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David Heinzerling\textsuperscript{a}, Tom Webster\textsuperscript{a}, Stefano Schiavon\textsuperscript{a}, George Anwar\textsuperscript{a}, Darryl Dickerhoff\textsuperscript{a,b}

\textsuperscript{a} Center for the Built Environment, University of California Berkeley, California, USA
\textsuperscript{b} Lawrence Berkeley National Laboratory, Berkeley, California, USA

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Indoor Environmental Quality (IEQ); IEQ model; Occupant satisfaction; Field measurements; POE; PMP
Abstract

Building Indoor Environmental Quality (IEQ) measurements are often complex, time consuming, expensive, and not easily proceduralized in a manner that covers all commercial building types, therefore evaluating IEQ is not standard practice. This paper presents a prototype toolkit that addresses existing barriers to widespread IEQ performance evaluation. A toolkit with both hardware and software elements was designed for practitioners around the IEQ requirements of the ASHRAE/CIBSE/USGBC Performance Measurement Protocols (PMP). This unique toolkit is built upon a wireless mesh network with a web-based data collection, analysis, and reporting application. The toolkit provides a fast, robust deployment of sensors, real-time data analysis, PMP-based analysis methods, and scorecard and report generation tools. A web-enabled GIS-based metadata collection system also reduces field-study deployment time. The toolkit was evaluated through three case studies, one of which is reported here.

1 Introduction

As standards and high performance building rating systems like LEED continue to push for better performing buildings, the need for evaluating performance beyond energy and water consumption has become increasingly relevant and pressing. Indoor environmental quality (IEQ) parameters (acoustics, indoor air quality, lighting, and thermal comfort) have strong influence over energy consumption, both through design related decisions and in the operation of the building [1,2]. Multiple studies have linked poor indoor air quality (IAQ) with sick-building-syndrome (SBS) [3–5]. There have also been multiple studies that have discussed the productivity gains associated with high IEQ, though this area of research is contentious and in need of additional studies [3,6–9]. Green building advocates also highlight the importance of IEQ in maintaining occupant comfort, suggesting that occupants represent the largest share of the operational costs of a building [10–13].

Guidance regarding indoor environmental quality measurements from the Performance Measurement Protocols (PMP) [14], the Performance Measurement Protocols: Best Practices Guide (BPG) [15], European standard EN15251 [16], and the REHVA Indoor Climate Quality Assessment guidebook [2] has given practitioners a collection of methods, procedures, and knowledge surrounding evaluation of building performance. However, the barriers to post-occupancy evaluations documented by Zimmerman and Martin [17]—lack of standard practice, presence of split incentives (between occupant (owner or lessee), designer, and contractor), a lack of standard indicators and benchmarks, and fear of liability—are largely still valid. There exists a strong need for both hardware and software tools that make implementation of these IEQ guides more feasible, including fast and robust deployment of sensors, real-time analysis of data, built-in PMP-based analysis methods and scorecard and report generation tools.

Previous studies have presented both hardware and software tools that have similar aims [18–21], though to the author’s knowledge none implement a completely wireless sensor network and a web-based analysis and reporting frontend with GIS-based metadata collection and retrieval. Additionally, there is currently a lack of guidance on how to summarize these IEQ evaluations for the purposes of whole-building IEQ benchmarking or rating systems. Overall evaluation of a building’s IEQ for the purposes of a case study report, a competition review, or rating system assessment requires rolling up sub-evaluations into a concise evaluation of performance. Such roll-ups are inherently subject to bias and interpretation, as both surveys and physical measurements offer a complex, interrelated picture of building performance. Many previous studies have offered methods for scoring IEQ performance [20–26] though none of these methods have been implemented in large-scale studies or evaluated outside of their own reports [27]. This study implements the method described in [22] and with modifications that are described in [27]. A critical literature review of the IEQ models is reported in [27].

