Relationships:
Energy Usage
Indoor Environmental Quality
Occupant Perception and Health
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 provides data that are currently not available. The indoor building factors 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 are necessary to properly assess building performance.

This article describes the integrated building performance database, its development, and what and how data are collected and analyzed. The measured environmental data undergoes 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 indoor air quality (IAQ). The database further allows association of IAQ parameters with operational data and building asset information. The database will be made available online to

third party researchers to conduct their own analyses. Selected results from an initial monitoring of three office buildings are presented.

BACKGROUND

The National Center for Energy Management and Building Technologies ("national center") was established in 2003 to carry out research relating to synergies between building energy performance, indoor environmental quality, and building security. The mission of the national center is to identify and fill the synergistic gaps through research, technology assessments, and market analysis. In a second step, the resulting knowledge base is to transform the appropriate market segment through education, training, and public policy (NEMI 2002). To fulfill this mission, the first major task of the national center was to develop tools to quickly and cost-effectively capture physical and operational data of existing buildings as they relate to energy performance and indoor environmental quality.

There have been a number of studies related to energy consumption of buildings, building envelope measures, and building systems improvements. Others have focused on the indoor environment and the occupants' perception of the environment to identify whether statistical criteria of acceptable indoor air quality are met or not. However, none of these studies focused on what defines a typical building with acceptable indoor air quality and with acceptable energy performance, and how these relate to fundamental building asset valuations.

The objective of this project is to develop a normative database of buildings. The database will allow various hypotheses to be tested with regard to energy performance, indoor air quality parameters, and building occupants' perceptions of their indoor environment. Furthermore, the database will allow for correlating energy and indoor environmental performance with fundamental economic building asset parameters. This study is designed to:

- Develop an integrated building performance (IBP) database that contains data from typical commercial and institutional buildings.
- Establish an integrated building protocol for monitoring and surveying buildings in the United States.
- Develop and begin a long-term multidimensional study of buildings

under various design, construction and hand-off procedures, and climate zones.

INTEGRATED BUILDING PERFORMANCE (IBP) DATABASE

The IBP database consists of four major datasets with regard to the building, the occupants, HVAC system, and IEQ measurements. Table 1 summarizes the datasets and what and how data are collected.

Data about the building itself will be captured through questionnaires about the building characteristics and asset valuation parameters commonly used by the investment community.

Energy consumption data will be extracted from utility bills or energy monitors if present. There will be no attempts made to monitor or aggregate data by major equipment components or major users of energy, such as office equipment, unless those data are made available by the facilities operator. The building characteristics questionnaire is based on ASHRAE procedures (ASHRAE 2004).

The IBP database will contain the results of the engineering and biological measurements and the results of the questionnaires. Multiple statistical analyses will be conducted to determine relationships that exist between selected elements of the database.

The flow chart in Figure 1 illustrates the relationships that exist between the different elements within the database as well as the correlations that will be derived from the individual data sets.

OCCUPANT QUESTIONNAIRES

Questions were developed to obtain information from the building occupants regarding their perception of thermal comfort, ventilation, IAQ, lighting, and sound in their workspaces. These questions are completed by the occupants during the days of monitoring.

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 questionnaire is computer administered to volunteer occupants in the building where measurements are collected. The questions are designed to obtain sufficient data to verify or refute their underlying hypotheses. Some of the data are attribute-based that will be used to identify the characteristics of an environmental parameter, such as sound. For example, occupants are asked to give a specific attribute to the type of sound that annoys and distracts them, such as dominant tonal or harsh content in the noise, significant impact noise, significant power level fluctuations, or distracting intelligible content. Other questions are focused on lighting, temperature, feelings of draft, and stuffy/stagnant air. This level of detailed information on occupant response is not currently available for comparison to detailed quantitative engineering measurements.

Table 1. Data Sources and Collection Methods

Data Source	*Collection Method*
Occupants	
• IEQ perception	▸ IEQ Perception Questionnaire
Building	
• Characteristics	
▸ Facilities manager	▸ Questionnaire
• Asset Valuation	
▸ Building owners	▸ Questionnaire
• Energy Usage	
▸ Utility bills, metered data	▸ Downloaded in the database
HVAC System	
• Building Automation System or energy management system data	▸ Downloaded in the database
IEQ	*All data recorded*
• Temperature, humidity, draft	▸ (6) Vivo sampling carts
• Mold	▸ Airborne and surface sampling
• VOCs	▸ Sensor
• Sound	▸ (6) Sound level meters
• Light	▸ (3) Meters; 1 ea. for luminance, illuminance and chromaticity
• CO_2	▸ Sensor

The responses on the questionnaire are used to stratify the total set of positive responses (annoyed and distracted) into groups that are positive due to certain characteristics. For example, occupants that are annoyed and distracted by sound from air supply diffusers due to the sound increasing and decreasing in intensity. Multiple different groups can be formed based on which characteristics are grouped together. This qualitative grouping can be used in conjunction with quantitative data collected on the frequency of sound annoyance and interruption.

