the individuals involved. After receiving 34,000 survey responses to thermal comfort questions in 215 buildings, researchers from UC Berkeley found that office workers who are satisfied with their thermal environment are more productive than those who were dissatisfied (Huizenga, Abbaszadeh, Zagreus, & Arens, 2006). Thermal discomfort has also been identified as contributing to sick building syndrome symptoms (Myhren & Holmberg, 2008). On the other hand, thermal discomfort is significantly affected by individual physiological and psychological mechanisms. Discomfort is linked to thermal stress, which can affect work performance and individual health (Wyon, 1996). According to Huizenga's research, 80 % or more occupants claimed that they were satisfied with thermal conditions (Huizenga et al., 2006).

Currently, most building thermal environmental controls and systems are adopting predicted mean vote / predicted percentage of dissatisfied (PMV and PPD) models by utilizing heat balance equations to estimate thermal comfort conditions that affect a building's tenants. Fanger's equations are used for PMV calculations of a large number of human samples with a particular thermal condition. This is a combination of dry ball air temperature, mean radiant temperature (MRT), relative humidity, air speed, metabolic rate, and clothing insulation (KE, 2003) (Figure 1).

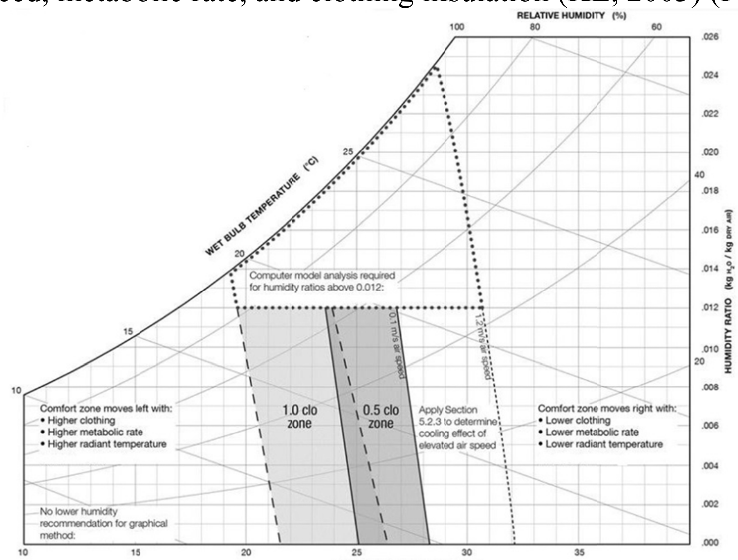

Figure 1. Psychometric chart-thermal comfort range of the PMV Method.

However, a lot of building occupants report their thermal stress, discomfort, and dissatisfaction during their time in a built environment, in spite of the thermal conditions monitored and regulated by the current Fanger's model. IFMA reported that too cold and too warm conditions were the most critical issues affecting the occupants' indoor environmental quality, including lighting, spatial, privacy, air quality, etc. While many efforts have been made to overcome the current control approaches that rely on conventional model-based environmental controls, the thermal comfort issue has not been resolved. This is a critical limitation in the current building environmental control strategies, and it is essential that a human-building integrative framework be developed to enhance human physiological benefits and environmental sustainability via optimization of energy use.

The human body has a biological thermoregulation mechanism (homeostasis) that enables it to maintain a stable and constant body temperature via changing physiological signals such as skin temperature and heart rate. These signal patterns, that are generated based on the human autonomic nervous system, have been validated as a potential variable for providing information about an individual's current thermal sensations. Among the numerous body segments and parts generating skin temperatures, facial skin is five times more sensitive to ambient thermal conditions than other skin surfaces. Therefore, based on the use of facial skin temperatures, this research will establish an adaptive thermal sensation model that can be applicable to automatic (individual) building mechanical system controls within the principle of human-building interactive strategy.

This study conducted a series of experiments with human subjects in an environmental chamber by collecting each individual's facial skin temperature and thermal sensation in real time while ambient thermal conditions were being changed. The collected subjective and objective data were processed using multiple data mining tools, such as a decision tree, neural network, and clustering, to develop a facial-skin temperature driven thermal sensation model. The developed model was also validated using human subjects who had not participated in the previous tests in order to prevent any over-fitting effect of the model.

