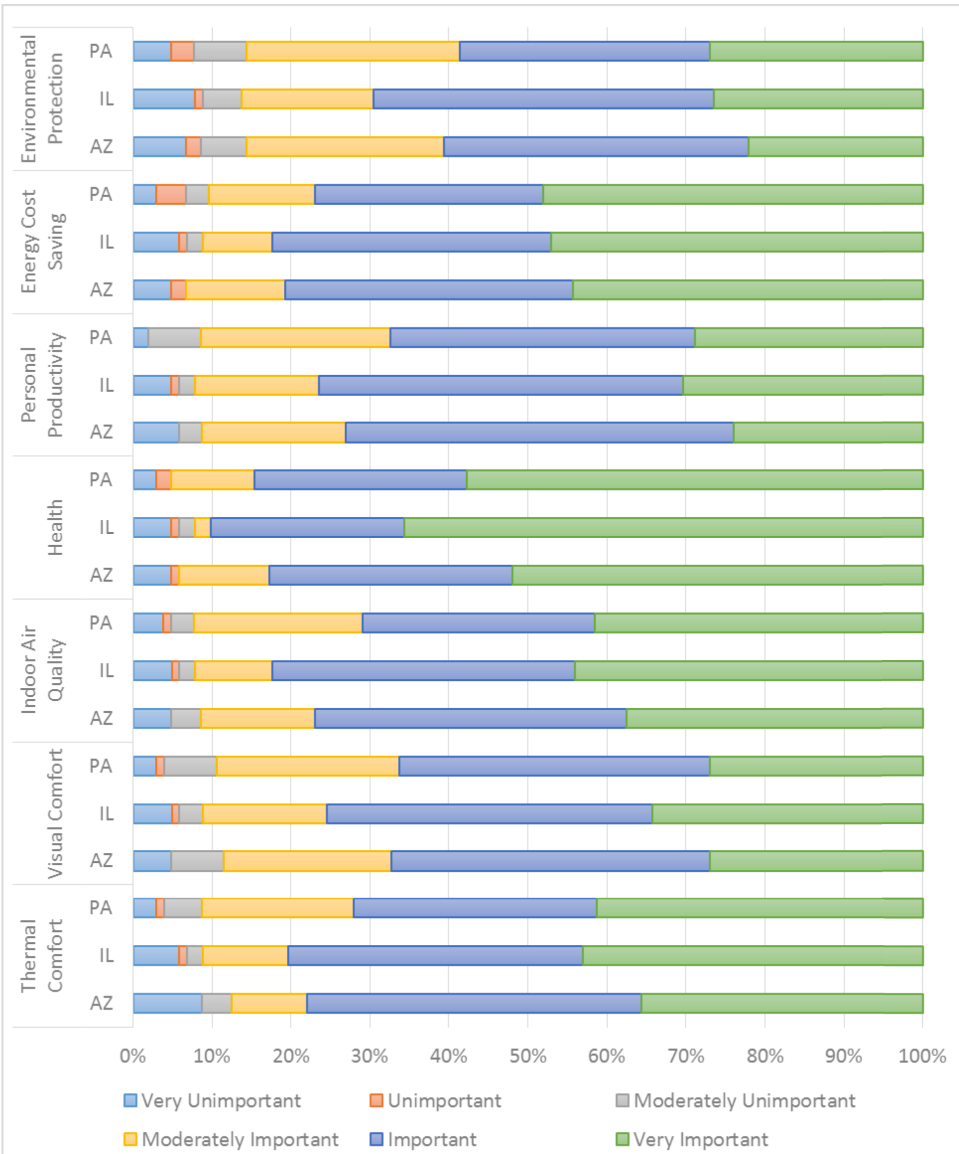

Figure 1: Importance of values to residential building occupants in AZ, IL, and PA

Table 2 and Figure 2 show the mean ratings and rankings of the values by occupants overall, in AZ, in IL, and in PA, and a comparison of the mean ratings of the values across these three states, respectively. As shown in the Table 2, all mean scores are higher than 4.00, which indicates that on average, occupants give importance to all seven values. On average, health was ranked highest among the values – overall, and across the three states, which indicates that occupants of residential buildings, across AZ, IL, and PA, valued health the most among the seven values. Previous studies are partially supportive of the survey results. For example, Zalejska-Jonsson and Wilhelmsson (2013) conducted an empirical study on residential building (single houses and apartment buildings) occupants in Sweden and investigated the importance of three values – IAQ, thermal comfort, and sound quality – through quantifying their impact on the overall satisfaction of occupants. The results showed that IAQ is the most important value, whereas sound quality is the least important value. On the contrary, however, Lai et al. (2009) conducted a study on residential apartment occupants in Hong Kong and found thermal and acoustic comfort as the most important and IAQ as the least important.