The questionnaire also has questions that are quantitative, giving the respondent several choices on a scale of increasing frequency of occurrence. The data from those responses can be quantified so that probability density functions, in the form of histograms, can be constructed for various sound, temperature, humidity, and lighting conditions in the work areas. Most of those questions use a four-point Likert scale:

❑ Rarely/Never ❑ Sometimes ❑ Often ❑ Most of the Time

Each response has an assigned value. The results are summated and appropriate statistical analyses performed. These include descriptive methods, such as determination of the mode and inter-quartile range, and plots showing the distribution of responses and inferential techniques, such as the Mann Whitney test, the Wilcoxon signed rank test, and the Kruskal Wallis test. Associations between two different sets of observations will be analyzed using a chi-squared test of association.

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

Hypotheses

Hypotheses were formulated for use in developing the occupants' IEQ perception questionnaire and are used in interpretation of the data. Each hypothesis is probed by one or more of the questions. The hypotheses were derived from current standards (ANSI/ASHRAE Standards 55 and 62) 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). It is anticipated that in the occupant perception survey some responses by dissatisfied occupants will

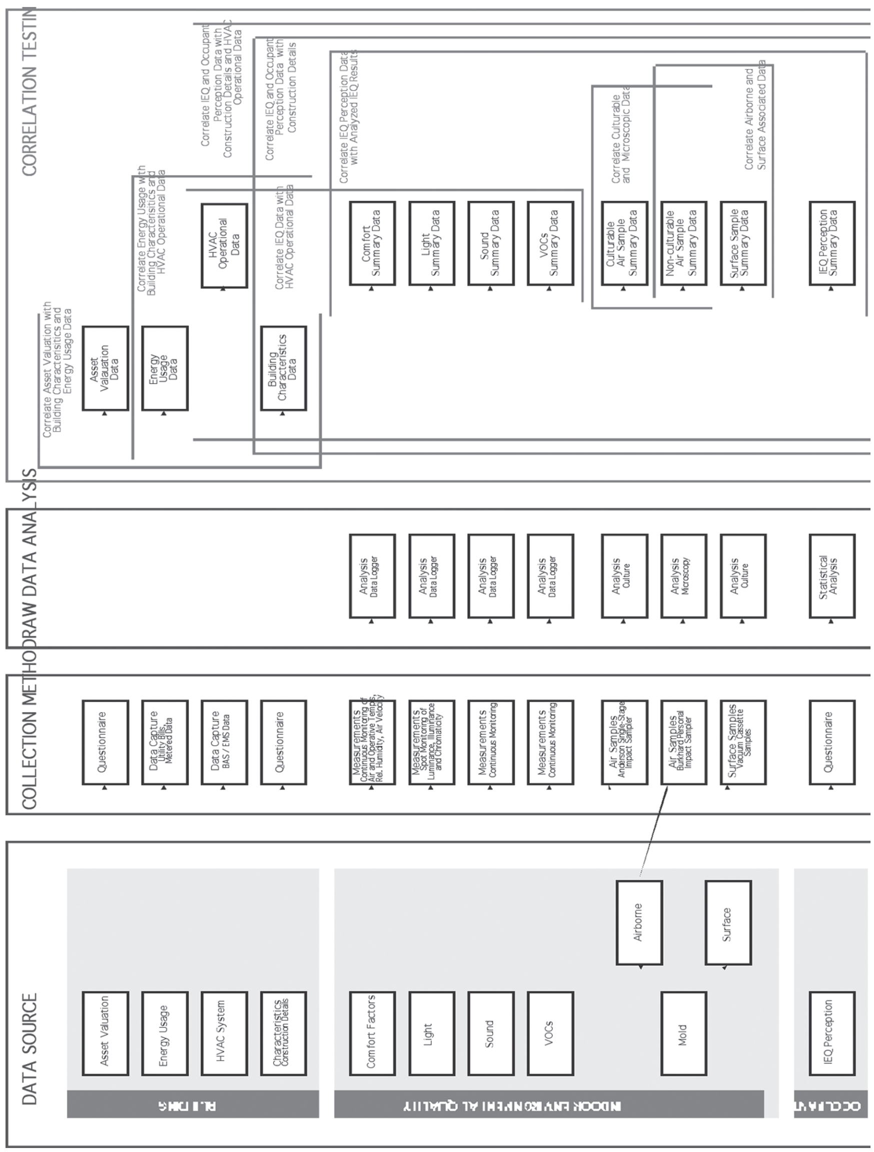

Figure 1. Elements of the IBP Database, Their Relationships and Correlations to be Derived.

show wider variations than that cited in available standards. Previous field studies suggest ranges for thermal comfort provided by ASHRAE Standard 55 have not captured the expected percentages of satisfied/dissatisfied people in those studies (Schiller 1988; Schiller 1990).