The outcome of this research, in the form of a computational model that uses real time facial skin temperature data as an input variable, will be applicable to any existing thermal control system in a building. This especially applies to any individual control system that is equipped with a personal environmental module / terminal reheating box, and is situated in an office building or a healthcare facility. The occupants' low mobility in these facilities can be helpful for collecting the facial skin temperature data remotely without being intrusive.

METHODS

This study conducted a series of experiments with human subjects in an environmental chamber. Since the study focused on a workplace environment, we set up a workstation in the chamber and test participants were asked to generate light office work, such as typing and a web search in each test. In this study, 15 subjects participated in the test, and each test was conducted for 100 minutes, which included the times for wearing sensors and waiting in a standby condition.

During the experiment, the temperature was controlled within a range of 20ºC to 30ºC. The sequence began from cooling to heating, or vice versa, to prevent any biased thermal sensation reporting from any test participant. Most human subjects were either undergraduate or graduate students at the University of Southern California. We selected 1.5ºC as a temperature change step based on the capacity of the HVAC systems in the environmental chamber. Each test consisted of seven change steps and, at the end of each step, the subject was asked to report his/her thermal sensation and comfort condition using a 7-point scale, as illustrated in Table 1 below.

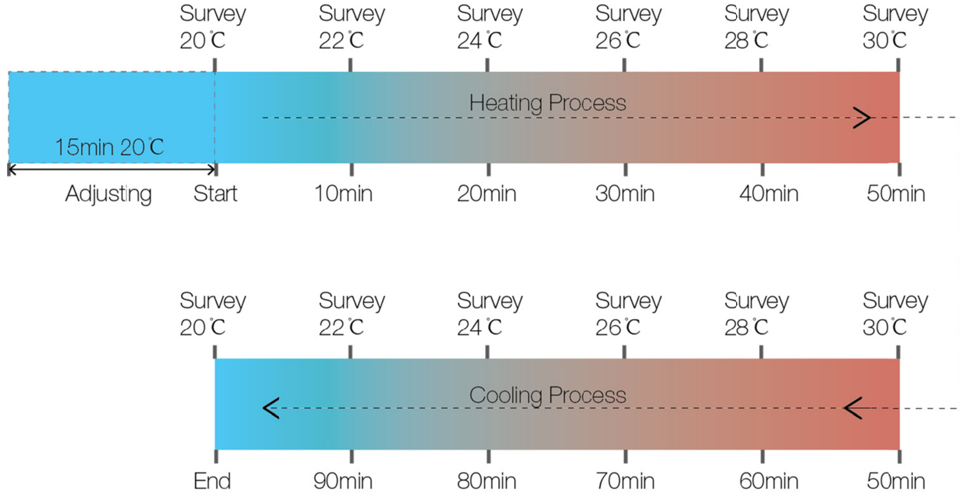

Figure 2. Experiment procedure

A 7-point scale is a very popular method for surveying user satisfaction; ASHRAE-55 also adopted this scale to estimate thermal comfort and sensation. Since it is neither too complicated nor too simple, a 7-point scale has been popularly adopted in the research domain of indoor environmental quality and environmental satisfaction studies. In order to obtain stable experimental conditions, subjects were requested not to have food for at least 30 minutes before the experiment in order to maintain consistent metabolic rates of the individual subjects.

