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Published version

PARK, Jihyun, LOFTNESS, Vivian and AZIZ, Azizan (2018). Post-Occupancy Evaluation and IEQ Measurements from 64 Office Buildings: Critical Factors and Thresholds for User Satisfaction on Thermal Quality. Buildings, 8 (11), p. 156.

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Post-Occupancy Evaluation and IEQ Measurements from 64 Office Buildings: Critical Factors and Thresholds for User Satisfaction on Thermal Quality

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Received: 22 July 2018; Accepted: 5 November 2018; Published: 12 November 2018

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Abstract: The indoor environmental quality (IEQ) of buildings can have a strong influence on occupants' comfort, productivity, and health. Post-occupancy evaluation (POE) is necessary in assessing the IEQ of the built environment, and it typically relies on the subjective surveys of thermal quality, air quality, visual quality, and acoustic quality. In this research, we expanded POE to include both objective IEQ measurements and the technical attributes of building systems (TABS) that may affect indoor environment and user satisfaction. The suite of three tools, including user satisfaction survey, workstation IEQ measurements, and TABS in the National Environmental Assessment Toolkit (NEAT) has been deployed in 1601 workstations in 64 office buildings, generating a rich database for statistical evaluation of possible correlations between the physical attributes of workstations, environmental conditions, and user satisfaction. Multivariate regression and multiple correlation coefficient statistical analysis revealed the relationship between measured and perceived IEQ indices, interdependencies between IEQ indices, and other satisfaction variables of significance. The results showed that overall, 55% of occupants responded as "satisfied" or "neutral", and 45% reported being "dissatisfied" in their thermal quality. Given the dataset, air temperature in work area, size of thermal zone, window quality, level of temperature control, and radiant temperature asymmetry with façade are the critical factors for thermal quality satisfaction in the field. As a result, the outcome of this research contributes to identifying correlations between occupant satisfaction, measured data, and technical attributes of building systems. The presented integrated IEQ assessment method can further afford robust predictions of building performance against metrics and guidelines for IEQ standards to capture revised IEQ thresholds that impact building occupants' satisfaction.

Keywords: post occupancy evaluation; indoor environmental quality; user satisfaction; thermal quality; IEQ field measurements; office buildings

1. Introduction

People spend 90% of their time indoors [1]. Numerous studies have indicated that indoor environmental quality (IEQ) in the workplace is critical for occupants' health and productivity [2–9]. Post-occupancy evaluation (POE) has been utilized to evaluate building performance in a systemic way to improve indoor environmental quality and user satisfaction on thermal, air, visual, and acoustic conditions [10,11]. Many researchers have revealed that subjective POE surveys should be complemented by objective measurements, to judge both subjective and objective conditions [12–17]. In particular, to assess the objective thermal environmental quality, air temperatures at 10 cm, 60 cm, and 110 cm from the floor, radiant temperature differences between walls, radiant temperature differences between the ceiling and the floor, air speed, and relative humidity should be considered in the field POE [9,18–20]. Many studies showed the importance of thermal conditions and identified indicators, as seen in Table 1. In a 2010 meta-analysis study concerning human comfort and indoor environmental quality, performed between 1977 and 2009, Wargocki et al., identified that thermal quality ranks as the highest contributing factor for overall satisfaction with IEQ, among other factors such as air, visual, and acoustic qualities [5]. In a 2004 meta-analysis of 100 US office buildings, Moschandreas and Sofuoglu found that temperature is the most crucial factor of occupant comfort [21], and the mean radiant temperature is an important factor for human discomfort, especially in buildings that have poor envelopes [22]. In a 2006 thermal comfort study in Turkey, Atmaca et al. found that although the indoor temperature was under the comfort level (27.1 °C, 50% RH), the high radiant temperature caused increased occupant thermal comfort [23]. In addition, several studies showed that temperature control can increase user satisfaction and productivity. In a 2003 building case study of an office building in Helsinki, Korhonen et al. identified a 24% improvement in self-reported work efficiency during summer, when individuals could control their temperature [24]. In a 2002 field intervention study at a call center in Finland, Niemala et al. identified a 7% improvement in productivity for call center employees (defined as the number of telephone communications divided by the active work time) by the installation of extra cooling capacity, supporting the need for individual temperature control [25].

Table 1. Indices of thermal quality assessment and indicators.

Thermal Quality	Goal	Indicator	Sources
Air Temperature (°C)	Adequate air temperature by season	Temperature management for occupant comfort	[9,26–37]
		Thermal comfort does not only occur around thermal neutrality	[27,28,38–40]
Radiant Temperature (°C)	Radiant temperature management through quality windows and walls	Radiant temperature for user comfort	[41–49]
Relative Humidity (%)	Adequate humidity management	Managing relative humidity	[50–53]
Air Velocity (ft/min)	Avoid drafts from air diffusers or windows	Most sensitive to draught at the head region	[25]
Personal Control	Support individual productivity, health and user satisfaction	Temperature control	[6,20,24,25,45,46,48,52,54–70]
		Humidity control	[52,59,71–74]

2. Method

The Center for Building Performance and Diagnostics (CBPD) at Carnegie Mellon University (CMU) has collected objective and subjective data on the IEQ at individual workstations in public and private sector buildings. The building performance dataset that has been gathered includes technical attributes of building systems, user satisfaction survey results, and workstation IEQ measurements, as shown in Figure 1 [7]. The purpose of creating this dataset is to explore the correlation between occupants, the technical attributes of the building systems, and the measured indoor environmental quality. It can be helpful for facility managers and architects to identify which of these variables have direct or indirect impact on an office worker's perceived satisfaction regarding thermal, air, visual and acoustic quality [75]. A database was created based on POE field data from 2003 to 2014 [76]. A total of 1719 workstations from 64 buildings were selected according to the following criteria:

- Type of organization: federal offices (n = 33), private sector financial, sales, and marketing companies (n = 31)
- Size of office: small- and medium-sized office (less than 500 m^2)

Three different kinds of data were collected to construct a database: occupant satisfaction surveys, technical attributes of building systems, and workstation IEQ measurements. Each workstation had a unique space ID, which was linked exclusively to thermal, air, visual, acoustic, and spatial quality survey data. In total, 29 user satisfaction variables, 110 building systems variables, and 15 IEQ field measurements variables were combined in MySQL. Each workstation had a unique space ID, which is linked exclusively to thermal, air, visual, acoustic, and spatial quality survey data. Table 1 presents variables which were included in the database. In this paper, we focused on the thermal quality evaluation. The variables that assigned to a single workstation for thermal quality assessment are in Table 2.

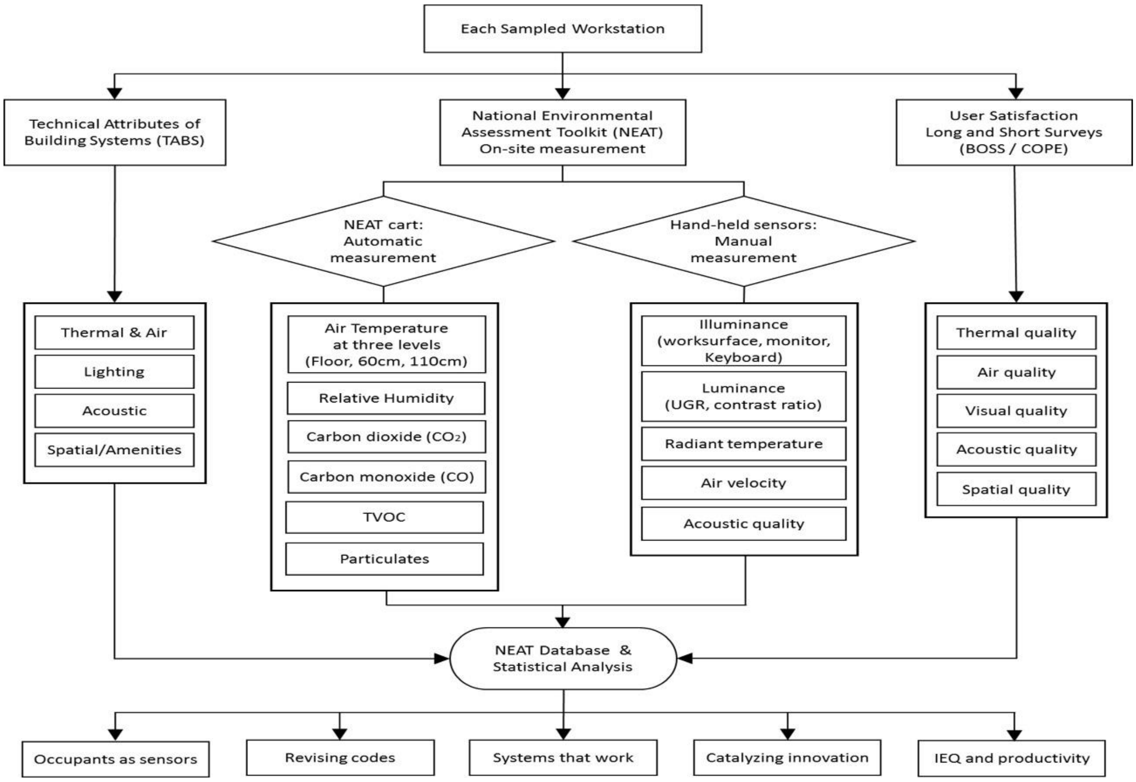


Figure 1. Carnegie Mellon University's (CMU's) 3 datasets: Building systems survey, indoor environmental quality (IEQ) field measurements, and user satisfaction survey.