BUILDING SELECTION

Selection criteria were developed for use in screening buildings as sites for potential monitoring. The focus of this monitoring is to obtain data from typical buildings. The questions are designed to be answered by the building owner/operator. Important considerations in screening for typical buildings are building age, history of water intrusion or repair, repair or modification to the HVAC system, the number of floors, and the approximate number of occupants of the building during the work day. Additionally, complaints to management that focus on thermal comfort, upper respiratory symptoms, and headaches are included as indicators of conditions present in problem buildings.

MEASUREMENT PROTOCOLS

All protocols for IEQ measurements are based on current national and international standards (ANSI/ASHRAE Standard 55-2004; ISO 7726:1989; ISO 7730:1994) and recent literature (Cena 2003, Chun 2004, Fanger 2002, Feriadi 2004, Ghiabaklou 2003, Kaynakli 2005; Kosonen 2004, Nyuk 2004, Picot 2004, Ye 2003, Zhao 2004).

The IEQ comfort parameters (air temperature, operative temperature, air velocity, relative humidity) are recorded using six Vivo instrumentation carts (see Figure 2) (Dantec Dynamics, Skovlunde, Denmark). 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.

Table 2 summarizes all parameters to be measured or calculated for comfort. These parameters include air temperature, air velocity, relative humidity, operative temperature for the measured variables, and several indices (i.e., predicted mean vote [PMV], predicted percent dissatisfied [PPD] and draught risk or rate [DR]) that are calculated using the standard definitions of these indices in the literature. Air