Table 2: Mean ratings and rankings of values across AZ, IL, and PA

		Health	Energy Cost Saving	Indoor Air Quality	Thermal Comfort	Personal Productivity	Visual Comfort	Environmental Protection
Overall	Mean rating	5.28	5.07	5	4.95	4.83	4.8	4.59
	Rank	1	2	3	4	5	6	7
AZ	Mean rating	5.18	5.07	4.96	4.84	4.77	4.73	4.53
	Rank	1	2	3	4	5	6	7
IL	Mean rating	5.37	5.08	5.08	5.02	4.88	4.9	4.66
	Rank	1	2	2	4	6	5	7
PA	Mean rating	5.3	5.06	4.96	4.98	4.84	4.76	4.59
	Rank	1	2	4	3	5	6	7

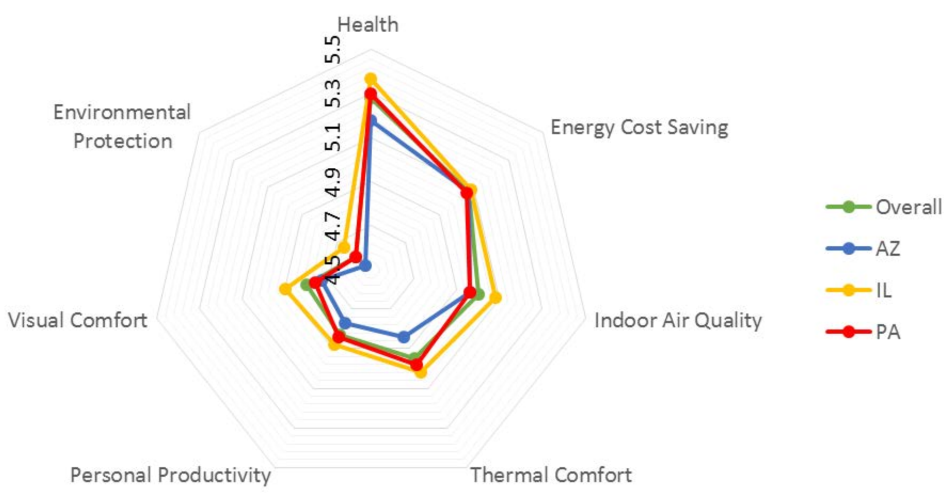

Figure 2: Comparison of mean ratings of values across AZ, IL, and PA

Kendall's coefficient of concordance (Kendall's W) was computed to examine whether there is a significant agreement on the ranking among occupants across the three states. The results of the test were interpreted based on the W value and the significance level of the test. If Kendall's W is 1 there is a complete agreement and if it is 0 there is no agreement at all, with the result being significant if the significant level is less than 0.05 (Kendall and Gibbons 1990). Kendall's W value is 0.96 ($p<0.05$), which indicates that there is a significant high agreement on the ranking of values among occupants across the three states.

4.2.4 Occupant Satisfaction with Values

Figure 3 and Figure 4 show the rating frequencies of satisfaction levels of occupants with the values and the impact of indoor environments on their perceived personal productivity and health, respectively. Overall, on average, occupants rated their satisfaction with energy cost saving, IAQ, thermal comfort (in summer and winter), visual comfort, and environmental protection as “moderately satisfied” or higher, but a considerable percentage of occupants rated their satisfaction with the values as “moderately unsatisfied” or lower. For example, 19.7% of the occupants are “moderately unsatisfied” or lower with energy cost saving, which is the least satisfied value. Environmental protection, thermal comfort in summer, thermal comfort in winter, IAQ, and visual comfort are rated by 15.8%, 15.5%, 13.9%, 11.6%, and 11.2% of the occupants as “moderately unsatisfied” or lower, respectively. For health and personal productivity, 27.8% and 24.8% of the occupants believe that the current indoor environment conditions have a negative effect on their health and perceived personal productivity, respectively. This is consistent with the findings of a recent study (Zalejska-Jonsson and Wilhelmsson 2013), which found that a considerable percentage of occupants are dissatisfied or very dissatisfied with their indoor environmental quality.