2.1. User Satisfaction Survey

The intention of the survey questionnaire was to understand how occupants experience their present work environments. Occupant surveys are widely used to assess the reactions and responses of occupants to their indoor environments; such surveys are a powerful tool in research [19,77,78]. The occupant was asked to complete a "user satisfaction questionnaire" related to today's specific environmental conditions, as compared to annual satisfaction questionnaires during the time when the workstation's IEQ measurements were recorded.

The Cost-effective Open-Plan Environment (COPE) questionnaire was developed by the National Research Council Canada (NRCC) to support their ongoing research about measured environmental performance and simultaneous levels of user satisfaction in various open-plan office environments [14]. A few questions have been added by CBPD at CMU as a result of recommendations from the General Services Administration (GSA) field study: seasonal temperature satisfaction (3a–3d), odor (2a), cleanliness (4a), and the reason of air movement dissatisfaction (14) [79,80]. The questionnaires were also deployed in closed offices because the overall IEQ evaluation framework and measurement protocols were the same in both conditions. The analyses were performed separately.

This survey was distributed via paper or iPad to selected employees in the workgroup being studied. About 30% of the occupants were recruited in the survey, and Appendix A shows the two pages of user satisfaction survey questionnaires.

Table 2. Illustration of variables assigned to a single workstation (Thermal quality).

Classification	User Satisfaction Survey	Technical Attributes of Building Systems	IEQ Field Measurements
Thermal Quality	Q. Temperature in your work area: Very Dissatisfied–Dissatisfied–Somewhat Dissatisfied–Neutral–Somewhat Satisfied–Satisfied–Very Satisfied (7-point scale user satisfaction) a. Temperature during Winter: b. Temperature during Spring: c. Temperature during Summer: d. Temperature during Fall: Cold–Cool–Slightly Cold–Neutral–Slightly Warm–Warm–Hot Q. Air movement in your work area: Very Dissatisfied–Dissatisfied–Somewhat Dissatisfied–Neutral–Somewhat Satisfied–Satisfied–Very Satisfied (7-point scale user satisfaction) a. If dissatisfied with the air movement, what are the conditions: Stuffy–Drafty–Both–N/A	Size of Zone Core System Type Level of control Diffuser Density Diffuser Alignment Seasonal switchover IAQ/QA management Dedicated exhausts Level of HVAC maintenance Window Quality Window Tightness Window Controls	Air Temperature - 110 cm (°C) - 60 cm (°C) - 10 cm (°C) Radiant Temperature - Exterior (°C) - Interior (°C) - Floor (°C) - Ceiling (°C) Radiant Temperature Asymmetry - Vertical (°C) - Horizontal (°C) Relative Humidity (%) - Air Speed (ft/min)
General Information	**Q. Age** *20~29, 30~39, 40~49, 50~59, 60+* **Q. Gender** *Female–Male* **Q. Job category** *Administrative–Technical–Professional–Managerial* **Q. Highest education level** *High School–Community College–Some University–Bachelor Degree–Graduate Degree–Doctorate* **Q. My department is a good place to work** **Q. I am satisfied with my job** Strongly Disagree–Disagree–Somewhat Disagree–Neutral–Somewhat Agree–Agree–Strongly Agree	Year Built Construction type Floor-to-floor height Floor-to-ceiling height Year of last building renovation Building shape and depth	-

2.2. IEQ Field Measurements

First launched in 2000, Carnegie Mellon's portable suite of instruments on the NEAT (National Environmental Assessment Toolkit) cart has evolved over the years (Figure 2), and it has continued to become more compact and robust as affordable sensor technology advances, and as field research reveals the attributes that truly need to be measured [18]. This cart was developed to ensure a simultaneous qualitative assessment of the thermal, visual, acoustic, and air environments. Positioned in place of the occupant's chair at each sampled workstation, the cart collects temperature data at 10 cm, 60 cm, and 110 cm from the floor, the Relative Humidity (RH), Carbon dioxide (CO_2) and Carbon monoxide (CO) concentrations, particulates (PM 2.5 and PM 10), and Total Volatile Organic Compounds (TVOC) at 110 cm, which is defined as the "breathing zone" [81]. Hand-held instruments measure the horizontal and vertical radiant temperature differences, and air velocity. A data logger connected to a tablet personal computer (PC) recorded data from the instruments for analysis [18].

While the physical measurements were recorded, the occupant was asked to sit nearby and to complete the questionnaire (within 15 min), to correlate their satisfaction with the conditions at the time of measurement. The sampling rates of the spot measurements were typically 30% of the total number of office workstations on each floor, or at least 15 workstations if the workgroup is small, with a mix of open and closed, perimeter and core workstations. Since sampling may occur during cooling, heating, and swing seasons, the size of the multiple building database was critical for cross-sectional analyses against codes and standards. Code analyses were based on ASHRAE-55 [82] and Environmental Protection Agency (EPA) guidelines for thermal quality assessment [83]. The specifications of the measurement instrument used in this study are in Table 3.

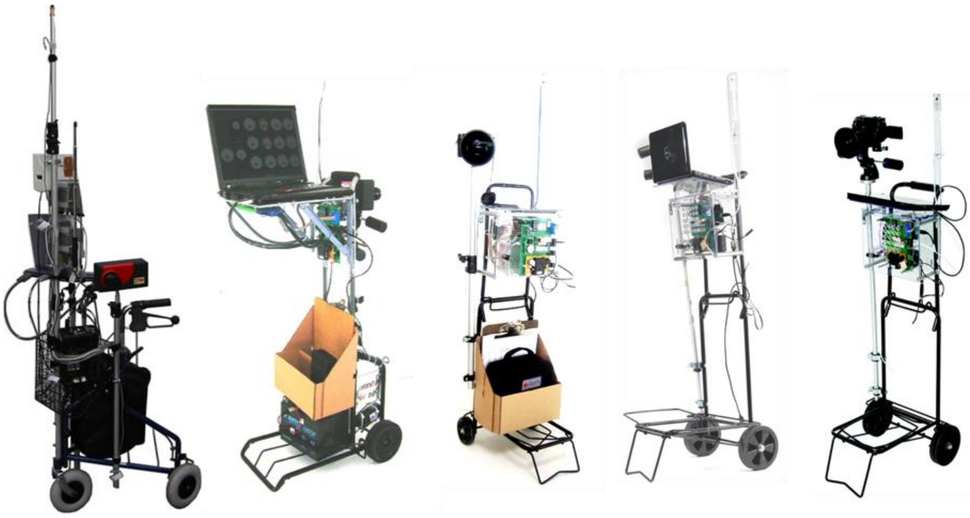


Figure 2. Image of five generations of the Enviro cart, Measure IEQ, with CMU's National Environmental Assessment Toolkit™.

Table 3. Specifications of the thermal quality measurement instrumentation used in this study.

Thermal Quality	Measurement Range	Accuracy
Air temperature at 110 cm	−55° to +150 °C	±0.5 °C
Air temperature at 60 cm	−55° to +150 °C	±0.5 °C
Air temperature at 10 cm	−55° to +150 °C	±0.5 °C
Air speed	Velocity: 0 to 2000 fpm (10 m/s) CFM: 0 to 99,990 CFM (99,990 m^3/h)	±5%
Handheld IR Temperature	−20 °C to 260 °C	±5 °C (at 23 °C, <70% RH)
Relative humidity	0 to 100% RH	±2% RH < 80% RH (±3% RH > 80% RH)

2.3. Technical Attributes of Building Systems

The CBPD team developed expert walkthrough worksheets to ensure that comparable data is recorded for the attributes of building systems that affect thermal and air quality (mechanical, enclosure, interior), lighting and visual quality (enclosure, lighting and interior), acoustic quality (mechanical, enclosure, interior) and spatial/ergonomic quality (individual and collaborative interior conditions as well as amenities). Appendix B shows the technical attributes of building systems questionnaires for thermal quality evaluation.

