INDOOR ENVIRONMENTAL QUALITY, ENERGY USAGE AND OCCUPANT PERCEPTION IN COMMERCIAL OFFICE BUILDINGS

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ABSTRACT

A multi-disciplinary study to comprehensively measure and analyze operational performance and indoor environmental conditions in a sample of typical, commercial office buildings in the United States is described. The study will provide data that are currently not available. The indoor building factors that will be investigated during this study have never been formally studied in a comprehensive and systematic manner. No normative database currently exists for typical buildings making it impossible to correlate occupant indoor environmental response data to corresponding building design information and related measured microbiological and engineering data. These data are necessary to properly assess building performance.

KEYWORDS

Building performance, indoor environmental quality, normative database, perception questionnaire

BACKGROUND

There are significant gaps in knowledge relating to synergies between building energy performance, indoor environmental quality (IEQ) and building security. The National Center for Energy Management and Building Technologies ("National Center") was established in 2003 to fill these gaps (NEMI 2002). The first major task of the National Center was to develop methods and protocols to quickly and cost-effectively capture physical and operational data of existing buildings as they relate to energy performance and indoor environmental quality.

Past studies have generally focused on either issues related to energy consumption of buildings, building envelope measures and building systems improvements or on indoor air quality (IAQ) and the occupants' perception of their indoor environment. Most IAQ studies have dealt with IAQ deficiencies and their detrimental impact on the occupants. Thus, there exists a large knowledge gap with regard to what defines a typical building with acceptable indoor air quality and with acceptable energy performance.

This paper reports on a project to develop a database of typical commercial and institutional buildings. The database will contain measured environmental data that underwent rigorous statistical analyses based on numerous hypotheses, which are designed to confirm or dispute standard industry assumptions with regard to comfort and occupant perceptions of IEQ. Building characteristics and operational and energy usage data will be incorporated as well.

INTERGRATED BUILDING PERFORMANCE DATABASE

Table 1 summarizes the four major datasets that will be incorporated in the integrated building performance (IBP) database. Questionnaires will capture the occupants' perceptions of IEQ, building characteristics and asset valuation parameters commonly used by the investment community. The building characteristics questionnaire is derived from previous ASHRAE work (2004a). Utility bills will generally serve to extract energy consumption data. Aggregation of energy usage by major equipment components or major users of energy, such as office equipment, will not be performed unless that data are made available by the facilities operator. The IBP database will contain the measured IEQ parameters, the questionnaire data and the results of the analyses of biological measurements. Multiple statistical analyses will be conducted to determine relationships that exist between selected elements of the database.

TABLE 1
Data sources and collection methods

DATA SET	DATA CAPTURED	DATA SOURCE	COLLECTION METHOD
OCCUPANTS	• IEQ perception	▶ Occupants	▶ IEQ Perception Questionnaire
BUILDING	• Characteristics • Asset Valuation • Energy Usage	▶ Facilities Manager ▶ Building Owners ▶ Utility Bills, Metered Data	▶ Questionnaire ▶ Questionnaire ▶ Downloaded in the Data Base
HVAC SYSTEM	• Operational Data	▶ Building Automation System	▶ Downloaded in the Data Base
IEQ	• Temperature, humidity, draft • Mold • VOCs • Sound • Light • CO_2	▶ (6) Typical locations within the building	*All data recorded* ▶ (6) Vivo Sampling Carts ▶ Airborne and Surface Sampling ▶ Sensor ▶ (6) Sound Level Meters ▶ (4) Meters; Luminance, Illuminance, Chromaticity and Spectral Power ▶ Sensor

The IEQ perception questionnaire was derived from previous work done by ASHRAE (1988), CBE (2004), Nakano (2003) and Spagnolo (2003) and significantly expanded in each area, particularly as it concerns acoustics and light. The questions were designed to obtain sufficient data to verify or refute their underlying hypotheses. The hypotheses were derived from current standards (ASHRAE 2004b, ASHRAE 2004c) or recent work by other researchers (ASHRAE 1998, Beranek 1993, Bies 1997, Cena 2003, Fanger 1989, Leventhall 2003, Martin 2002, Pellerin 2004, Rea 2000, Schiller 1988, Schiller 1990, Westman 1981, Witterseh 2002, Yamazaki 1998, Yizai 2000). Each hypothesis is probed by one or more of the questions. The questionnaire is computer-based and is completed by occupants during the days of monitoring in the building where measurements are collected.