This paper is divided into three main sections: (Section 2) Toolkit hardware outlines the prototype set of IEQ measurement tools that use a wireless mesh networking system; (Section 3) Toolkit software outlines
the open-source, web-based analysis and reporting tool for evaluating IEQ performance data; (Section 4) **Case study** presents the results of a case study that used the toolkit described in the first two sections; and then **Discussion** and **Conclusions**. The prototype toolkit described in this paper is named the CBE Building Performance Evaluation Toolkit (CBE stands for the Center for the Built Environment) and is hereon referred to as the “Toolkit.”

The aim of this paper is to present the aspects of the Toolkit that make it uniquely powerful and suited for evaluating IEQ performance in commercial buildings and provide examples through a case study.

## 2 Toolkit hardware

The hardware components of the Toolkit include a wireless mesh networking system, sensors, and custom devices designed to house multiple sensors. Usability and accuracy were the major objectives behind the Toolkit hardware design. Cost also played an important role, though costs were assumed to be high for a prototype design. The word “usability” masks a broad set of design parameters that together achieve an intuitive and usable system. The following sections will highlight where decisions were made to achieve greater usability within the target group of commissioning agents, mechanical/electrical/plumbing (MEP) consultants, and building operators. Table 1 provides an overview of the Toolkit instrumentation and cost based on off-the-shelf pricing in low volumes for a system including 20 Indoor Climate Monitors (ICMs – see section 2.2.1) and one underfloor air distribution commissioning cart (PUCC – see section 2.2.2).

Table 1: Toolkit instrumentation summary

<table>
<thead>
<tr>
<th>Basic Level</th>
<th>Sensor/Instrument</th>
<th>Accuracy (±)</th>
<th>Quantity</th>
<th>Cost (per sensor)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Acoustics</strong></td>
<td>Sound level meter</td>
<td>-</td>
<td>1</td>
<td>$1495</td>
</tr>
<tr>
<td><strong>Indoor Air Quality</strong></td>
<td>CO₂</td>
<td>30 ppm ± 3% measured value</td>
<td>20</td>
<td>$65</td>
</tr>
<tr>
<td><strong>Lighting/Daylighting</strong></td>
<td>Illuminance</td>
<td>5%</td>
<td>20</td>
<td>$440</td>
</tr>
<tr>
<td></td>
<td>Camera (HDR photography for luminance)</td>
<td>-</td>
<td>1</td>
<td>$200</td>
</tr>
<tr>
<td><strong>Thermal Comfort</strong></td>
<td>Infrared temperature (surface temperature)</td>
<td>2 °C or 1.5% of reading</td>
<td>2</td>
<td>$345</td>
</tr>
<tr>
<td></td>
<td>Thermistor (air and globe temperature)</td>
<td>0.056 °C</td>
<td>50</td>
<td>$9</td>
</tr>
<tr>
<td></td>
<td>Anemometer (air speed)</td>
<td>0.075 m/s</td>
<td>20</td>
<td>$385</td>
</tr>
<tr>
<td></td>
<td>Relative humidity</td>
<td>2%</td>
<td>20</td>
<td>$45</td>
</tr>
<tr>
<td></td>
<td>Differential pressure</td>
<td>1%</td>
<td>1</td>
<td>$273</td>
</tr>
<tr>
<td><strong>Wireless System</strong></td>
<td>Mote + IO Board</td>
<td>-</td>
<td>20</td>
<td>$650¹</td>
</tr>
<tr>
<td></td>
<td>Embedded computer</td>
<td>-</td>
<td>1</td>
<td>$1000</td>
</tr>
<tr>
<td></td>
<td>Tablet w/ 4G cellnet</td>
<td>-</td>
<td>1</td>
<td>$700</td>
</tr>
<tr>
<td></td>
<td>Wireless router</td>
<td>-</td>
<td>1</td>
<td>$200</td>
</tr>
</tbody>
</table>