2.4. Statistical Analysis

Among 1719 data points, data from 118 workstations were dropped after being identified as multivariate outliers, leaving 1601 cases for analysis. In each variable, missing values were ignored. Based on the literature review, the four critical variables were also included in the data analysis as follows:

- Season (i.e., heating, cooling, and swing season): Depending on the season, buildings run different Heating, Ventilation, and Air Conditioning (HVAC) systems (heating or cooling) and people wear different types of clothing. According to Fanger's comfort equation, clothing is a critical factor in thermal comfort [84,85]. It is expected that the season needs to be considered to assess perceived thermal satisfaction.
- Gender: There is a significant difference between men and women in thermal dissatisfaction. This difference between the genders may be due to clothing insulation and metabolic differences, so that gender was considered in the data analysis [8,86–88].
- Perimeter vs. Core workstations: Occupants working in perimeter offices have shown higher user satisfaction than those working in the core. The location of the workstation needs to be considered for perceived user satisfaction. Since the environmental variables such as view, thermal control, and air movement, and so on, are quite different between perimeter and core workstations, it is expected that the location of the workstations needs to be considered for perceived user satisfaction [75,78,89].
- Open-plan and closed offices: It has been shown that open-plan office occupants are more satisfied with their environments than closed-office occupants [14]. It is expected that occupant satisfaction may be related to privacy and control issues in the office, so the office types were considered in the analysis [12].

Table 4 show the demographics of participant. Since demographic questions were not mandatory and because some of the organizations did not want to be included in the questionnaire, the total number (n = 1050) was less than other COPE answers.

Table 4. Participant demographics.

General	Category	People	%
Age	20–29	248	23.6%
	30–39	294	28.0%
	40–49	244	23.1%
	50–59	205	19.5%
	60+	8	0.8%
Gender	Female	531	50.7%
	Male	519	49.3%
Education level	High School	10	0.9%
	Community College	166	15.8%
	Some University	458	43.6%
	Bachelor Degree	180	17.2%
	Graduate Degree	237	22.5%
Job Category	Administrative	206	19.6%
	Technical	139	13.2%
	Professional	390	37.1%
	Managerial	316	30.1%

In this research, five models were developed as shown in Table 5. Using five models, we could confirm and re-check the results. A range of statistical methods and data mining algorithms were utilized to test the research hypotheses formalized in the POE field studies. The adopted tools includes descriptive statistics, two-sample t-tests, analysis of variance, and Baron and Kenny's mediated regression analysis methods [90]. Bivariate analysis was applied using the chi-squared test for contingency tables. A t-test was used with a 95% confidence interval for the mean by gender, the location of the workstation (perimeter vs. core), and office type (open-plan vs. closed) that were approximately normally distributed. Density analysis were used to define the thresholds by a 7-scale user satisfaction level. Finally, multiple logistic regression was used to identify significant predictors of user satisfaction. Differences among the 7-scale user satisfaction levels were calculated by prediction expression equations. In each model, outliers on the variables used in that phase only were excluded. Therefore, the number of cases in the analyses were slightly different from model to model.

Table 5. Objectives of five models and each diagram.

Model	Objective	Model Diagram	Statistical Method
MODEL 1	Correlation between user satisfaction and workstation IEQ measurements	NEAT → COPE	Ordinary Least Squares Ordered Logistic Fit Density Analysis One-way ANOVA, *T*-Test
MODEL 2	Correlation between user satisfaction and technical attributes of building systems	TABS → COPE	Ordinary Least Squares Ordered Logistic Fit Contingency Analysis Pearson Correlation
MODEL 3	Correlation between workstation's IEQ measurements and technical attributes of building systems	TABS → NEAT	Ordinary Least Squares Ordered Logistic Fit One-way ANOVA
MODEL 4	Correlation of user satisfaction with the combination of building attributes and workstation IEQ measurements	TABS + NEAT → COPE	Ordinary Least Squares Ordered Logistic Fit
MODEL 5	Correlation of user satisfaction with interaction of building attributes and workstation IEQ measurements	TABS × NEAT → COPE	Ordinary Least Squares Ordered Logistic Fit Effect Wald Test Effect Likelihood Ratio

2.4.1. Model 1

The purpose of Model 1 is to assess the correlation between the perceived user satisfaction and the physical IEQ measurements, and to identify which IEQ measurements have a direct impact on office worker's perceived satisfaction on thermal quality. To identify the critical variables, ordinary least squares, which covers a wide spectrum of standard models, including regression, Analysis of variance (ANOVA) and analysis of covariance, and Pearson's chi-squared test, were utilized in 10 measured IEQ variables against selected user satisfaction questions. If the differences among user satisfaction levels were statistically significant ($p < 0.05$), we conducted density analyses and visualized the thresholds based on the 7-scale user satisfaction level.

2.4.2. Model 2

Model 2 was utilized to define the correlation between perceived user satisfaction and the technical attributes of the building systems, as well as to identify which attributes of building systems predicted perceived satisfaction. The ordinary least squares and Pearson's chi-squared test methods were conducted to identify critical physical building characters that were related to perceived user satisfaction. Among variables in TABS, the indices that were not binomial characters were converted to factor variables.

2.4.3. Model 3

Model 3 was used to define correlations between IEQ measurements and building attributes, and identify which building attributes predict IEQ. The correlation analysis was conducted for TABS variables and NEAT measurements of IEQ. An ordinary least squares and ordered logistic fit were conducted to identify critical physical building characters which were related to IEQ measurements.

2.4.4. Model 4

In Model 4, the correlation between user satisfaction and all variables including technical attributes of building systems, as well as workstation IEQ measurements was tested. In addition, gender, perimeter versus core workstation location, open-plan versus closed-office types, and season were also tested with those variables for correlation with user satisfaction. In this model, the correlation between a total of twenty variables (10 physical attributes investigated in the TABS record and 10 sets of workstation IEQ measurements assessed by a NEAT instrument) and two user satisfaction responses investigated in the COPE questionnaires (i.e., air temperature in the work area and air movement in the work area) were analyzed using ordinary least squares and ordered logistic fit. The mediation effects were also tested in this stage, followed by Baron and Kenny's regression analysis methods [90].

2.4.5. Model 5

The goal of Model 5 was to identify which combination of technical attributes of building systems and workstation's IEQ measurements affected user satisfaction, as well as defining how much % was affected. Initially, all variables (10 technical attributes of building systems and 10 IEQ measurements) were tested against user satisfaction using ordinary least squares and ordered logistic fit. However, because of the multicollinearity and omitted values in the process, we developed 'Model 5', which included critical variables selected from models 1 to 4. To quantify the correlation of each variable and to predict the effectiveness, an ordered logistic fit and generalized linear model tests were performed, accompanied with a maximum likelihood estimation and the Wald test.

3. Results

Given the NEAT database of 1197 workstations in 64 buildings, overall, 55% of occupants responded as 'satisfied' or 'neutral', and 45% of occupants reported as 'dissatisfied' with their thermal conditions. The average temperature satisfaction was 3.5, which fell between 'somewhat dissatisfied' and 'neutral' with their temperature satisfaction on a 7-point scale (very dissatisfied, dissatisfied, somewhat dissatisfied, neutral, somewhat satisfied, satisfied, and very satisfied) survey.

The combination of technical attributes of the building systems and workstation IEQ measurements that had significant correlation with user satisfaction are as follows (Table 6).

- Occupants in closed offices showed higher satisfaction than occupants in an open-plan office location ($p = 0.01$).
- A smaller "size of zone" could increase user satisfaction ($p = 0.01$).
- Individual control of the thermostat could increase user satisfaction ($p = 0.001$).
- Better "window quality (enclosure)" could increase user satisfaction ($p = 0.03$).
- The air temperature at 60 cm from the floor and radiant temperature asymmetry between the exterior and interior walls significantly affected user satisfaction ($p < 0.05$).

Table 6. Correlation of user satisfaction with a combination of technical attributes of building systems and workstation thermal quality measurements: Thermal quality.

