POST OCCUPANCY EVALUATION INDOOR ENVIRONMENT QUALITY TOOLKIT :ENVIROBOT:

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Abstract

This EnviroBot is part of an Indoor Environment Quality Assessment toolkit that is used in the U.S. General Services Administration (GSA) "WorkPlace 2020" project. The goal of the project is to investigate the relationship of physical environment, building attributes and best practice workplace strategies to workers performance and organizational effectiveness. The toolkit has been beta-tested at more than 30 "WorkPlace 2020" project sites. The collected data are used as an environmental benchmark to capture baseline before and after thermal, visual, acoustic, air quality, and spatial quality in buildings. The data can be used to quantitatively prove the impact of sustainable strategies related to indoor environmental qualities on occupants' health, comfort and satisfaction. The development of easy to use, cost effective techniques for evaluating the actual thermal, acoustic, visual and air quality conditions in occupied buildings is crucial to ensure building performance and the effectiveness of sustainable strategies.

Keywords: Post Occupancy Evaluation (POE), Indoor Environmental Quality (IEQ) Assessment, sensor, environmental benchmark, thermal, air quality, acoustic, visual, spatial

1. Introduction and Motivation

Beginning in 2001, Public Building Service (PBS) assembled an interagency research team and retained recognized academic and private sector leaders to identify 'best practice' workplace strategies and the research tools holding the most promise for evaluating their effect. In 2002 PBS launched a program of applied research, "WorkPlace 20.20". This has become a cooperative research effort among US General Services Administration (GSA), Public Works and Government Services Canada, five major Universities (including the Center for Building Performance and Diagnostics at Carnegie Mellon University), and nearly a dozen leaders in the design and building products industries. The premise of the WorkPlace 20.20 program is PBS' acknowledgement that their ability to serve their customer is fundamentally linked to their ability to transform the workplace into a tool to support organizational performance. A focus of this research effort is the development of a set of building evaluation protocols linking environmental, technical and spatial quality to individual and organizational effectiveness - the National Environmental Assessment Toolkit.

A number of subjective evaluation techniques are needed to understand the effectiveness of the physical environment to support the changing nature of work and individual and organizational productivity, health and satisfaction. A range of tools are being developed by the larger GSA team, including collaboration/trust analysis, social network analysis, nature of work analysis, and user satisfaction questionnaires. The Center for Building Performance and Diagnostics at Carnegie Mellon University (CBPD) team has taken primary responsibility for the development and testing of an affordable, robust, and portable suite of instruments for thermal, air, and lighting quality field measurements. This effort has included the development of a National Environmental Assessment Toolkit (NEAT) cart for affordability, robust measurements and for portability; the refinement of a field sampling strategy and PC interface for affordability and robust measurements; the refinement of direct data entry from instruments into a database that includes other field measures; data mining for drawing baseline environmental assessment and automatic reporting; and the graphic presentation of all measures for comparisons and potential linkage to physical attributes.

The key thrust of the WorkPlace 20.20 program at CMU is the development of cost effective techniques for evaluating the actual thermal, acoustic, visual and air quality conditions in occupied buildings. Information acquired will be used to:

- Measure whether the performance specified in design documents and contractually guaranteed has been achieved
- Evaluate whether the whole building performance differs from sub-assembly performance
- Serve as a necessary first step in identifying whether the minimum IEQ standards establish an adequate threshold for occupant health and satisfaction
- Establish baseline data allowing the effect of environmental quality to be correlated with individual and organizational performance

NEAT, developed by CBPD, comprises the following tools: Envirobot, environmental instrumentation cart, 24-hr continuous measurement unit, eGIS[1] (PDA-based physical indicator recording), eSoft[1] (web-based online surveys), eDatabase[1] (web-accessible database, with graphing capability). Subjective questionnaire tools (EnviroQuest) as well as tools to capture the technical attributes of building systems (TABS) are used. This toolkit supports field data collection, web-based data download, storage and analysis. These tools are used to conduct indoor environmental quality assessments of buildings.

This paper provides an overview of the Envirobot.