¹ Custom manufactured, research level pricing
### 2.1 System architecture

A major challenge facing IEQ measurement lies in the connection of each of the required pieces. Traditionally, IEQ measurement consisted of using sensors/devices that independently stored measurements in on-board storage; thus, there was no connection between measurement devices. This lack of connection includes communication, power, and metadata relationships. These connections represent a major usability hurdle of tradition IEQ measurement. Advances in wireless technology have brought the price of wireless mesh sensor networks into a range viable for use in this field. Wireless mesh networks provide a communication connection between sensors and allow a single point of data storage. Figure 1 provides an overview of how system components link together to achieve this single data collection location.

At the building level, a set of sensors/devices is connected to wireless mesh nodes (also named motes) that transmit data to a local buffering database. This buffering database is connected to the Internet via either a building network connection or a cellular broadband connection. Data is sent through this Internet connection to an application server located outside of the building. Because the data is accessible through the Internet, data access is possible from inside and outside of the building network.

In addition to the set of sensors and devices in the Toolkit, an optional connection between the Building Management System (BMS) and the Internet can be made to facilitate read-access of BMS data from the same location as Toolkit data. Both the BMS and Toolkit data connections are made via a secure connection using the Simple Mapping and Actuation Profile (sMAP) [28] that is detailed in section 3.1. Drivers for Johnson Controls Metasys, Siemens Apogee, and Automated Logic Controls have been used successfully to import BMS data in real-time.
2.2 Toolkit devices

The Toolkit includes several single and multiple-sensor devices that simplify the process of collecting IEQ data in buildings. This section details the design and implementation of those devices.

2.2.1 Indoor Climate Monitor (ICM) – Indoor air quality, lighting, and thermal comfort

The Indoor Climate Monitor (ICM) is a wireless device that is capable of sensing PMP-suggested thermal comfort, lighting, and indoor air quality parameters (Figure 2). This device is designed to be placed on an occupant’s desk and to measure dry-bulb temperature, globe or split-globe temperature, air speed, relative humidity, horizontal illuminance, and CO₂ concentration. Continuous measurement of sound levels was not deemed necessary (or recommended in the PMP) and thus an acoustics meter was not included on the ICM. The ICM was developed as part of a previous research project involving occupant comfort in buildings with operable windows [29,30]. While the primary shells of the original ICMs were reused for the Toolkit, temperature and relative humidity sensors were replaced (for compatibility and increased accuracy), an illuminance sensor and a CO₂ sensor were added to the device, and all sensors were wired to a new wireless enabled input-output board.

The set of sensors chosen for the ICM represent a compromise in cost and accuracy, though all the sensors were chosen with accuracy and interchangeability as primary factors. The following three sections discuss the different hardware and applications that were developed for the ICM.
2.2.1.1 Thermal comfort sensors
The ICM measures dry-bulb temperature using a radiation-shielded thermistor. Both the globe temperature sensor and the dry-bulb temperature sensor use thermistors that are accurate to 0.1°C with 1% interchangeability. Each thermistor was calibrated using a refrigerated bath calibration unit while connected to the wireless input-output board that computes temperature based on a 10,000-ohm reference resistor. The details of the radiation shielding and ICM globe temperature sensor are available in Paliaga [29]. Additional theory behind the globe temperature sensors are available in [31,32]. Currently, operative temperature is computed as the average of mean-radiant temperature and dry-bulb temperatures.

2.2.1.2 Lighting sensor
The basic level of the PMP suggests measurements of horizontal illuminance in areas that were deemed problematic in an occupant survey. At the intermediate level, the PMP suggests full grid measurement of horizontal illuminance of a representative area of occupancy and luminance measurements of areas with potential glare problems. While a hand-held Licor illuminance meter may be used to obtain full-grid illuminance measurements as suggested by the PMP, such a procedure is impractical and overkill for the purposes of IEQ evaluation. The ICM is capable of measuring horizontal illuminance, but not luminance. The Toolkit uses HDR photography coupled with the lighting simulation program Radiance to evaluate luminance information, though analysis is not currently integrated with the web-based application discussed in section 3. Future implementations of the Toolkit web application aim to include luminance analysis methods similar to those provided by [33].