Thermal Quality	Variables	Coefficient	*p*-Value
General	Gender	0.22	0.21
Location	Perimeter–Core	−0.16	0.44
Office type	Open plan office–Closed office	0.51	0.01 **
Season	Winter–Spring	−0.30	0.32
	Winter–Summer	−0.49	0.11
	Winter–Fall	−0.30	0.32
Size of thermal zone	More than 25 vs. 10~15	0.28	0.44
	More than 25 vs. 5~10	0.46	0.17
	More than 25 vs. 2~5	1.25	0.01 **
	More than 25 vs. Individual control	1.49	0.001 ***

Table 6. *Cont.*

Thermal Quality	Variables	Coefficient	*p*-Value
Main System	Constant volume	0.75	0.16
	Variable air volume/terminal reheat	−0.37	0.66
	Separate thermal and ventilation	−0.95	0.57
Level of Control	Locked vs. Locked but visible thermostat	−0.12	0.05 *
	Locked vs. Controllable thermostat	2.13	0.93
Window Quality	Leaky, single pane vs. Moderate tight, two panes	1.09	0.05 *
	Leaky, single pane vs. Tight, three panes	1.49	0.03 *
NEAT Measurements	Air temperature at 110 cm	0.10	0.05 *
	Air temperature at 60 cm	0.11	0.05 *
	Air temperature at 10 cm	0.03	0.85
	Relative humidity	−0.05	0.16
	Radiant temperature of interior wall	−0.03	0.52
	Radiant temperature of ceiling	0.05	0.41
	Radiant temperature of floor	0.01	0.10
	Radiant temperature of exterior wall	−0.03	0.44
	Horizontal radiant temperature asymmetry	−0.13	0.05 *
	Vertical radiant temperature asymmetry	−0.10	0.07

Notes: * $p \leq 0.05$, ** $p \leq 0.01$, *** $p \leq 0.001$.

3.1. Air Temperature

CMU's analysis of the NEAT database revealed that during the heating and swing seasons, 85% of the measured temperatures were within the ASHRAE 55 thermal comfort range, which is between 20 °C and 25.6 °C. However, during the cooling season, 36% of measured temperatures were below the comfort range, and resulted in 58% dissatisfaction in the user thermal survey (Figure 3).

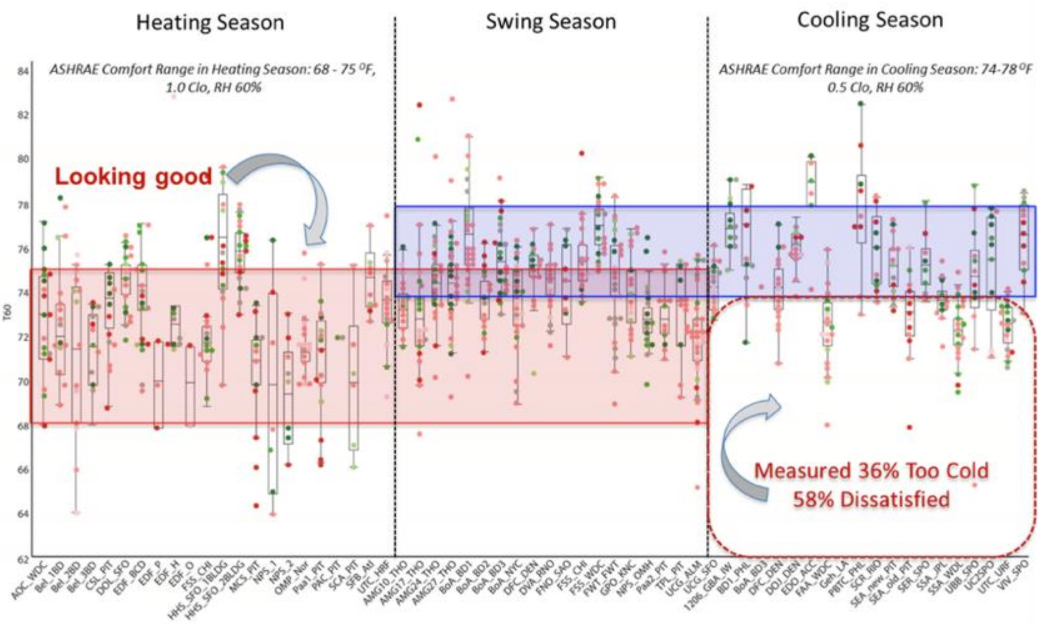
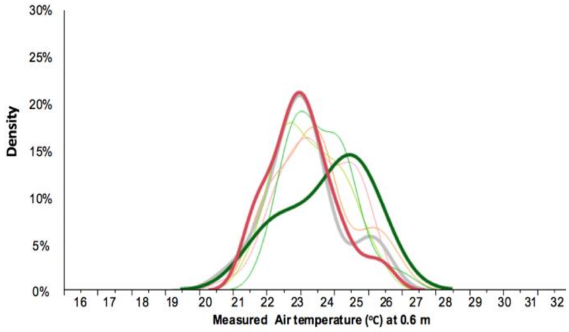


Figure 3. Air temperature at 60 cm from the floor (n = 1282).

To identify the thresholds of the satisfaction with the temperature in the summer, density analyses were conducted, as shown in Table 7. The red curve shows the range of temperatures from the dissatisfied group, and the green curve is the satisfied group. The majority of the temperatures for the dissatisfied workstations were around 22.7 °C, and the satisfied group's temperatures were around 24.8 °C. The difference was statistically significant ($p < 0.05$). The result showed that warmer temperatures are considered in cooling season by looking at measured field temperatures in workstations correlated with user satisfaction level.

Table 7. Analysis of variance of air temperature at 60 cm from the floor by user satisfaction, cooling season (n = 309).



Thermal Quality	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Temperature	6	23.86	3.98	2.69	0.0148
Satisfaction Level	***n***	**Mean**	**StdError**	**Lower 95%**	**Upper 25%**
Very Dissatisfied	45	22.17	0.18	21.7	23.53
Dissatisfied	43	22.67	0.19	22.04	23.88
Somewhat Dissatisfied	54	22.94	0.17	22.25	23.96
Neutral	60	23.44	0.16	22.39	23.56
Somewhat Satisfied	41	23.67	0.19	23.2	23.95
Satisfied	47	24.50	0.18	23.58	24.95
Very Satisfied	19	24.83	0.27	23.5	25.33

t-test (95% confident interval, $p < 0.05$), statistically significant. Mean of temperature at satisfaction range: 24.8 °C, Mean of temperature at dissatisfaction range: 22.7 °C.

3.2. Size of Themral Zone

Figure 4 shows the distribution in the size of the zone for 1155 workstations in 64 buildings, divided between the perimeter and core office locations. A total of 13% of offices had one thermostat shared by more than 25 people, 32% of the offices were controlled by 10–15 persons per thermostat (n = 419), 36% of workstations had 5–10 people per thermostat (n = 373), and 19% had less than five people (individual control 5%, n = 58; and 2–5 people 14%, n = 158).

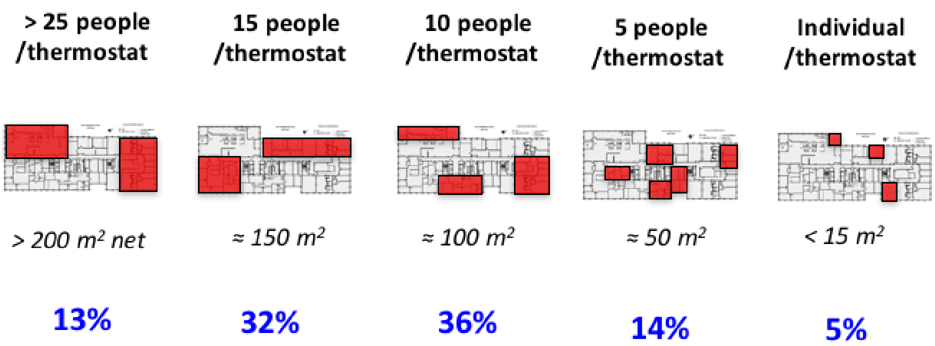


Figure 4. Distribution in Size of thermal zone for 1155 questionnaire respondents in 64 buildings.

The results showed that temperature satisfaction increased as the thermal zone decreased by size, as fewer people shared a single thermostat in both heating and cooling seasons (Figure 5). Table 8 shows the variables used in the size of thermal zone and satisfaction analysis in both Cooling and heating seasons. The relationship between size of thermal zone and user satisfaction levels are highly correlated as examined in Table 9. On average, 80% of occupants were satisfied with an individual thermal zone, while only 20% of occupants were satisfied when 15–25 people shared one thermostat (n = 737, b = 44, $p < 0.001$).