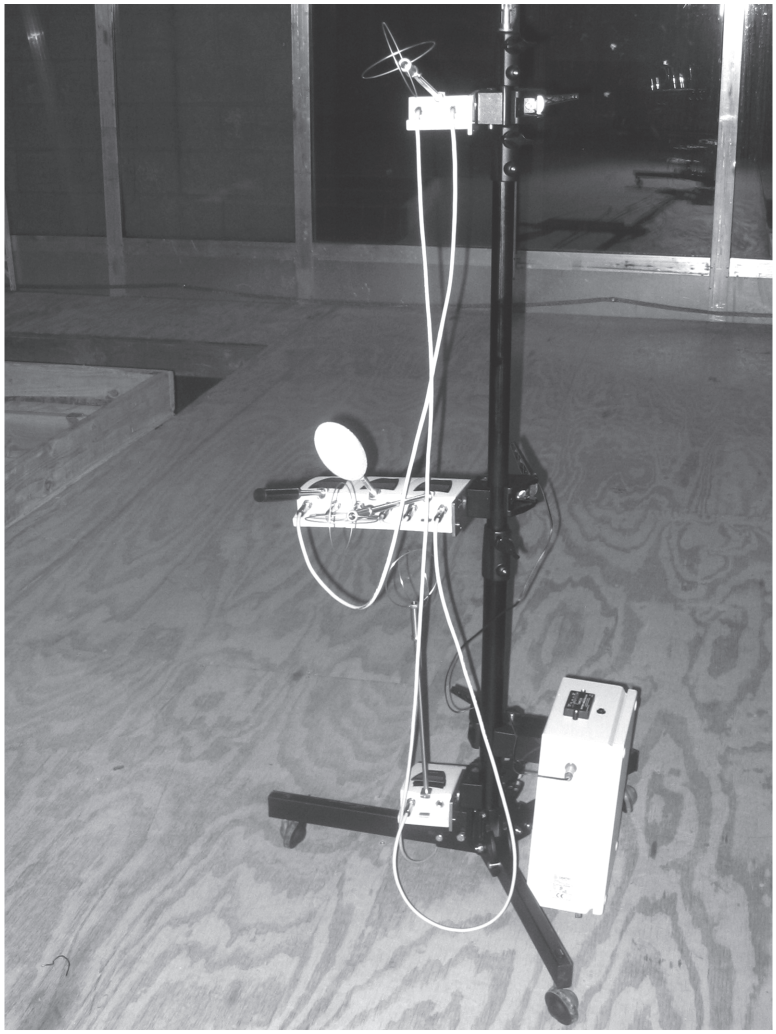

Figure 2. VIVO Instrumentation Cart for Measurement and Recording of Comfort Parameters.

temperature and air velocity are variables for global comfort and local comfort while relative humidity is a variable for global comfort.

ANSI/ASHRAE Standard 55-2004 specifies that air temperature, air speed, relative humidity, and the operative temperature are to be measured at heights of 0.1, 0.6, and 1.1 m (4, 24, and 43 in.) for sedentary occupants at locations where occupants are expected to spend their time. Standing activity measurements are made at 0.1, 1.1, and 1.7m (4, 43, and 67 in.) above floor level. The operative temperature is measured at 0.6 m (24 in.) for seated occupants and 1.1 m (43 in.) for standing occupants.

Microbiology samples are taken for culturable airborne fungi, airborne fungal spores, and surface-associated culturable fungi. Each sampling procedure has specific protocols for collection and analysis (Buttner 2002, Macher 1999).

Table 2. Summary of Comfort Parameter Measurements and Calculated Indices.

Height	*Sensors*	*Raw Data*	*Calculated Indices*
0.1 m	Vivo Draught	Air Temperature Air Velocity	PD/DR
0.6 m for sedentary occupants/ 1.1 m for standing occupants	Vivo Draught	Air Temperature Air Velocity	PD/DR (not necessary)
	Vivo Operative Temperature	Operative Temperature	PMV PPD ET* Radiant Temperature
	Vivo Humidity	Relative Humidity	Absolute Humidity
1.1 m for sedentary occupants/ 1.7 m for standing occupants	Vivo Draught	Air Temperature Air Velocity	PD/DR Vertical Air Temperature Difference[1] (may be ignored)

Air samples for culturable fungi are collected using the Andersen single-stage impactor sampler (Graseby Andersen, Atlanta, Georgia, USA) mounted on a mobile cart and operated at the manufacturer's recommended flow rate of 28.3 liter/min. for 2 minutes (0.057 m^3 of air per sample). Samples are collected onto malt extract agar (Difco Laboratories, Sparks, MD) amended with chloramphenicol (MEAC). The sampler is decontaminated with an ethanol wipe between each sample location. All agar plates are taped, bagged, and transported to the laboratory for incubation and analysis. Culturable fungi on the Andersen samples are identified using macroscopic and microscopic morphology.

Samples for airborne fungal spores are collected using the Burkard personal impactor sampler (Burkard Manufacturing Co., Ltd., Rickmansworth Hertfordshire, England) mounted on a mobile sampling cart and operated at the fixed flow rate of 10 liters/min. Samples are collected for 2 to 5 minutes (0.02-0.05 m^3 of air). The sampler is decontaminated with an ethanol wipe between each sample location. Burkard slides are transported to the laboratory for analysis where they are stained and viewed with light microscopy for the presence of recognizable fungal spores.

Surface sampling for culturable fungi is performed using vacuum sampling with an individual field filter cassette attached to a vacuum pump. Each cassette is labeled and placed in a plastic bag and transported to the laboratory. Surface samples are collected in close proximity to the location of the airborne samples.

Volatile organic compounds (VOCs) are measured using the RAE Systems' IAQ monitor model IAQRAE 042-1211-012 with calibration kit (RAE Systems World Headquarters, Sunnyvale, California, USA), and carbon dioxide (CO_2) is measured using Hobo (Telaire, Goleta, California, USA) and Bacharach (New Kensington, Pennsylvania, USA) sensors.

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 IAQ measurements are being collected. 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.