Horizontal illuminance is measured using a Licor Photometric sensor which has cosine correction and is accurate to ±5%. An amplification circuit was designed and built to convert the μA signal from the sensor into a 0-10V signal that the mote can interpret. The Licor sensors were compared against a recently calibrated Minolta T-1H illuminance meter which is accurate to ±2% to obtain calibration.

2.2.1.3 Indoor air quality sensor
Indoor air quality is the result of a complex interaction of hundreds of chemicals present in the indoor air. Accurate IAQ measurements are typically difficult and expensive. For typical commercial buildings that do not have specific outdoor air quality problems (PM$_{10}$, PM$_{2.5}$, ozone, or air-toxics non-attainment
problems), the primary method for managing IAQ is to guarantee an adequate outside airflow rate [34]. For this reason, the basic and intermediate levels of the PMP require verification of outdoor air flow rates to ensure compliance with ASHRAE Standard 62.1 [34]. The Toolkit deviates from the PMP and does not include a tool for the measurement and analysis of outdoor airflow rates, though such a tool could be added in the future. Methods for accurately measuring outdoor airflow rates can be expensive. CO₂ measurement was chosen as the parameter to indicate indoor air quality because of its prevalent use in buildings for demand-controlled ventilation and as an effective proxy for occupant generated pollutants. Both ASHRAE Standard 62.1 and the European Standard 15251 allow the control of outdoor airflow rate as a function of the CO₂ concentration [16,35]. Ozone, volatile organic compounds (VOCs), and particulate matter (PM₂.₅ and PM₁₀) were also considered, though reasonably priced sensors were deemed to be too inaccurate to provide valuable IAQ performance evaluation. The PMP suggests that CO₂ measurement is a highly inaccurate, but nevertheless potentially useful tool for diagnosing ventilation issues. Persily [36] provides details on the connection between CO₂ measurement and IAQ and how to appropriately interpret CO₂ measurement as an indicator of IAQ.

The ICMs provide the opportunity for making multiple local CO₂ measurements in one zone, whereas most buildings with CO₂ sensors have only one sensor per zone. A K-30 CO₂ module with 1% repeatability and 3% accuracy was selected for the ICM as a balance between accuracy and cost. The sensor uses the automated baseline calibration (ABC) method for self-correction. This method assumes that the lowest CO₂ measurement in a building will be 400 ppm (baseline outdoor level). The sensors were spot checked against an EGM-4 CO₂ sensor by PP Systems that has an accuracy of <1% and found to be within 50 ppm.

2.2.2 Portable UFAD Commissioning Cart (PUCC) – Advanced thermal comfort

The Portable UFAD Commissioning Cart (PUCC) was designed to be a portable and wireless alternative to a previously designed UFAD commissioning cart [37]. Underfloor air distribution (UFAD) is a type of air distribution system in which air is delivered in the occupied space from an underfloor plenum. The PUCC measures temperature at 0.1 m, 0.25 m, 0.6 m, 1.2 m, 1.7 m, and 0.1 m from the ceiling as well as floor and ceiling surface temperatures using infrared temperature sensors (IRTs). Underfloor plenum temperature and pressure are also measured. Figure 3 is a photograph of the PUCC.
2.2.3 Acoustics measurement
The Toolkit includes a Larson Davis LxT sound level pressure meter connected to a wireless mote. At the basic level, the PMP requires A-weighted sound pressure level measurements in representative spaces. At the intermediate level, the PMP requires octave band analysis to be performed by an acoustics consultant. The Toolkit deviates from the PMP in this regard and does not include a tool or analysis method for completing octave band analysis, though the LxT meter has the add-on capability if such analysis were deemed appropriate in the future.