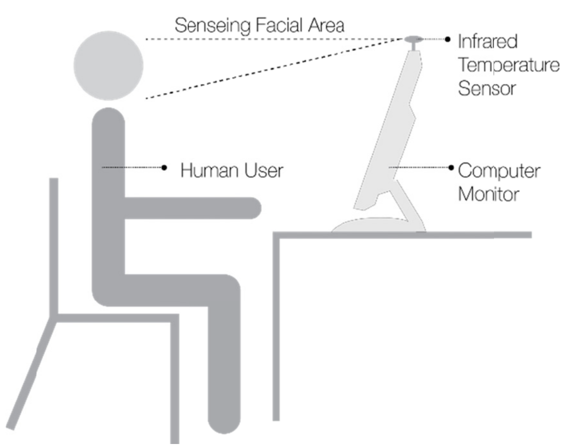

Figure 3. An experimental setting in this study

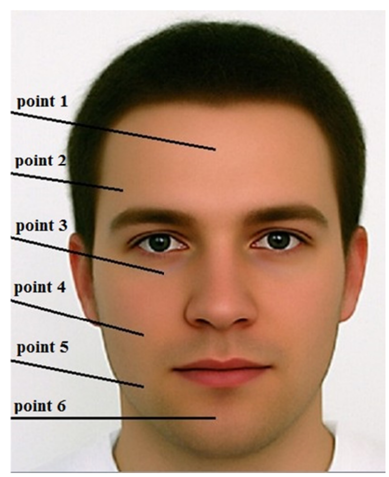

Figure 4. Selected facial temperature sensing points

RESULTS

Individually collected skin temperatures at six facial points of each subject were categorized based on the thermal sensation and conditioning mode, i.e., cooling and heating. Figure 6 illustrates the generated temperatures (including dry bulb temperature and operative temperature), and the average skin temperature collected from one sampled subject during the experiment. It looks very stable in Figure 6, but the average skin temperatures varied depending on the test participants. In addition, even though the thermal conditions generated in the chamber were almost the same or very similar, the subjects' reported thermal sensations were totally different because of their physiological or personal conditions. However, this was very obvious when compared with the existing literature. As shown in Figure 7, two sampled subjects reported entirely different sensations, even though the same thermal procedure was used during the test.

Table 1. Thermal sensation and comfort survey

1. What is your overall level of thermal comfort?						
Very unsatisfied	Unsatisfied	Slightly unsatisfied	Neural	Slightly satisfied	Satisfied	Very satisfied
□	□	□	□	□	□	□
2. What is your overall thermal sensation?						
Very Cool	cool	Slightly cool	Neural	Slightly warm	warm	Very warm
□	□	□	□	□	□	□

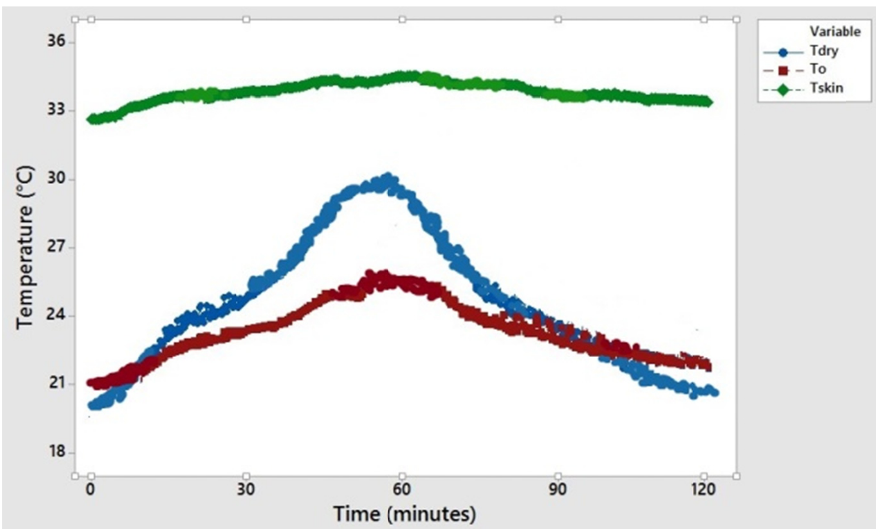

Figure 5. Time series plot of Tdry (dry bulb air temperature) and To (operative temperature) and T skin (average)