2. The Current State of Practice

A number of standard setting organizations have established recommended levels of performance for certain building systems. GSA has incorporated many of these standards as policy and criteria in the document “The Facilities Standards for the Public Buildings Service (P-100-2003)”. These standards, however, lack the methods for verifying that the required level of performance is actually delivered in an occupied building. Moreover, there is little data correlating the physical criteria established by these standards with occupant satisfaction or organizational performance. Finally, these standards are applied independently in separate design and engineering documents, and therefore may not accurately predict the cumulative effect of the constituent sub-assembly’s contribution to whole-building performance.

Furthermore, buildings are constructed with the assumption that they will function as designed and will be operated as intended. Environmental quality measurements are necessary to validate the design intent and the proper operation of the facility. Off-the-shelf commercial environmental sensors vary in their ease of use, data-logging capabilities and cost. Some toolkits have been developed by other research institutions. A summary of some of these toolkits[2] studied is presented in Table 1.

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[1] ‘e’ here implies environmental

[2] AEC (ENFORMA & MDL): http://www.archenergy.com/aecproducts.htm
Casella CEL (Microtherm): http://www.casellausa.com/en/acrofiles/casella/microtherm_iaq.pdf
Berkeley Chair “Mark II”: http://arch.ced.berkeley.edu/resources/bldgsci/bsl/cart.html
Australian Chair “Sputnik”: Cena, Krzysztof and de Dear, Richard (1998)
Field study of occupant comfort and office thermal environments in a hot-arid climate, ASHRAE RP-921, December 1998
“Suitcase” by James Woods: The Building Diagnostics Research Institute, Inc., Bethesda, MD
NRC-CNRC Cope: http://irc.nrc-cnrc.gc.ca/ie/cope/02-3-Details_e.html

From this literature search it was concluded that no integrated sensor package that includes all 5-performance criteria of acoustic, visual, spatial, thermal, and air quality, is available on the market. The decision was made to purchase off-the-shelf sensors and dataloggers and integrate them as required for this project.

		AEC (ENFORMA & MDL)	Casella CEL (Microtherm)	Berkeley Chair "Mark II"	Australian Chair "Sputnik"	Suitcase (J.Woods)	NRC Chair	Dantec Vivo
								
Thermal	Air Temperature	X	X	X	X	X	X	X
	Relative Humidity	X	X	X	X	X	X	X
	Globe Temperature		X	X	X			
	Operative Temperature							
	Radiant Temperature Asymmetry			X	X			
	Air Velocity	X	X	X	X		X	X
	Turbulunce Intensity (calculated)				X			
	Draft Risk (calculated)			X	X			
	Dew Point Temperature			X	X			
	Wet Bulb Temperature		X					
IAQ	Carbon Dioxide		X	X		X	X	X
	Carbon Monoxide		X					
	Ozone		X					
	Particulates / Aerosols		X			X		
	Volatile Organic Compounds					X		X
	Air Flow	X						
	Ventilation Effectiveness							
	Mold							X
Visual	Light Level	X		X		X	X	X
	Light Intensity		X					
	Luminance							X
Acoustics	Sound Level		X	X		X	X	X
	Reverberation							
Data	Acquisition	X	X	X	X	X		X
Analysis	Software	X	X			X		

Table 1: A comparison of some toolkits

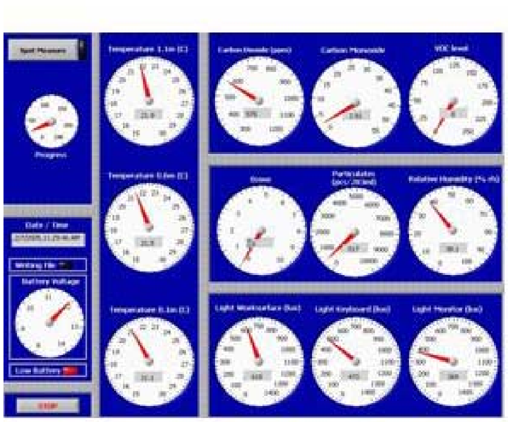
3. The Envirobot Development

The Envirobot (Fig. 1) is developed as an integrated sensor package to objectively capture indoor environmental quality of a space within a building. The current generation of the Envirobot includes sensors measuring air temperature at 3 heights, radiant surface temperature, relative humidity, carbon dioxide, carbon monoxide, volatile organic compounds, particulates, air velocity, light levels at 3 locations, sound