3 Toolkit software
The Toolkit software consists of the data management backend and the analysis and visualization web frontend. The open-source code for this frontend is hosted at http://code.google.com/p/cbesmap. The documentation for the frontend is hosted at http://smap.cbe.berkeley.edu/static/doc/_build/html/.

3.1 Backend details
There are two backends that support the web frontend of the Toolkit: the Simple Mapping and Actuation Profile (sMAP) system and Django (PostgreSQL). sMAP handles the collection and retrieval of all time-series data. Django handles the relational aspects of the backend: metadata, users, groups, security, and project information. In the context of the Toolkit, metadata refers to descriptive data that is tied to the sensor data. Metadata is primarily composed of spatial and temporal information, but also includes other
information that is detailed later in this section. Django is a python-based web development framework designed for rapid development of database driven websites [38]. The Toolkit uses Django, coupled with a PostgreSQL database, to allow for simple python-based interaction with sMAP.

sMAP is a set of tools to enable simple and efficient exchange of time-series data through web-enabled applications [28]. sMAP has three major components which are shown in Figure 4.

Figure 4: sMAP components and data exchange paths [39]

1. Instrument drivers: A library of instrument drivers is available to enable the connection of devices to sMAP through HTTP. There are drivers for wireless devices, for BMS systems (Johnson Controls, Siemens, and Automated Logic Controls), weather services, power meters, and others. Additionally, new drivers are easily written in Python based on the existing example drivers.
2. Repository: The sMAP repository (Archiver) is a database system optimized for time series data (fast-retrieval, efficient compressible storage), including archival data. The repository also includes a querying language that allows simple retrieval and manipulation of data based on metadata filtering.
3. Web frontend: sMAP comes with an example web-frontend that is a full-featured trend viewer. This frontend example served as the model for the Toolkit frontend.

sMAP greatly simplifies the handling of time-series data. While a traditional relational database such as MySQL could be used to store sensor data, the query response times from such databases prevent quick in-field analyses of near-real time data. Additionally, sMAP’s pre-existing instrument drivers accelerate the process of combining disparate data sources into one database. The sMAP querying language is another powerful aspect of sMAP that allows fast retrieval of data based on user-defined metadata. This querying language also allows on-the-fly manipulation of data streams, allowing users to apply mathematical functions to streams of data (e.g. resample, average).

3.2 Frontend overview
The web frontend of the Toolkit is built on top of the backend using HTML and Javascript. The frontend is used for three main tasks: (1) toolkit setup and data collection procedure, (2) real-time analysis of data, and (3) scorecard and report generation.

3.2.1 Toolkit setup and data collection procedure
An overview of the toolkit setup and data collection procedure is provided in Figure 5.

**Figure 5: Overview of project setup**

The use of GIS-enabled floor plan maps is one of the key aspects of the Toolkit that makes it powerful and easy-to-use. Floor plan maps are generated using MapTiler [40] with the Olwidget framework for OpenLayers [41]. These tools allow users to draw zones (Figure 6) and specify testing locations on a GIS-enabled floor plan map (Figure 7), which is also used for data analysis.
Figure 6: Users can draw and edit zones on a GIS-enabled floor plan
3.2.2 Real-time analysis of data

The analysis capabilities of the web-based frontend are summarized in Table 2. All analyses are available on real-time data, helping users to catch instrumentation problems and arrive at actionable results faster, potentially shortening the data collection period. The data can be both temporally and spatially filtered to drill down into specific spaces or time-periods. Additionally, the user can aggregate data spatially to provide summary charts for spatial groups (e.g. orientation or space-type).