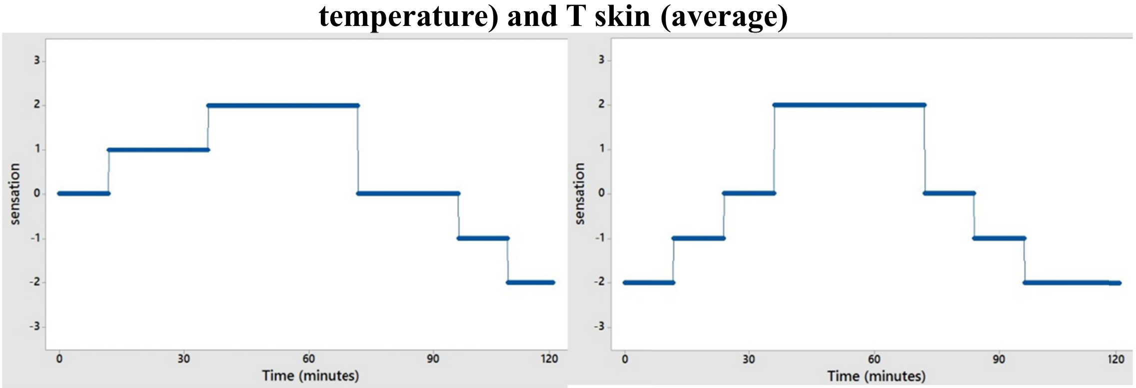

Figure 6. Thermal sensation reported by two different test subjects

Figure 8 also illustrates how diverse temperatures were measured from six facial skin points and the average of one sampled subject. This finding indicates that individual sensing points on a face generate different levels of skin temperature even though those sensing spots are exposed to the same thermal conditions. Not surprisingly, all of the test subjects showed dynamic patterns per sensing point, and it was nearly impossible to find a consistent rule for the measured skin temperatures of all subjects.

Based on this finding, the average facial skin temperature was selected as the representative variable for a thermal index of a face. The data from all of the subjects were assembled and categorized into seven different thermal sensations, as shown in Figure 9. The absolute values of the temperatures were totally different, depending on the sensing spots on a face, and also on the test subjects. Their physiological thermoregulation principles were very similar to each other in order to maintain a heat balance between the human body and the ambient thermal condition. Therefore, 5 minutes was selected as a time window frame for estimating a gradient of the average facial skin temperature per thermal sensation while the temperature in the chamber was continuously being changed.

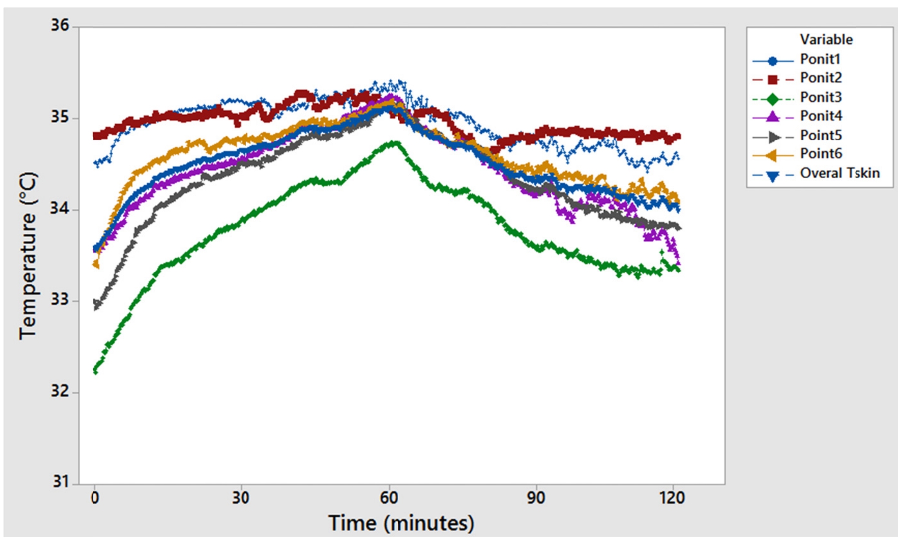

Figure 7. Patterns of skin temperatures at six selected facial skin points, as air temperature (from one sampled subject).