Fig. 1: From left, Generation 1 Envirobot, Generation 2 Envirobot, Generation 3 Envirobot, the Acoustic Cart

levels, and a photometric camera that analyzes brightness/contrast and glare. Attached to this cart are a data logger, a PDA, and a digital camera. This entire toolkit is designed to be packed and shipped in standard cases via air planes.

The development of the Envirobot involved multiple generations, each improved over the previous. The first generation Envirobot cart had mounting plates and telescopic poles attached to a walker to support the sensors, a photometric camera, a notebook computer and the portable dataloggers. The toolkit had a self-contained power supply (multiple batteries) and could be packed into two standard-sized travel suitcases for transport. In generation 2, a foldable luggage carrier was used as the base and OEM sensors were integrated to a notebook PC (Fig. 2) based data acquisition card. This version was easily maneuverable in the restricted space of offices and required about 15 minutes for assembly and disassembly. A sealed lead acid battery was used to extend the operation time of the computer.



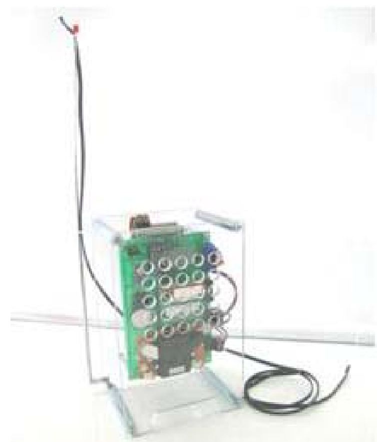


Fig. 2: From left, Generation 2 Envirobot interface, the 24 hour unit

The current generation of the Envirobot, generation 3, replaces the notebook computer with an embedded micro controller custom programmed by the CBPD. This controller has a removable flash memory card providing easy data transfer capability. This development allowed a substantial reduction in power requirements and allowed the replacement of the lead acid battery with a smaller lithium ion battery. A new, lighter camera for photometric analysis was integrated and the sensor suite was upgraded to improve accuracy and robustness. This version of the Envirobot requires less than 5 minutes for assembly and disassembly. A hand held sensor unit (HSU) (Fig. 3) was developed to measure light levels, radiant temperature and air velocity. The HSU communicates with the Envirobot via blue tooth. An acoustic cart was also developed and integrated into the toolkit. This cart includes a sound generator and power supply to measure acoustic qualities.

Fig. 3: From left, front view of HSU belt in operation, rear view of HSU belt in operation

Along with spot measurements using the Envirobot, stationary measurements of indoor air quality (IAQ) are recorded to establish base levels for the space being measured. The stationary unit (Fig. 2) measures 6”x9.5”x4.5” and uses an embedded micro-controller as a data logger. This unit is designed for long term (24 hours to 72 hour) IAQ measurements and is connected to a wall outlet. The sensing capability is designed the same as the Envirobot – air temperature at 3 different heights, relative humidity, carbon dioxide, carbon monoxide, volatile organic compounds, and particulates. Custom software for this unit has also been developed by the CBPD.

4. Operation Procedures and Sampling Strategy for the Toolkit

The protocol for sampling is as follows – the instrument cart is placed in the position of the occupant’s chair (Fig. 4) for approximately 15 minutes for each workstation sampled. For the first few minutes, the sensors are allowed to acclimatize to the environment in the workspace. Immediately thereafter, hand held readings of light levels (at 3 locations in the workstation), radiant temperature (2-4 locations), and air velocity (2 locations) are logged into the data logger. Then, automated sensor readings of temperature at three heights, relative humidity, and four air quality indices are taken over the next four minutes, at 15-second intervals, and averaged to obtain the final measurements in that workstation.