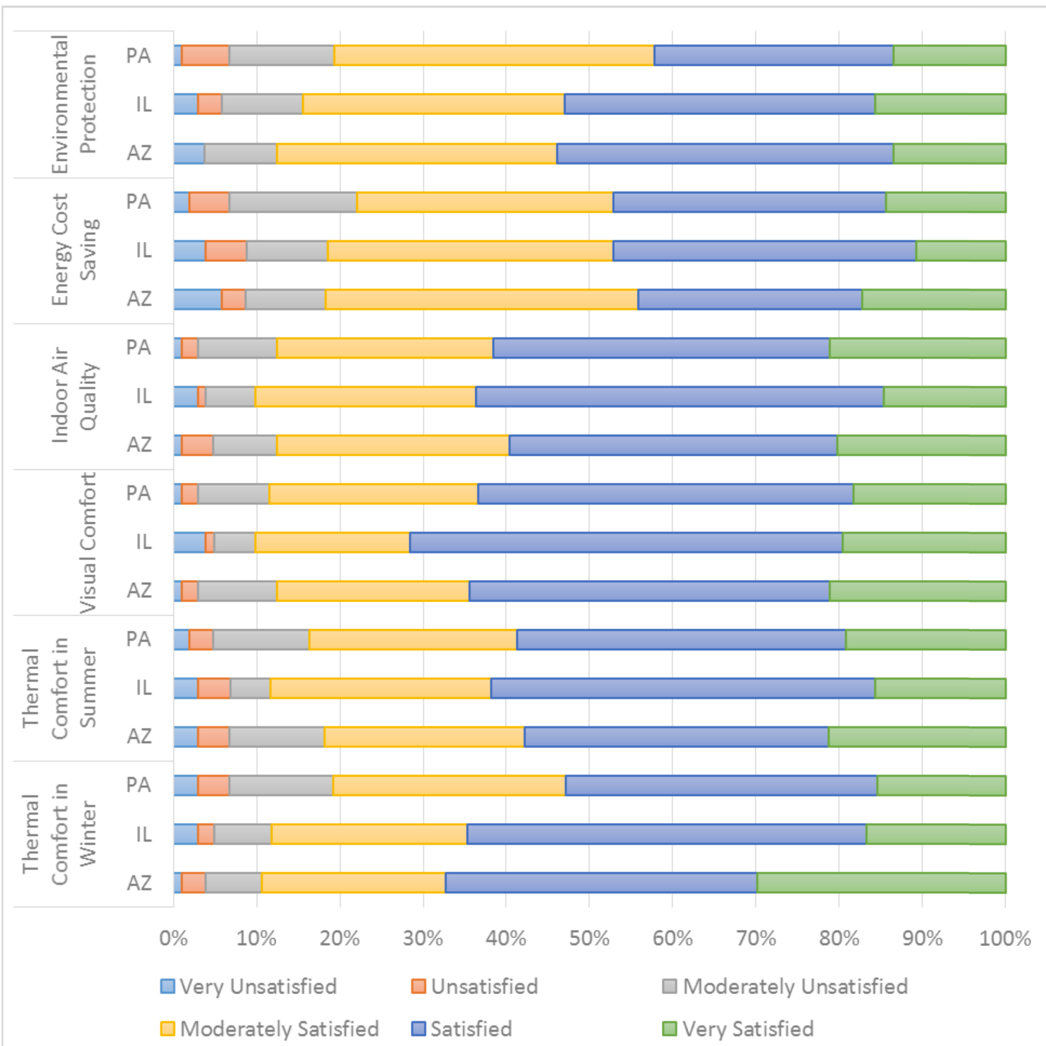

Figure 3: Satisfaction levels of occupants with the values across AZ, IL, and PA

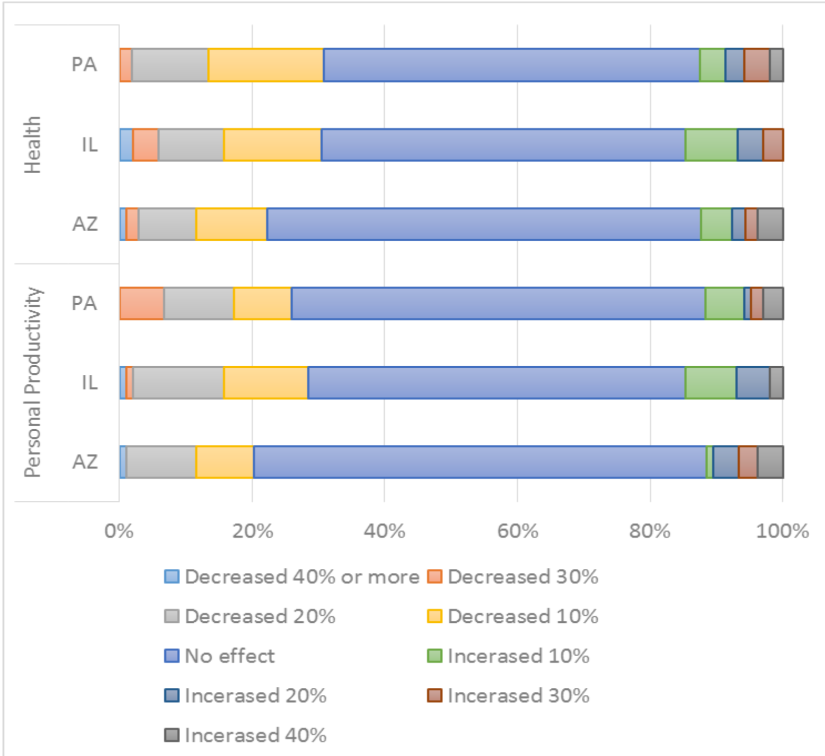

Figure 4: Reported impact of indoor environmental conditions on health and perceived personal productivity of occupants

The difference in the satisfaction levels across the three states was examined using Kruskal Wallis-H test which is the non-parametric version of one way analysis of variance. The results show a significant difference, across the three states, in the satisfaction levels occupants with thermal comfort in winter. Occupants in AZ are more satisfied with thermal comfort in winter, than those in IL and PA. In order to identify where the differences between the groups lie, a post-hoc pairwise comparison test was conducted. The test shows that occupants in AZ are more satisfied with thermal comfort in winter than those in PA. This difference could be explained by the different weather characteristics of the two states. Other than that, there was no significant difference in the rating of satisfaction levels among occupants across the three states. Similarly, across the three states, there was no significant difference among occupants in the impact of indoor environmental conditions on their health and perceived personal productivity.

5 CONCLUSION AND FUTURE WORK

This paper presents an empirical study to discover energy-related values of building occupants. Seven energy-related values were identified and classified into three main categories: thermal comfort, lighting/visual comfort, indoor air quality, health, personal productivity, environmental protection, and energy cost saving. The importance of these values to occupants and the satisfaction levels of occupants with these values were then investigated using a questionnaire survey. The survey focused on residential building occupants in AZ, IL, and PA. The results show that