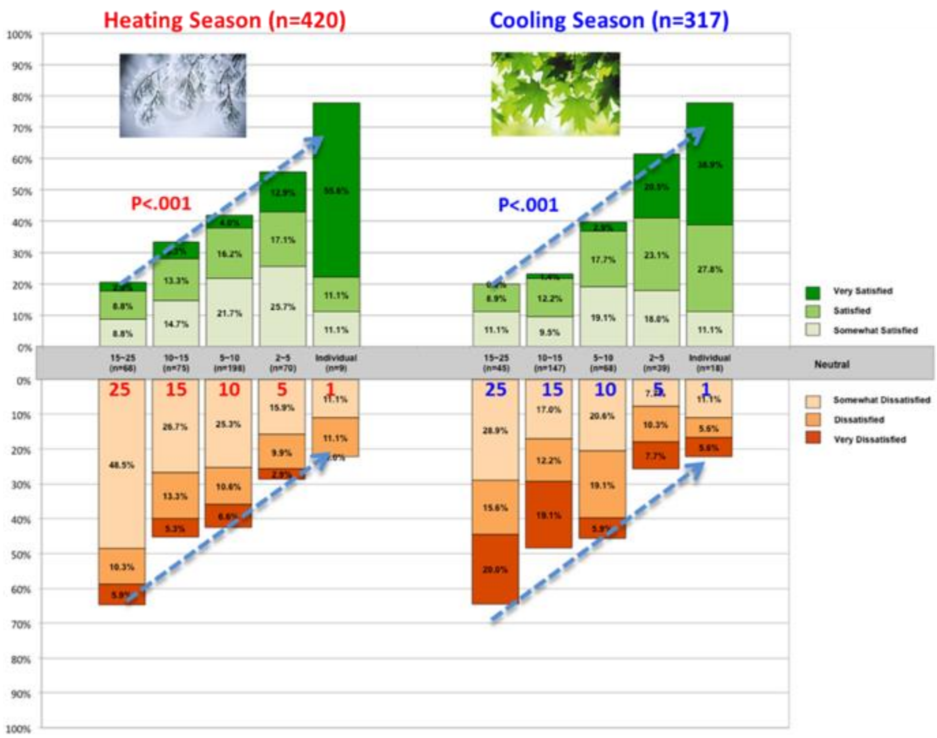


Figure 5. User satisfactions on air temperature by the size of zone (heating and cooling season, n = 737).

Table 8. Descriptive statistics for user satisfaction on air temperature by the size of the zone.

Season	Size of Zone	n	Very Dissatisfied	Dissatisfied	Somewhat Dissatisfied	Neutral	Somewhat Satisfied	Satisfied	Very Satisfied
Heating (n = 420)	15~25	68	5.88%	10.29%	48.53%	14.71%	8.82%	8.82%	2.94%
	10~15	75	5.33%	13.33%	26.67%	21.33%	14.67%	13.33%	5.33%
	5~10	198	6.57%	10.61%	25.25%	15.66%	21.72%	16.16%	4.04%
	2~5	70	2.86%	12.86%	22.86%	15.71%	25.71%	17.14%	2.86%
	Individual	9	0%	11.11%	11.11%	0%	11.11%	11.11%	55.56%
Cooling (n = 317)	15~25	45	20%	15.56%	28.89%	15.56%	11.11%	8.89%	0%
	10~15	147	19.05%	12.24%	17.01%	28.57%	9.52%	12.24%	1.36%
	5~10	68	5.88%	19.12%	20.59%	14.71%	19.12%	17.65%	2.94%
	2~5	39	7.69%	10.26%	7.69%	12.82%	17.95%	23.08%	20.51%
	Individual	18	5.56%	5.56%	11.11%	0%	11.11%	27.78%	38.89%

Table 9. Contingency analysis of user satisfaction on air temperature by size of zone by Season.

Season	n	Test Statistics	Chi-Square	Prob > ChiSq
Heating Season	420	Likelihood Ratio	50.304	0.0013 **
-	-	Pearson	43.420	0.0089 **
Cooling Season	317	Likelihood Ratio	67.022	<0.0001 ***
-	-	Pearson	77.380	<0.0001 ***

Notes: * $p \leq 0.05$, ** $p \leq 0.01$, *** $p \leq 0.001$.

The disparity was especially significant for females during the cooling season, with the highest thermal dissatisfaction in large zone areas (with colder temperatures and seasonal clothing) as shown in Figure 6. The clo values, the thermal insulation of clothing, are considered as a value of 1.1 in heating season, 0.8 in swing season and 0.5 in cooling season. There is a significant correlation between size of thermal zone and female occupants' satisfaction level regardless of the seasons (Table 10). Thermal satisfaction on females can be affected by their clothing because clo value in females is 0.5 whereas males is value of 0.7 [76]. During the cooling season, when 15–25 people shared one thermostat, only 7% of female occupants were satisfied with the air temperature, while the workstations with individual thermostat showed 64% satisfaction (n = 422, b = 22, $p < 0.001$).

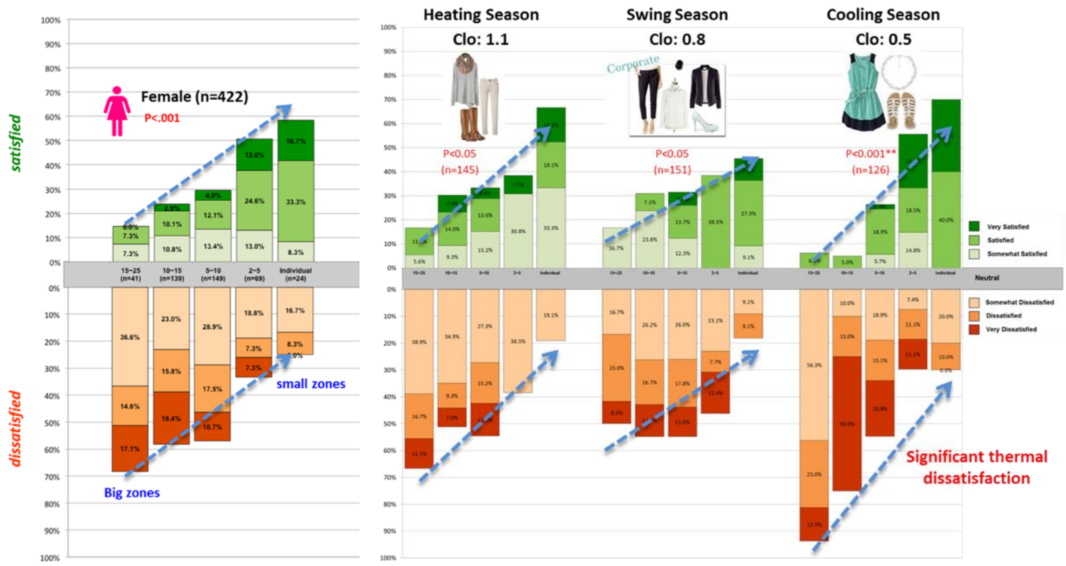


Figure 6. User satisfactions on air temperature for female occupants by size of zone by season (clo).

Table 10. Contingency Analysis of User Satisfaction on Temperature by Size of Zone, Female.

Season	*n*	Test Statistics	ChiSquare	Prob > ChiSq
Heating Season	145	Likelihood Ratio	34.542	0.0755
Female (clo: 1.1)	-	Pearson	40.889	0.0171 *
Swing Season	151	Likelihood Ratio	44.235	0.0072 *
Female (clo: 0.8)	-	Pearson	45.237	0.0055 *
Cooling Season	126	Likelihood Ratio	67.775	<0.0001 ***
Female (clo: 0.5)	-	Pearson	62.828	<0.0001 ***

Notes: * $p \leq 0.05$, ** $p \leq 0.01$, *** $p \leq 0.001$.

Looking at the cooling season data more closely revealed that when the size of the thermal zone was less than five controls and two to five people per thermostat, over 90% of the measured temperatures were within the ASHRAE comfort range, as highlighted in Figure 7. However, when the size of zone was over 10, or 10–25 people/thermostat, about 80% of workstations were deemed as "too cold" at an average temperature of 21.7 °C. Summer data can be statistically addressed by redirecting the size of thermal zone to less than five, and by raising air temperature. At present, there are no code mandates limiting the size of thermal zones, with value engineering often reducing the number of engineered zones before construction even begins. The results revealed that 80% satisfaction might only be achievable with 'micro-zoning (the size of zone is less than 5)', providing a level of temperature control at every workstation.

3.3. Level of Temperature Control

The level of user control can predict user satisfaction on temperature. In this paper, the level of control was surveyed in three categories: hidden thermostat, visible but locked thermostat, and controllable thermostat. A total of 65% had hidden thermostats in the office among 1004 respondents, a majority of workstations, and only 18% of occupants could control their thermal environment, as summarized in Table 11.