Figure 9 summarizes the distribution of the gradient of average skin temperature per thermal sensation, based on the collected data from all of the subjects. ANOVA (Analysis of variance) test results showed significant differences in gradients between any two different thermal sensations. To increase the statistical significance, the cold sensation data (i.e., -3, -2. -1) were grouped as one cool sensation, and the warm sensations (i.e., +3, +2. +1) were also combined as one warm sensation, while keeping the neutral sensation as a single baseline norm. This transformation of the data generated more highly significant low p-values < 0.00.

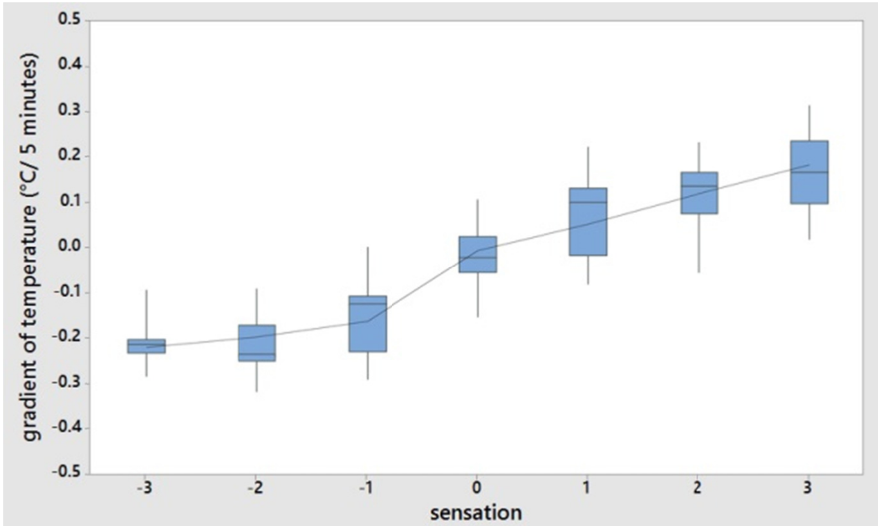

Figure 8. Change rate ranges of the average skin temperature of all subjects' facial skin points.

DISCUSSION

The findings in this research led to the conclusion that a gradient of average skin C is a critical indicator for revealing each subject's thermal sensation. In addition, even though the absolute average skin temperature was the same between subjects, it could be a good indicator to illustrate an "overall" sensation per person since the range of skin temperatures for each sensation was not wide enough. On the other hand, an ambient temperature was also recognized as a signficant parameter since it was good enough for illustrating the "overall" thermal sensations of the subjects.

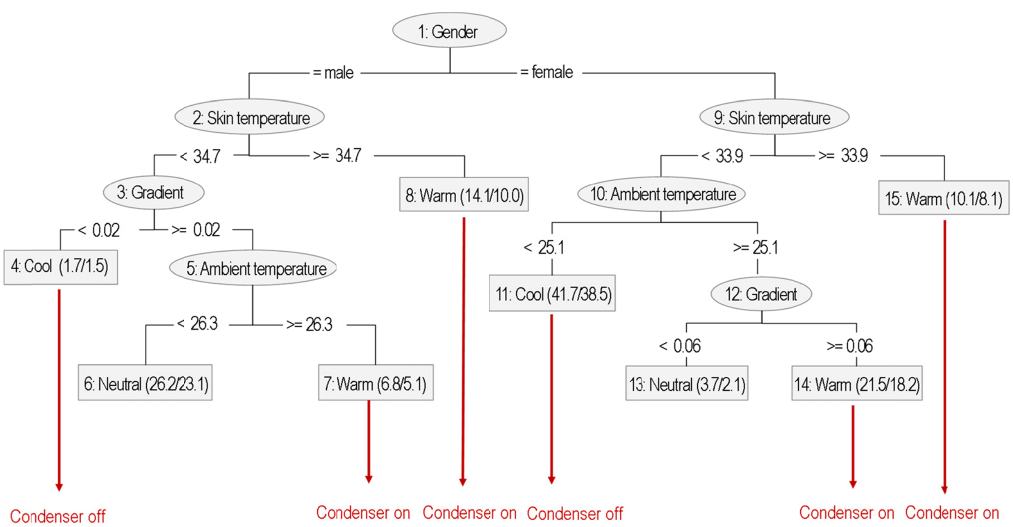

Figure 9. Sensation and AC Task decision in cooling process.