The questionnaire was reviewed and approved by the University of Nevada, Las Vegas Institutional Review Board, a United States federal government requirement.

MEASUREMENT PROTOCOLS

IEQ, light and sound measurements are conducted using standard industry procedures (ASHRAE 2004b, ISO 1989; ISO 1994) or established research protocols (Cena 2003, Chun 2004, Kaynakli 2005; Kosonen 2004, Ye 2003, Zhao 2004).

The IEQ comfort parameters (air temperature, operative temperature, air velocity, relative humidity) are recorded at six typical locations within the building. Each building is monitored for three days. The measurement locations remain unchanged from day to day. Vivo instrumentation carts (Dantec Dynamics, Skovlunde, Denmark) capture the IEQ comfort parameters as specified by ANSI/ASHRAE Standard 55-2004. All data are digitized at a periodic interval of three minutes for an eight-hour span. Depending on the type of sensor either two-level averaging or three-level averaging is performed.

The concentration of carbon dioxide (CO_2) is recorded using Hobo (Telaire, Goleta, California, USA) and Bacharach (New Kensington, Pennsylvania, USA) sensors at each of the six locations as well as outdoors. Volatile organic compounds (VOCs) are measured at the six indoor locations using the RAE Systems' IAQ monitor model IAQRAE 042-1211-012 with calibration kit (RAE Systems World Headquarters, Sunnyvale, California, USA).

Sound measurements are made with portable precision sound level meters (models 912, 947 and 948 manufactured by Svantek Ltd., Warszawa, Poland) at two locations in each monitoring area where the IEQ comfort parameters are being recorded. The measurement for each position spans enough time to capture continuous sound levels of the general background sound with no building occupants present and continuous sound levels over a typical workday.

Four different lighting parameters are captured at the same locations as the IEQ parameters. Illuminance is measured at the work surface and the computer monitors using the Illuminance Meter T10 (Konica Minolta, Tokyo, Japan). Luminance of wall, partitions and the floor is recorded by the Luminance Meter LS-100 (all by Konica Minolta, Tokyo, Japan). The color temperature is measured with the Chroma Meter CS-100A (Konica Minolta, Tokyo, Japan), and spectral power distributions are measured using the Lightspex from GretagMacbeth.

Microbiology samples are collected for culturable airborne fungi and total fungal spores, and surface-associated culturable fungi at the same locations where IEQ measurements are made. Each sampling procedure has specific protocols for collection and analysis (Buttner 2002, Macher 1999) summarized in Table 2.

TABLE 2
Microbiology samples and collection and analysis methods

SAMPLE	COLLECTION METHOD	SAMPLE SIZE	ANALYSIS METHOD
Culturable fungi	Andersen single-stage impactor sampler (Graseby Andersen, Atlanta, Georgia, USA) on malt extract agar (Difco Laboratories, Sparks, MD) amended with chloramphenicol (MEAC); decontaminated with an ethanol wipe between each sample location	28.3 liter/min. for 2 minutes (0.057 m^3 of air per sample)	macroscopic and microscopic morphology
Airborne fungal spores	Burkard personal impactor sampler (Burkard Manufacturing Co., Ltd., Rickmansworth Hertfordshire, England)	10 liters/min for 2 to 5 minutes (0.02-0.05 m^3 of air)	stained and viewed with light microscopy for the presence of recognizable fungal spores
Surface sampling for culturable fungi	vacuum sampling with an individual field filter cassette attached to a vacuum pump	dust amounts collected vary by surface loading/soiling	macroscopic and microscopic morphology

INITIAL RESULTS

Initial data obtained from three large commercial buildings located in Chicago, USA are validating the utility of the protocols selected.

Table 3 summarizes the preliminary results of the comfort data. The measured comfort data are within the acceptable range of operative temperature and relative humidity according to ANSI/ASHRAE Standard 55-2004. There also seems to be good agreement between the measured data and the occupants' perceptions of the indoor air quality. The comfort indices of Predicted Percentage Dissatisfied (PPD) and Predicted Mean Vote (PMV) also indicate acceptable comfort conditions.

All three buildings were well ventilated with indoor carbon dioxide concentrations ranging from 490 to 575 ppm. The differential to outdoor concentration was between 119 and 215 ppm, well below the requirement of ANSI/ASHRAE Standard 62.1-2004 of 700 ppm or less.