Lighting measurements are conducted at the same locations as the other parameters. Four meters are used: Illuminance Meter T10, Luminance Meter LS-100, and Chroma Meter CS-100A (all by Konica Minolta, Tokyo, Japan), and spectral power distributions are measured using the Lightspex from GretagMacbeth. Lighting has previously not been included in building monitoring, but lighting is an important energy usage component of buildings and the data obtained will be valuable in providing previously unavailable information on the quality of lighting in the occupied workplace. These data will also be correlated to occupant perception data obtained with the occupant perception questionnaire.

Each building is monitored for three days. The measurement locations remain unchanged from day to day.

INITIAL RESULTS

Initial data obtained from three large commercial buildings are validating the utility of the protocols selected. Each building is monitored for three consecutive days and the questionnaire is available for completion by the occupants over the course of the three days. Preliminary evaluation of the data suggests that the selected buildings do not have excessive data values outside of anticipated values. 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.

Table 3 summarizes the preliminary results of the comfort data for three large office buildings located in the Midwest. The data indicate that the measured 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 120 and 220 ppm, well below the requirement of ANSI/ASHRAE Standard 62.1-2004 of 700 ppm or less.

The measured lighting data (illuminance) ranging from 675 to 710 Lux was 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.

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

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

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. In addition to the commercial office building data obtained in this study, the national center will conduct field studies of other commercial and institutional buildings in the coming years investigating different aspects. Performance data from those projects will be incorporated in the IBP database.

The IBP database is designed 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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Table 3. Summary of Preliminary Analyses of Comfort Data for Three Large Office Buildings in the Midwest.

Bldg. No.	Parameters	Temperature	Relative Humidity	Velocity	Mean Radiant Temperature	PPD	PMV	Vertical Temperature Difference
	Unit	°F	%	fpm	°F			°F
	Comfort Range	67-79	<60	<50	67-79	<10	-0.5< PMV <0.5	<5.4
1	Mean	72.5	17	17.7	72.6	7	-0.29	0.17
	95% Confidence Interval for Mean	72.3-72.7	16.7-17.4	15.8-19.7	72.5-72.7	6.7-7.2	(-0.31)-(-0.27)	0.19-0.2
	Median	72.5	17	15.8	72.7	6.9	-0.3	0.11
	Standard Deviation	0.26	1.8	7.9	0.2	1.2	0.1	0.14
	Set Point	72±1	N/A	N/A	N/A	N/A	N/A	N/A
	Perception Survey Results	Slightly Cool	Slightly Dry	Slightly Drafty	Slightly Cool	14.4	-0.65	No Draft Felt
2	Mean	72.1	37.2	15.8	72.7	5.7	-0.14	0.11
	95% Confidence Interval for Mean	72.1-72.3	35.1-39.2	15.8-17.7	72.5-72.7	5.5-5.8	(-0.16)-(-0.11)	0.09-0.12
	Median	72.3	39	15.8	73	5.1	-0.1	0.11
	Standard Deviation	0.18	9.7	5.9	0.26	0.8	0.12	0.06
	Set Point	72±1	N/A	N/A	N/A	N/A	N/A	N/A
	Perception Survey Results	Comfortable	Slightly Dry	Comfortable	Comfortable	6	0.21	No Draft Felt
3	Mean	73.9	37.2	11.8	73.9	5.5	0.06	0.13
	95% Confidence Interval for Mean	73.6-73.9	35.6-38.7	9.8-13.8	73.9-74.3	5.3-5.6	0.03-0.09	0.19-0.26
	Median	1	33.3	11.8	74.5	5.3	0.1	0.11
	Standard Deviation	0.29	7.4	5.9	0.33	0.6	0.14	0.11
	Set Point	73.4±1	N/A	N/A	N/A	N/A	N/A	N/A
	Perception Survey Results	Comfortable	Comfortable	Slightly Stagnant	Comfortable	9.9	0.48	No Draft Felt

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At the national center, Mr. Novosel leads the development of technology strategy and manages the portfolio of multi-disciplinary R&D projects developing solutions to energy management, indoor environmental quality, and security concerns in new and existing buildings. He identifies strategically important technology projects and provides support and input to affect the successful development and deployment of such projects.

Prior to joining the national center, Mr. Novosel was a principal with the Chelsea Group, where he managed and executed IAQ investigation, remediation, and verification projects for a wide variety of commercial and institutional clients. He also assisted strategic consulting clients develop and market products, technologies, and services that improve the indoor environment.

In his professional career, Mr. Novosel held various technical and marketing positions with U.S. and European heating, ventilating, and air-conditioning companies.

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