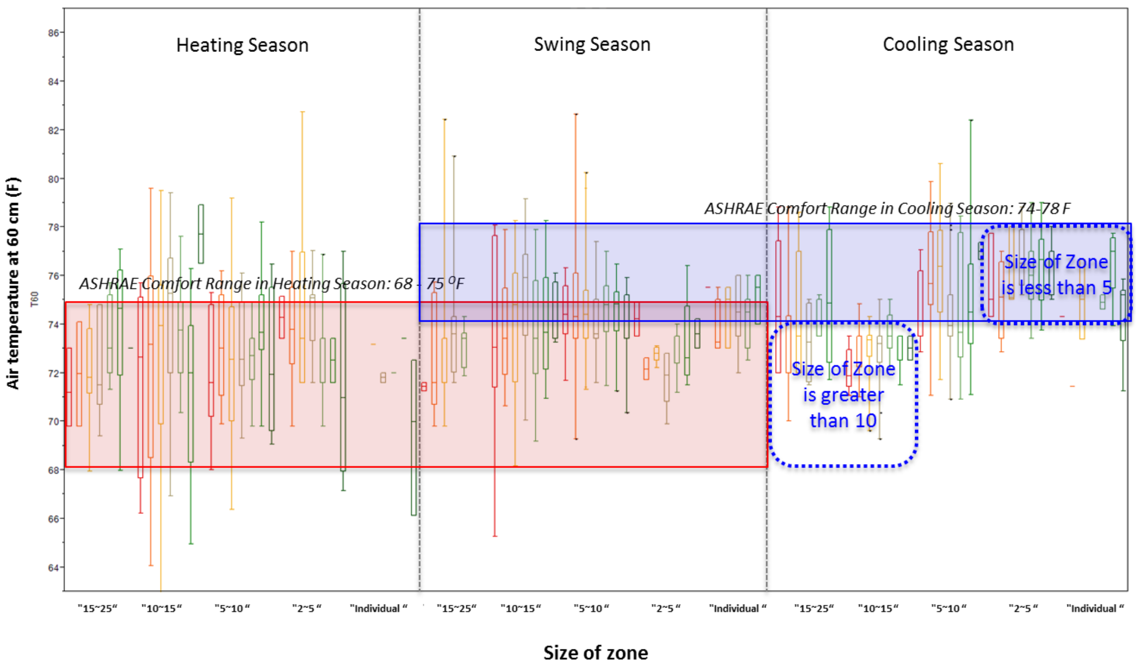


Figure 7. Air temperature of 60 cm from the floor by size of zone, and temperature satisfaction colored by seven scales.

Table 11. Distribution in level of control for questionnaire respondents in 64 buildings (divided between open and closed office locations).

Level of Thermal Control (n = 1004)			
Type	**Hidden Thermostat**	**Locked But Visible Thermostat**	**Controllable Thermostat**
N, Ratio (%)	n = 656 (65%)	n = 170 (17%)	n = 178 (18%)
Office type	484 open offices 172 closed offices	110 open offices 60 closed offices	60 open offices 118 closed offices

Table 12 shows the variables and summery statistics for user satisfaction on air temperature by the level of control. The level of thermostat control is significantly related to occupant satisfaction in both open-plan offices and closed offices (Table 13). The result showed that occupants with access to controllable thermostats had higher satisfaction (62%), while locked but visible thermostats yielded worse satisfaction (22%) than hidden thermostats (36%). Locked but visible thermostats were worse than hidden thermostats in both open-plan (n = 654, b = 64, $p < 0.01$) and closed offices (n = 350, b = 64, $p < 0.05$) (Figure 8).

Table 12. Descriptive statistics for user satisfaction on air temperature by the level of control.

Office Type	Thermal Control	n	Very Dissatisfied	Dissatisfied	Somewhat Dissatisfied	Neutral	Somewhat Satisfied	Satisfied	Very Satisfied
Open-plan (n = 654)	Hidden	440	6.4%	15.5%	23.2%	19.5%	15.5%	15.0%	5.0%
	Locked	74	16.2%	13.5%	32.4%	10.8%	16.2%	8.1%	2.7%
	Controllable	116	3.4%	6.9%	20.7%	3.4%	19.0%	37.9%	8.6%
Closed (n = 350)	Hidden	208	7.7%	7.7%	31.7%	17.3%	12.5%	16.3%	6.7%
	Locked	88	9.1%	27.3%	40.9%	6.8%	6.8%	6.8%	2.3%
	Controllable	38	11.1%	0.0%	25.9%	11.1%	18.5%	7.4%	25.9%

Table 13. Contingency analysis of user satisfaction on temperature by level of control by office type (open-plan vs. closed office).

Level of Control	*n*	Test Statistics	Chi Square	Prob > ChiSq
Open-plan Office	654	Likelihood Ratio	47.242	0.0002 **
-	-	Pearson	42.202	0.0010 **
Closed Office	350	Likelihood Ratio	32.951	0.0169 *
-	-	Pearson	33.022	0.0166 *

Notes: * $p \leq 0.05$, ** $p \leq 0.01$, *** $p \leq 0.001$.

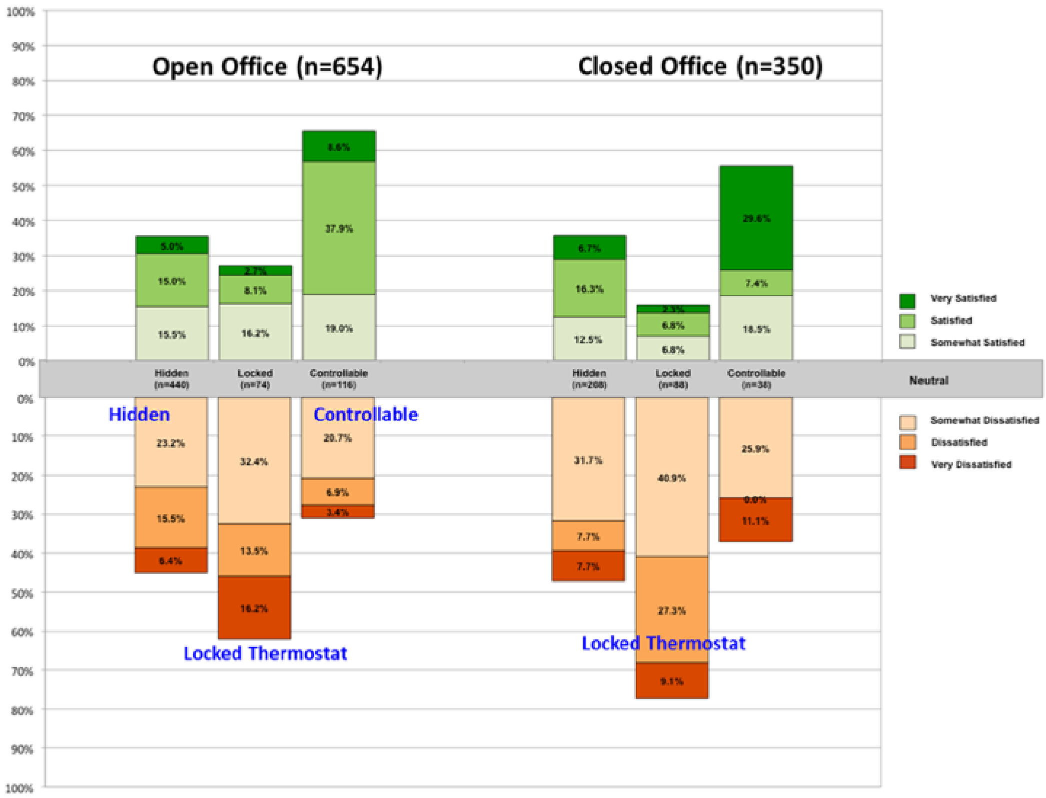


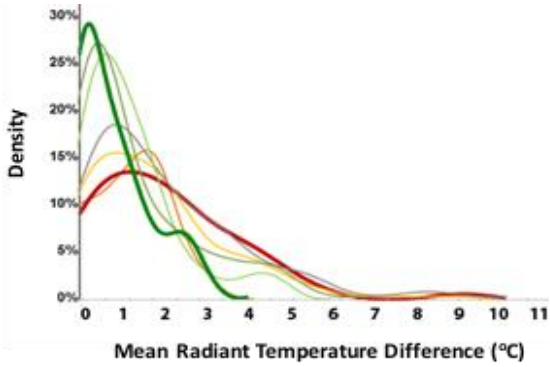
Figure 8. User satisfaction on air temperature by the level of control (Open and Closed Offices).