Table 2: Summary of frontend analysis capabilities

<table>
<thead>
<tr>
<th>Analysis method</th>
<th>IEQ categories</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trending</td>
<td>All</td>
<td>The trending application allows real-time trend analysis of any data stream.</td>
</tr>
<tr>
<td>Setpoint analysis</td>
<td>Thermal comfort</td>
<td>Setpoint analysis is designed to compare any two parameters, though typically it is used to assess how well a device is controlling to its setpoint, such as zone temperature compared to zone setpoint or air handler static pressure and static pressure setpoint. This particular analysis is most useful when BMS data are</td>
</tr>
</tbody>
</table>
available, though Toolkit device data can also be used. For example, this analysis could be used to check the accuracy of zone thermostats by comparing BMS thermostat readings to Toolkit readings of calibrated devices placed next to the thermostats.

<table>
<thead>
<tr>
<th>Comfort zone analysis</th>
<th>Thermal comfort</th>
</tr>
</thead>
<tbody>
<tr>
<td>The Toolkit comfort zone analysis webpage allows users to analyze the comfort data from the Toolkit Indoor Climate Monitors (ICMs). The setup for the comfort zone chart is similar to the setpoint analysis chart except instead of defining setpoint pairs, the user can choose to filter according to spatial parameters, such as orientation or zone type. Users have multiple chart types to choose from, including: relative humidity vs. operative temperature, CBE Thermal Comfort Tool for ASHRAE 55, time-series charts and map-based charts for PMV and operative temperature.</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Stratified systems analysis</th>
<th>Thermal comfort</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stratification refers to the increasing temperature gradient of the air in a space that is conditioned by a stratified system: an underfloor air distribution system (UFAD) or displacement ventilation system (DV). The Toolkit includes two analysis types for analyzing stratification data: room-air stratification and comfort zone analysis – stratification.</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Whole test-period analysis</th>
<th>Acoustics</th>
</tr>
</thead>
<tbody>
<tr>
<td>The whole test period analysis is used for short-term tests. There are three chart types to choose from: column, boxplot, and map. The column chart shows the average over the whole test period for each test that matches the filtering. The boxplot chart will take the length of the test and split it into 1-minute chunks which are then summarized as a boxplot. The map chart will show the mean value over the whole test period for the zone in which the measurement was taken colored according to a user-definable scale.</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Time-slices analysis</th>
<th>Lighting, IAQ</th>
</tr>
</thead>
<tbody>
<tr>
<td>The time slices analysis is used for long term tests and is dependent on the resample/average rate chosen by the user. For example, a user could look at hourly lighting values from an ICM with this analysis. There are three chart type options: line, boxplot, and map.</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Performance summary model analysis</th>
<th>All</th>
</tr>
</thead>
<tbody>
<tr>
<td>The performance summary model analysis is used to determine what percentage of measured values fall within certain classes. See [27] for more details.</td>
<td></td>
</tr>
</tbody>
</table>

### 3.2.3 Scorecard and report generation

One of the goals of the Toolkit frontend is to lead users to results simply and quickly. Quick access to results helps facilitate communication of performance results to decision-makers that can enact changes to address any performance concerns. The Toolkit scorecard and report generation features enable users to summarize and communicate performance results quickly. The scorecard is based on both subjective and objective measurements and is detailed in [27]. Report generation is a tool that pulls together user-saved analysis charts and places them in a PDF-exportable document that includes documentation on how the data were collected and tips on appropriate interpretation of the charts.

### 4 Case study

A case study was performed on a small section of a major office building complex in Los Angeles, California. The tenants of the space are an engineering consulting firm and partners in the study. The study was designed to test the Toolkit and obtain feedback on usability and operation. The characteristics of the studied space are:

- 2195 m² (23,633 ft²) gross floor area, 1 floor
- Underfloor air distribution system, with one section of chilled beams
- CO₂ demand-controlled ventilation

[https://escholarship.org/uc/item/7jh9h72t](https://escholarship.org/uc/item/7jh9h72t)
The case study results presented here are not meant to be exhaustive, but rather provide an overview of some of the features of the Toolkit. All figures are screenshots taken from the web-based software and are color-dependent. Refer to the online copy of the article for color figures. The method used for this case study (measurements and procedure) is summarized in Table 3.