Based on these determinations, study investigators selected average facial skin temperuatre, gradient of the average skin temperature, and the ambient dry bulb temperature, as well as gender (due to its cricial role in thermal sensation) as parameters. By adopting these parameters and considering the human factor, a decision tree (using J48) was established per the HVAC system model (i.e., cooling and heating). Figures 9 and 10 illustrate how the decision trees was applied to AC and heater controls. Depending on the estimated thermal sensation, the condenser and heater were "on" or "off" to maintain a subject's thermal comfort condition, a thermal neutral sensation. For these decision trees, a 10-fold cross valdiation was adopted. This estimation approach achieved 78% , 86%, and 86% accuracy in estimating the thermal sensations: cool, neutral, and warm conditions, respectively, as a function of facial skin temperature and the ambient thermal condition, as well as gender as a human factor.

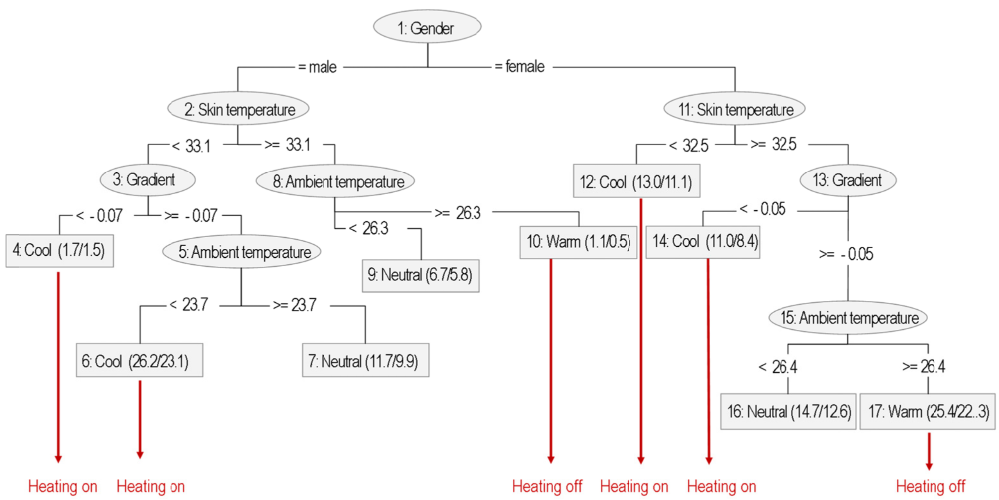

Figure 10. Sensation and Heater task decision in heating process.

CONCLUSION

This study focused on determining the potential use of facial skin temperature to estimate an individual's thermal sensation (especially in a workstation setting) and to identify any significant responses of facial skin temperature to ambient thermal conditions. For purposes of testing the relationship between facial skin temperatures and thermal conditions, and to identify potential effects, a series of human subject experiments were conducted in an environmental chamber located at the University of Southern California. Even though absolute levels of facial skin temperature were totally different, depending on the six selected sensing spots and also the various subjects, the gradient of the average facial skin temperature was practically consistent for all test subjects. In addition, the average skin temperature and the ambient dry bulb temperature did not readily reveal the individual thermal sensations, although it was possible to provide an overall thermal sensation within certain ranges. Based on these findings, this study adopted ambient temperature, average facial skin temperature, and its gradient to develop a thermal sensation prediction model in the form of a decision tree (J48), with an estimated prediction accuracy of 81% ± 5%, depending on the thermal sensation.

In spite of the significance of these research findings, a few research limitations affecting this study certainly warrant further investigation. The outcome could have been influenced by the number of test participants. The total number of participants was 20, which is good enough for t-statistics. However, to attain robust statistical significance in this study, sample sizes should have been larger in order to fully validate research discoveries with regard to estimated thermal sensations as a function of facial skin temperature. In addition, due to the significance of human factors, such as gender, age, and body mass index, which contribute to overall thermal sensations, a future study should consider additional human physiological characteristics of the subject samples.