3.4. Radiant Temperature Asymmetry with Façade

Large differences in the thermal radiation of the surfaces surrounding an occupant may cause local discomfort. The ASHRAE Standard 55 sets limits on the allowable temperature differences between various surfaces [82]. Ensuring that the temperature asymmetry between exterior and interior walls is less than 3.9 °C increased user satisfaction by 0.73 points in perimeter offices ($n = 692$, $b = 64$, $p < 0.001$). There was a significant correlation between radiant temperature asymmetry between the exterior and interior walls, and user satisfaction in perimeter offices ($p < 0.0001$), but the relationship was not relevant in core offices ($p = 0.08$). There is a significant correlation between radiant temperature asymmetry between exterior and interior walls, and user satisfaction in perimeter offices ($p < 0.0001$). The mean radiant temperature asymmetry between exterior and interior walls in perimeter offices was only 1.7 °C, which was far below ASHRAE's temperature of 10 °C [76].

To identify the thresholds of satisfaction, density analyses were conducted (Table 14). The majority of the temperature differences for the dissatisfied group were greater than 2.2 °C, and the satisfied group's temperatures were less than 1.0 °C. The difference was statistically significant (95% confident interval, $p < 0.05$). Based on this analysis, there was a possibility that people were less satisfied when the radiant asymmetry between exterior and interior walls was greater than 2.2 °C.

Table 14. Density comparisons: radiant temperature asymmetry between the exterior and interior walls in perimeter offices (n = 391).



Thermal	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Temperature	6	135.8	13.74	1.58	<0.001
User Satisfaction	***n***	**Mean**	**Std. Error**	**Lower 95%**	**Upper 25%**
Very Dissatisfied	29	2.04	0.3	1.56	2.52
Dissatisfied	40	2.24	0.26	1.75	2.73
Somewhat Dissatisfied	95	2.03	0.17	1.71	2.36
Neutral	65	1.87	0.2	1.48	2.26
Somewhat Satisfied	69	1.27	0.2	0.88	1.63
Satisfied	62	1.19	0.21	0.8	1.59
Very Satisfied	31	0.88	0.29	0.32	1.45

95% CI, $p < 0.001$, Statistically significant. Mean of the temperature at the satisfaction range: 1.0 °C, Mean of temperature at the dissatisfaction range: 2.2 °C.

4. Discussion

4.1. Prediction of User Satistacion for Future Studies

We have developed predictive analytics equations for predicting the occupant satisfaction levels in given IEQ conditions. Predictive analytics is the use of data, statistical algorithms, and machine learning techniques to identify the likelihood of future outcomes based on historical data [91].

Table 15 shows the result of prediction expression, and it can provide an insight of user satisfaction for individualized thermal quality management in the field. The stepwise multiple logistic was used to identify significant predictors of user satisfaction. Differences in user satisfaction level were calculated by prediction expression equations in SAS software [91].

We also conducted correlation analysis to test that the selected indices are critical and can successfully predict user satisfaction. Table 16 shows the correlation between user satisfaction and an interaction of building attributes and IEQ measurements when p-value is less than 0.05. The result confirmed that a combination of critical factors can inform user satisfaction.

Using these research results, we can develop simplified IEQ field toolkit. We can expect that simplified IEQ tools that combine critical thermal measurement instrument with user surveys can provide a statistically significant insight into IEQ conditions at a fraction of the cost of complex field instrumentation, to provide a first tier of evaluation critical field evaluation of built environment.

Table 15. Prediction expression of user satisfaction in thermal quality.

Thermal Quality Satisfaction Prediction		
= - 0.35		
+	Match [Size of Zone]	15-25 people => - 0.69 10-15 people => - 0.20 5-10 people => + 0.02 2-5 people => + 0.59 Individual => + 1.06 Else=>.
+	Match [Window Quality]	Leaky => - 1.47 Moderate => + 0.16 Tight => + 0.34 Else=>.
+	Match [Level of Control]	Hidden => 0 Locked => - 0.59 Controllable => +1.32 Else=>.
+	Air temperature at 60cm	≤ 73.43 F => 0 ≤ 74.15 F => + 0.09 Else=>.
+	ΔT (Ex-In)	ΔT (Ex-In) ≤ 3.14 => 0 3.14 < ΔT (Ex-In) ≤ 7.01 => -0.56 ΔT (Ex-In) > 7.01 => -0.72 Else=>.

Table 16. Correlation of user satisfaction with the interaction of building attributes and IEQ measurements.

Variables	Contrast	t-Ratio	*p*-Value
Size of Zone	0.627	4.804	0.002 **
Perimeter vs. Core office × Temperature asymmetry between the exterior and interior walls	0.375	2.872	0.007 **
Size of Zone × (Air temperature at 60 cm)^2	−i.307	−3.353	0.022 *
Window quality	0.291	2.230	0.030 *
Temperature asymmetry between the exterior and interior walls × (Air temperature at 60 cm)^2	−i.274	−2.097	0.041 *
Open workstation vs. Closed office	0.270	2.071	0.044 *
Open workstation vs. Closed office × Perimeter vs. Core office × (Air temperature at 60 cm)^2	0.264	2.020	0.048 *
Perimeter vs. Core office × Air temperature at 60 cm × Temperature asymmetry between the exterior and interior walls	0.222	1.699	0.095

Notes: * $p \leq 0.05$, ** $p \leq 0.01$, *** $p \leq 0.001$.

4.2. Research Limitations

There are some limitations of this research. First, the conclusions were based on field measurement data, as opposed to controlled experiments derived from an existing mixed-quality building stock. Second, the data are collected from NEAT short-term spot measurements in one season per building. Third, data collection for the technical attributes of building systems was dependent on interpretations of experts in the field. For example, sometimes, diffuser alignments were recorded by the perception of on-site building performance measurement professionals. Not always from the building system drawings.

5. Summary and Conclusions

The goal of this research was to develop and design guidelines to enhance user satisfaction by providing optimized individual IEQ components. Three objectives were established toward this research goal.

- To identify critical IEQ and physical factors for user satisfaction on thermal quality.
- To identify correlations between building systems, measured IEQ, and user satisfaction in concurrent time frames.
- To define thresholds for highest user satisfaction in the field.

To achieve this goal, five statistical models were established to test hypotheses and to define the relations between IEQ measurements and technical attributes of building systems, as well as the user satisfaction survey. The main findings and contributions can be summarized as follows.

First, this research provided an integrated approach to POE with indoor environmental quality measurements and technical attributes of building systems by using filed survey to capture IEQ conditions in a work environment. This approach identified critical factors in the physical environment that impact building occupant satisfaction and provided practical IEQ assessment methods and procedures, centered on the occupants' perspective. Table 17 illustrates the IEQ and technical attributes of building systems that significantly impacted user satisfaction on the thermal quality.

Table 17. Measured IEQ and technical attributes of building systems that significantly impacted user satisfaction on thermal quality.

Measured IEQ (NEAT)	Technical Attributes of Building Systems (TABS)	User Satisfaction Questions (COPE)
• Air temperature at 60 cm from the floor • Air temperature at 110 cm from the floor • Radiant temperature asymmetry between the exterior and interior wall	• Size of the zone • Window quality • Level of thermal control	• Are you satisfied with the temperature in your work area

Second, the analysis can help inform design decisions. Among all technical attributes of building systems, three TABS parameters, including size of zone, window quality and level of thermal control, are deemed to be critical to ensure user satisfaction. As such, for thermal quality, having a smaller size of zone, tight windows, and controllable thermostats are recommended.

Third, the results also suggest that occupant satisfaction survey response can re-calibrate thermal quality thresholds. Given our dataset, using 1601 workstation's IEQ measurements and user satisfaction survey responses from 64 buildings, refined IEQ thresholds for the highest building occupant satisfaction on thermal quality were suggested, as shown in Table 18.

Table 18. Redefined thresholds for user thermal satisfaction derived from 64 office buildings.

IEQ Measurements	Thresholds for Highest Satisfaction (Given 64 Office Buildings)		Recommended Level (Standards)
Air temp at 60 cm in heating season	22.6–23.2 °C (Female)	22.2–22.8 °C (Male)	20–27 °C (ASHRAE 55-2013)
Air temp at 60 cm in cooling season	24.5–25.0 °C (Female)	24.3–24.7 °C (Male)	23–28 °C (ASHRAE 55-2013)
Horizontal radiant temperature asymmetry (cool wall)	<1.77 °C (Female)	<2.23 °C (Male)	<10 °C (ASHRAE 55-2013)
	<2.16 °C (Overall)		<10 °C (ASHRAE 55-2013)

To summaries, the outcome of this research contributes to exploring correlations between occupant satisfaction and measured data with an integrated survey method to assess building IEQ. The holistic IEQ assessments further afford a capability of predicting users' satisfaction from captured IEQ data and inform revised IEQ thresholds linking to higher occupants' satisfaction.