TABLE 3
Summary of preliminary analyses of comfort data for three large office buildings in Chicago

Building No.	Parameters	Temperature	Relative Humidity	Velocity	Mean Radiant Temperature	PPD	PMV	Vertical Temperature Difference	Indoor to Outdoor CO_2 Concentration Differential
	Unit	°C	%	m/s	°C			°C	ppm
	Comfort Range	20-24	<60	<0.25	20-24	<10	-0.5 -0.5	<3	<700
1	Mean	22.5	17.0	0.09	22.6	7.0	-0.29	0.30	119
	95% Confidence Interval for Mean	22.4-22.6	16.7-17.4	0.08-0.1	22.5-22.6	6.7-7.2	-0.31/-0.27	0.35-0.36	106-132
	Median	22.5	17.0	0.08	22.6	6.9	-0.30	0.20	104
	Standard Deviation	0.46	1.8	0.04	0.36	1.2	0.10	0.25	61.5
	Set Point	22.2±0.5	None	N/A	N/A	N/A	N/A	N/A	None
	Perception Survey Results	Slightly Cool	Slightly Dry	Slightly Drafty	Slightly Cool	14.4	-0.65	No draft felt	Fresh some of the time
2	Mean	22.3	37.2	0.08	22.6	5.7	-0.14	0.19	215
	95% Confidence Interval for Mean	22.3-22.4	35.1-39.2	0.08-0.09	22.5-22.7	5.5-5.8	-0.16/-0.11	0.17-0.21	197-233
	Median	22.4	39.0	0.08	22.8	5.1	-0.10	0.20	208
	Standard Deviation	0.32	9.7	0.03	0.47	0.8	0.12	0.10	85.7
	Set Point	22.2±0.5	None	N/A	N/A	N/A	N/A	N/A	None
	Perception Survey Results	Comfort	Slightly Dry	Comfort	Comfort	6.0	0.21	No draft felt	Fresh most of the time
3	Mean	23.3	37.2	0.06	23.3	5.5	0.06	0.23	212
	95% Confidence Interval for Mean	23.1-23.3	35.6-38.7	0.05-0.07	23.2-23.5	5.3-5.6	0.03-0.09	0.19-0.26	201-224
	Median	23.4	33.3	0.06	23.6	5.3	0.10	0.20	211
	Standard Deviation	0.53	7.4	0.03	0.59	0.6	0.14	0.19	53.5
	Set Point	23.0±0.5	None	N/A	N/A	N/A	N/A	N/A	None
	Perception Survey Results	Comfort	Comfort	Slightly Stagnant	Comfort	9.9	0.48	No draft felt	Fresh most of the time

The sound data demonstrate that the interior noise levels were very similar in all three buildings with ambient levels below 45 dBA, which would characterize these three buildings as being quiet.

The measured illuminance of work surfaces ranged from 675 to 710 Lux, thus being higher than the recommended design range of 300 to 500 Lux. These measurements correlate well to the occupants' perception of the brightness of their work surface with the vast majority of occupants indicating it as being bright. Similar results were obtained for the vertical illuminance of computer monitors, which ranged from 261 to 330 Lux, whereas the recommended value is 50 Lux for offices. All other lighting data (illuminance uniformity on the work surface; luminance of walls, partitions and the floor; correlated color temperature; and color rendering index) were within the recommended ranges for office environments.

Results of analyses of indoor airborne mold data indicate presence of fungal species in genus and concentrations reflective of the outdoors. Surface samples indicate similar composition.

Statistical evaluation of the data will be conducted when a larger data set is obtained. This evaluation will include comparison of data obtained during the three days of collection to determine if multiple sampling days are required or if a single collection day captures "average" values.

Comprehensive analyses of all data as well as associations between data and the hypotheses will be published at the end of this year in a report, which at that time may be downloaded from the National Center's website at www.ncembt.org.

FUTURE PLANS

The study described here is the first phase of a multi-year effort to obtain performance data from typical commercial and institutional buildings. The current phase will monitor ten office buildings in five locations in the United States. Plans are being made to study education buildings and healthcare facilities in the coming years. The IBP database has been designed to allow inclusion of data from other projects as well, and to be accessible online via web browsers. Once the current phase of this project is complete, the National Center will make the database available to other researchers to perform their own analyses.

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