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Advancing Occupant-Centered Performance Simulation Metrics Linking Commercial Environmental Quality to Health, Behavior, and Productivity

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Abstract

Integration of the human dimension in product and process modeling, as related to the integrated design process, requires the accounting of the impact of the factors that determine Indoor Environmental Quality (IEQ). Their influences upon occupant comfort remain the primary measures for predicting productivity and satisfaction within the workplace. The aim of this proposal is to present the outcomes of a yearlong literature review summary of four IEQ elements that most influence occupant health, comfort and wellbeing (i.e., thermal, ventilative, luminous, and acoustic comfort). The study's results presented provide evidence to modify office environmental design guidelines to improve economic, health, and environmental benefits. Our work postulates that case study data in co-relational analysis is critical to the development of new metrics for simulation predictability in new and repurposed design.

Our assessment concludes that two critical steps are necessary to develop predictive measures to insure comfort sufficiency in new and especially retrofit buildings: 1) Because occupants are exposed to multiple factors simultaneously we speculate that the weighted value of the interrelationships of these influences are the critically important factor required to develop articulate sensitivity in simulation schedules; and 2) Because most of the decisions regarding economic investments (especially in repurposing and retrofit design) continue to be made based on the first cost systems replacement rather than on a cohesive model of comfort sufficiency that inclusively embraces both energy efficiency and attaining a high level of environmental quality.

BACKGROUND

Numerous case studies have been performed over the years with respect to Indoor Environmental Quality (IEQ). These case studies have articulated the standards that determine the qualitative aspects of IEQ. Moreover, they have had a marked impact on directing various design guidelines such as LEED and the current WELL Building Standard. This study has conducted an extensive review of case study literature on office building environments in the U.S. and abroad. It provides a threshold for the reconsideration of how the indoor environmental conditions of air quality, thermal quality, and lighting and acoustics have been evaluated and how user satisfaction with respect to environmental quality has been differentiated. The goal of this project has been to focus the research of the past decade. It has collated the results of these case studies to develop an understanding of how the research is typically conducted and to determine if the reported results contain information that supports the development appropriate metrics for measuring commercial office environment performance by quantifying IEQ influences on behavior.

METHOD

The primary research has involved a deep literature review, as evidenced in the bibliography. The project explored the various case studies that have been performed over the years with respect to IEQ in commercial and institutional facilities. During the initial phases of the project, the team compiled this data and assembled a detailed summary. During the latter phases of the project, the team has focused on using the data to develop quantifiable metrics equated with an integrated sustainable practice model; considering "People (occupant wellbeing) Planet (behavioral levels of change associated with satisfaction resulting in energy efficiency) and Profit (predictive return on investment associated with healthy building practices). These metrics will focus on the combined effects of the various components of indoor environmental quality (i.e. air quality, visual comfort, etc.)

The body of this paper is composed (as was the literature review) into the four primary areas of research that have topically defined human comfort Thermal Comfort, Ventilative Comfort, Luminous Comfort and Acoustic Comfort. The following sections have been written by our research assistants. They are edited annotations from the original 35 page document that summarizes the research. These sections represent a sample of the outcomes from which over all conclusions have been drawn. They provide only a sample of the complete annotated summary of findings that will be edited and published in the project final report. The bibliography is a complete compendium of the literature reviewed.

THERMAL COMFORT

The literature demonstrates that thermal comfort has a significant impact on health, productivity and workplace satisfaction. LEED credits for Thermal Comfort, EQc7.1and EQc7.2 respectively, require HVAC design compliance with ASHRAE Standard 55-2004 and require building occupant surveys to determine whether the working environment has satisfied the thermal conditions of ASHRAE 55. If the result of survey shows more than 20 percent of occupants are dissatisfied, implement corrective action plan should be considered. It shows the importance of conducting research on thermal comfort and its impact on occupants.

This assessment quantifies occupant productivity benefits, through literature review and comparison of papers using the Well Building and ASHRAE-55 standards. In this section, the analysis and synthesis of the literature review on the impact of thermal comfort on health, productivity and satisfaction in addition to the