residential building occupants in AZ, IL, and PA value all seven values. On average, health was ranked highest among the values – overall and across the three states. The results also show that there is a significant agreement on the ranking of values by occupants across the three states. The ratings of the satisfaction levels with the values show that a considerable percentage of occupants (11.2% to 19.7%) are unsatisfied with the fulfilment of their values, with 27.8% and 24.8% of the occupants thinking that the current indoor environmental conditions have a negative effect on their health and personal productivity. The survey results also show that there is a significant difference in the satisfaction levels with thermal comfort in winter across AZ and PA.

In their future/ongoing research, the authors will focus on three main areas: (1) developing a semantic data sensing system (including sensors and algorithms) for automatically measuring and monitoring energy consumption, indoor climate and lighting, plug loads, and occupant location, and interactively measuring and monitoring energy use behavior (e.g., energy use patterns in terms of use of plug loads, lighting, cooling, etc.) and satisfaction with occupant values; (2) developing a semantic (computer-understandable and meaning-rich) context-aware model for representing and reasoning about the sensed data and user values and deriving contextual information about the interrelationships between user values, energy use behavior, and energy consumption to analyze human values and actions and how they impact energy usage; and (3) developing hybrid semantic and machine-learning (ML) data analysis models and algorithms for analyzing the sensed data and learning how to automatically operate building controls in a way to minimize energy consumption while maintaining the values identified in this study.

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