Fig. 4: The Envirobot being used to measure a space

During the time when the physical measurements are recorded in a workstation, the occupant is asked to complete the ‘User Satisfaction Questionnaire’ nearby. Finally, four digital pictures with a fish-eye lens are taken to capture brightness contrast. Conventional digital photographs are taken to record the workstation configuration and furniture as well as the primary worksurfaces. Environmental indicators revealing local control or modification of lighting, thermal, indoor air quality, acoustic, and spatial/ergonomic conditions are logged into a PDA with GIS identified locations.

For each floor or workgroup, approximately 20% of the occupied workstations are sampled. The workgroup is divided into spatial/environmental zones with a minimum of two sample workstations selected in each zone. These are based on several factors including:

- Distance from the building perimeter sampling – The work group is divided into perimeter zones (those workstations at the exterior wall or window), interior zones (occupants seated less than 20 feet from the window wall, but not at the window wall), and core zones (workstations more than 20 feet from a window wall).
- Orientation sampling – This sampling of three zones is then completed at each basic orientation of the occupied floor – north, south, east or west.
- Open versus closed office sampling – Within these three zones and four orientations, the number of open workstations and closed offices sampled reflects the proportion of these two types of workstations on the floor.
- Unique condition sampling – Based on information obtained about the idiosyncratic nature of the mechanical or lighting system, variations in work tasks, distributed equipment/service areas, or specific occupant concerns, additional samples are taken.
- Special function spaces sampling – Conference rooms and copy rooms are considered separately. Additional samples are taken for acoustic privacy in meeting rooms and closed offices as needed.

5. Results and Conclusions

The GSA WP20•20 project has now completed subjective questionnaires and field measurements at over 40 sites in 18 federal facilities allowing for cross site comparison (Fig. 5) of thermal, air quality, acoustic, and visual quality measures.

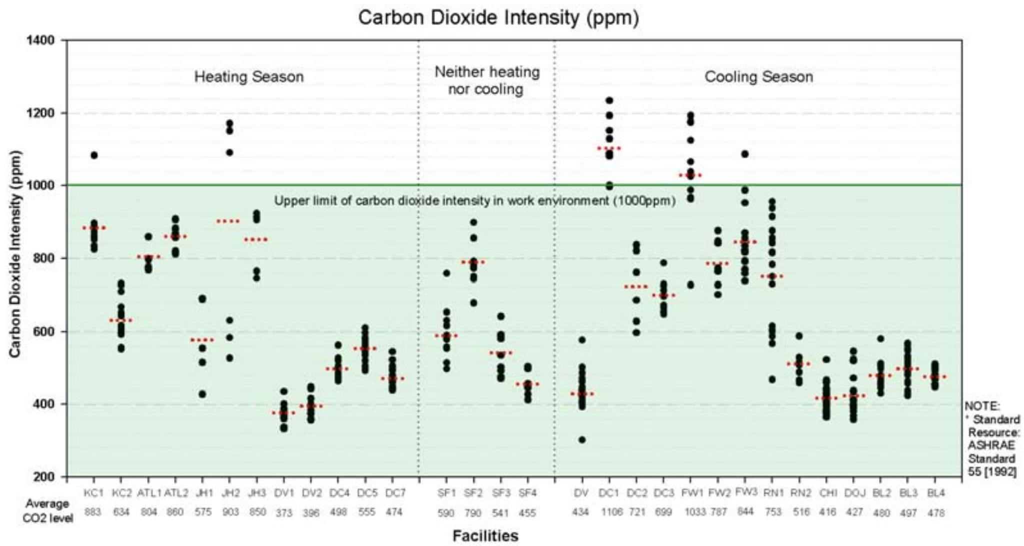


Fig. 5: An example of cross site comparison – a chart displaying carbon dioxide levels measured across multiple sites

A report has been prepared for each of the measured sites containing the following information:

- o Executive Summary: a briefing for decision makers, containing a synopsis of the physical measurements ("EKG's"), results from the User Satisfaction Survey, and recommendations for change;
- o Detailed Report: a comprehensive description of thermal, acoustic, visual, and air quality conditions, relevant spatial attributes and background information about the building's design, operation and systems; and
- o Appendices: data sheets that provide aggregated and raw toolkit data, photographs, floor plans, descriptions of test methods, specifications of toolkit instrumentation and complete User Satisfaction Survey results in a digital format.
- o

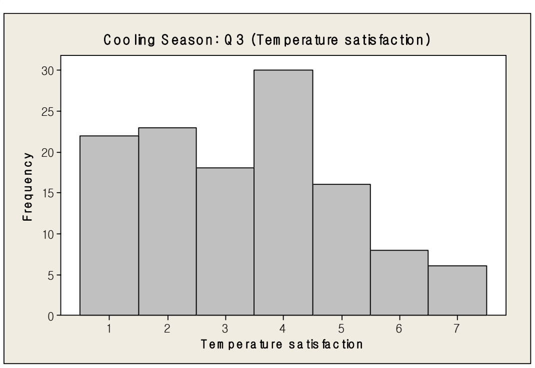


Fig. 6: A chart displaying occupant responses to the question "Satisfaction with Air Temperature (1..7)"

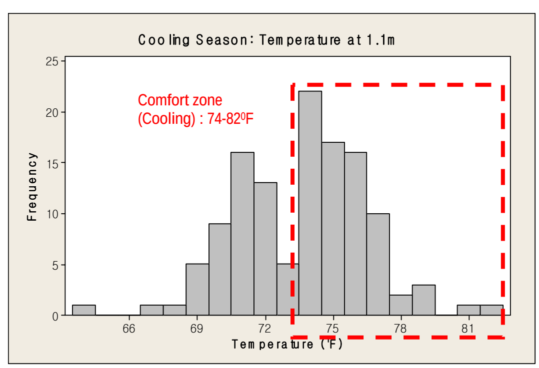


Fig. 7: A chart displaying air temperature measured at 1.1m

As an example of the analysis performed on the collected data, on average (mean = 3.50) it was found that a group of occupants were somewhat dissatisfied with the temperature (Fig. 6) during the cooling season with only 54% of the measured temperatures (Fig. 7) recorded within the ASHRAE recommended comfort range (74^0F – 82^0F). The average measured temperature at 1.1m during the cooling season was 73.61^0F and average relative humidity was recorded at 38%. During the cooling season, almost 40% of the occupants were very dissatisfied or dissatisfied with the temperature compared to 21% occupants during the heating season. Occupants have a tendency to be more satisfied with higher temperatures during the cooling season ($P = 0.099$). A conclusion therefore is that the buildings studied are typically overcooled during the summer months.

Thus, the toolkit developed by CBPD is capable of coordinating a range of subjective and objective measures relating physical attributes, environmental quality, user satisfaction, and organizational behavior. A range of output vehicles, key to the effective "diagnostics" linking the quality of the physical environment to subjective and objective assessments of quality and business goals are obtained through this toolkit. NEAT provides a path for the research community to coordinate baseline measures and methods of data collection towards creating an international database for comparative assessment of the role of real estate and facilities in individual and organizational effectiveness.

6. Future Developments and Applications

This toolkit is used to measure and analyze indoor environmental quality (IEQ) as well as a teaching tool in building diagnostics. The CBPD team continues to develop a database and an intuitive input and output interface for the range of physical attribute data sets, subjective/occupant measures and objective /expert measures collected in before and after productivity/workplace effectiveness studies. It is our objective to develop this toolkit into a robust commercial product for assessment of indoor environmental quality for use by Facilities Management staff, Building Commissioning Agents, and for use in Architecture/Building Engineering courses. Development work for the toolkit is underway such that automated data may be collected as described in the following scenario: the Envirobot is deployed in an office and programmed to independently navigate the facility, collecting IEQ data from office to office. Collected data are transmitted and downloaded into a central server and a report is automatically generated. The report contains baseline information (the current state of the facility) and recommendations if necessary. The development of such easy to use, cost effective techniques for evaluating the actual thermal, acoustic, visual and air quality conditions in occupied buildings is crucial to ensure that buildings are performing to their full potential.

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