Author Contributions: Conceptualization, J.P.; Supervision V.L. and A.A.; Project Administration J.P. and A.A.; Methodology J.P., V.L. and A.A.; Software J.P., Writing—Original Draft Preparation J.P.; Writing—Review & Editing V.L. and A.A., Visualization J.P.; Investigation J.P., V.L. and A.A.

Acknowledgments: The authors would like to thank a host of students of the Center for Building Performance and Diagnostics at Carnegie Mellon University, who supported data acquisition, processing, analysis, and reporting.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A. User Satisfaction Survey Questionnaire

CMU's On-Site User Satisfaction Questionnaire *(based on NRC COPE [i])*

Office Type: ☐ Office Cubicle or Open Plan Workstation
☐ Shared Closed Office 2, 3, 4, or more
☐ Individual Closed Office

View: ☐ No View
☐ Seated View

What building are you in (address or title)? ____________

What floor? ____________

How long have you worked here? ____________

In a typical work week how many hours do you spend here? ____________

How do you feel about?	Very Dissatisfied	Dissatisfied	Somewhat Dissatisfied	Neutral	Somewhat Satisfied	Satisfied	Very Satisfied
1. Light on the desk for paper-based tasks (reading & writing)	-3	-2	-1	0	1	2	3
2. Overall air quality in your work area	-3	-2	-1	0	1	2	3
2a. Odors in your work area	-3	-2	-1	0	1	2	3
3. Temperature in your work area	-3	-2	-1	0	1	2	3

Temperature in your work area during:	Cold	Cool	Slightly Cool	Neutral	Slightly Warm	Warm	Hot
3a. Winter	☐	☐	☐	☐	☐	☐	☐
3b. Spring	☐	☐	☐	☐	☐	☐	☐
3c. Summer	☐	☐	☐	☐	☐	☐	☐
3d. Fall	☐	☐	☐	☐	☐	☐	☐

How do you feel about?	Very Dissatisfied	Dissatisfied	Somewhat Dissatisfied	Neutral	Somewhat Satisfied	Satisfied	Very Satisfied
4. Aesthetic appearance of your work area	-3	-2	-1	0	1	2	3
4a. Cleanliness of your work area	-3	-2	-1	0	1	2	3
5. Level of acoustic privacy for conversations in your work area	-3	-2	-1	0	1	2	3
6. Level of visual privacy within your work area	-3	-2	-1	0	1	2	3
7. Amount of noise from other people's conversations while you are at your workstation	-3	-2	-1	0	1	2	3
8. Size of your personal work area to accommodate your work, materials and visitors	-3	-2	-1	0	1	2	3
9. Amount of background noise from mechanical or office equipment you hear at your workstation	-3	-2	-1	0	1	2	3
10. Light for computer work	-3	-2	-1	0	1	2	3

How often do you experience glare:	Always	Morning	Noon	Late Afternoon	Night	Never
11. On your computer screen	☐	☐	☐	☐	☐	☐
12. From electric lighting fixtures	☐	☐	☐	☐	☐	☐
13. From daylight	☐	☐	☐	☐	☐	☐

How do you feel about?	Very Dissatisfied	Dissatisfied	Somewhat Dissatisfied	Neutral	Somewhat Satisfied	Satisfied	Very Satisfied
14. Air movement in your work area	-3	-2	-1	0	1	2	3

	Stuffy	Drafty	Both	N/A
If dissatisfied with the air movement, what are the conditions:	☐	☐	☐	☐

How do you feel about?	Very Dissatisfied	Dissatisfied	Somewhat Dissatisfied	Neutral	Somewhat Satisfied	Satisfied	Very Satisfied
15. Your ability to alter physical conditions in your work area	-3	-2	-1	0	1	2	3
16. Your access to a view of outside from where you sit	-3	-2	-1	0	1	2	3
17. Distance between you and other people you work with	-3	-2	-1	0	1	2	3
18. Overall quality of lighting in your work area	-3	-2	-1	0	1	2	3
19. Frequency of distraction from other people	-3	-2	-1	0	1	2	3
20. Degree of enclosure of your work area by walls, screens or furniture	-3	-2	-1	0	1	2	3

Rank of importance (1-7)	Noise	Temperature	Privacy	Air Quality Ventilation	Size of Workspace	Window Access	Lighting
21. Rank from 1st-7th what should be improved to support your effectiveness at work (1st is the most important and 7th is the least important)	—	—	—	—	—	—	—

Please check the appropriate box:

22. Age	20-29	30-39	40-49	50-59	60-69	70+
23. Gender	Female	Male				
24. Highest level of education	High School	Community College	Some University	Bachelor Degree	Graduate Degree	Doctorate
25. Job category	Administrative	Technical	Professional	Managerial		

How do you feel about?	Strongly Disagree	Disagree	Somewhat Disagree	Neutral	Somewhat Agree	Agree	Strongly Agree
26. My department/agency is a good place to work	-3	-2	-1	0	1	2	3
27. I am satisfied with my job	-3	-2	-1	0	1	2	3
28. The environmental conditions in my work area support my personal productivity	-3	-2	-1	0	1	2	3
29. I am satisfied with the indoor environment in my work area as a whole	-3	-2	-1	0	1	2	3

Please add any comments that you would like to share with us related to your work environment:

[1] Based on the COPE survey of the Institute for Research in Construction, National Research Council Canada, and revised by the Center for Building Performance and Diagnostics at Carnegie Mellon University.

Please fax or mail this completed survey to:
Azizan Aziz, Center for Building Performance and Diagnostics, Carnegie Mellon University,
5000 Forbes Avenue, 410 Margaret Morrison Carnegie Hall, Pittsburgh, PA 15213
Telephone: 412-268-6882 | Fax: 412-268-6129

Appendix B. Technical Attributes of Building Systems

Thermal & Air Quality: for XXX floor, answer as many characteristics as possible for the most typical workstation

CORE HVAC SYSTEMS:

Core system Type:

All Air Systems:
- ❑ VAV
- ❑ VAV with terminal reheat
- ❑ CV

Air and Water Systems
- ❑ Fan Coil + CV
- ❑ Radiator + CV

Size of Zone in core (number of occupants per thermostat):
- ❑ >75
- ❑ 25-75
- ❑ 15-25
- ❑ 10-15
- ❑ 5-10
- ❑ <5
- ❑ Individual Control

Level of Control:
- ❑ Hidden thermostat (no control)
- ❑ Locked but visible thermostat with setpoint
- ❑ Locked but visible with setpoint and status
- ❑ Accessible thermostat with setpoint
- ❑ Accessible thermostat with setpoint and status
- ❑ Individual or Group temp/volume control or air direction/ speed control
- ❑ Separate thermal and ventilation control

Room Air Diffusion Methods:
- ❑ Mixing system
- ❑ Displacement Ventilation
- ❑ Under Floor Air Distribution and Task/Ambient Conditioning

Supply air diffuser density:
- ❑ >5 occupants per diffuser
- ❑ 3-5 occupants per diffuser
- ❑ 2 occupants per diffuser
- ❑ 1 occupant per diffuser
- ❑ ≥2 diffusers per occupant or relocatable

Return air diffuser density:
- ❑ <1 per 50 workstations
- ❑ 1 per 25-50 workstations
- ❑ 1 per 10-25 workstations
- ❑ 1 per 5-10 workstations
- ❑ > 1 per 5 workstations

PERIMETER HVAC SYSTEMS:

Perimeter system type:
- ❑ Radiator
- ❑ Fan coil units
- ❑ Induction units
- ❑ Electric baseboard
- ❑ Other: ________

Level of control:
- ❑ Central control, entire façade by orientation (eastern, western, southern and northern)
- ❑ Central control, multiple units
- ❑ Central control, individual units
- ❑ Local control, 2-3 units shared
- ❑ Local control, individual unit
- ❑ Separate thermal and ventilation control

LEVEL OF CONTROL IN CLOSED OFFICES:

Level of Control:
- ❑ Hidden thermostat (no control)
- ❑ Locked but visible thermostat with setpoint
- ❑ Locked but visible with setpoint and status
- ❑ Accessible thermostat with setpoint
- ❑ Accessible thermostat with setpoint and status
- ❑ Air temperature and/or volume and/or direction and/or speed control

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