Table 3: IEQ objective measurements methods with temporal and spatial measurement resolutions

<table>
<thead>
<tr>
<th></th>
<th>Spatial</th>
<th>Temporal</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Acoustics</strong></td>
<td>• Background noise level (dBA&lt;sub&gt;eq&lt;/sub&gt;): in representative zones, every 6 m x 6 m for large zones. In locations near noise sources (near HVAC equipment, operable windows near streets)</td>
<td>• Background noise level (dBA&lt;sub&gt;eq&lt;/sub&gt;): 30 second measurement periods</td>
</tr>
<tr>
<td><strong>IAQ</strong></td>
<td>• CO&lt;sub&gt;2&lt;/sub&gt;: in representative zones, capturing unique space types (conference room, open plan, private office, kitchen, lobby, etc.), multiple floors only if known source pollutant differences between floors (major occupancy differences, operable windows, off-gassing furniture)</td>
<td>• CO&lt;sub&gt;2&lt;/sub&gt;: continuous measurement</td>
</tr>
<tr>
<td><strong>Lighting</strong></td>
<td>• Illuminance: in representative spaces, capturing all unique space types, lighting types (direct, indirect, direct/indirect, task, skylight, window, etc.), and orientations (direction glazing faces)</td>
<td>• Illuminance: continuous measurement</td>
</tr>
<tr>
<td><strong>Thermal comfort</strong></td>
<td>• Air temperature, globe temperature, relative humidity, and air velocity: in representative zones, capturing unique space types (conference room, open plan, private office, kitchen, lobby, etc.)</td>
<td>• Air temperature, relative humidity, globe temperature, and air velocity: continuous measurement</td>
</tr>
</tbody>
</table>

Figure 8 shows the floor plan of the space divided into colored zones with the dots representing locations were measurements were taken and the type of measurement taken. There were 15 ICM devices placed, 13 PUCC measurements taken, and 8 sound-level measurements taken to provide good coverage of the office space.
4.1 Case study results

There are many ways to break down field study data into results that provide a meaningful and accurate evaluation of the space being studied. This section will start with the broadest measure of performance—an overall scorecard—and work down toward more specific results that highlight some of the underlying issues in the space. Figure 9 shows a screenshot of the scorecard webpage for the case study building.
Figure 9: Scorecard webpage for case study building

Scorecards, as described in [27], are useful for summarizing a large amount of performance data. They can also be useful for building a database to use for benchmarking. From the scorecard, we see both subjective (survey) and objective measurement results. A Center for the Built Environment Survey [42] was conducted with a 20% response rate (17 out of 85), which is lower than the typical 50% response rate that is normally considered representative of the occupants. The scores in the “Survey” column on the scorecard represent the percentage of satisfied respondents in the corresponding categories, which represents an aggregate of responses to multiple questions in each category. The scores in the “Survey Benchmark” column represent the percentile rating of the survey score within the CBE survey benchmarking database. Both the measured and survey scores from the scorecard in Figure 9 suggest that there is dissatisfaction with acoustics and potential issues with both thermal comfort and lighting.

The “measured” column scores represent the average of the percentage of collected data that fell within the constraints outlined for each category in the PMP across all space-types (e.g. private office, open plan, conference room, etc.). The overall score for the entire space is 50 out of 100 and is referred to as the Environmental Quality Index (EQI), which is computed using the method specified in [22]. The scorecard chart shows these objective measurement results graphically and split by space-type. The “Default and other space types” group represents all space types that do not specifically have a unique set of assessment conditions that they are evaluated against, so they are evaluated against the default set of conditions, which are summarized in Table 4. The “∗” symbol in Table 4 means that the condition is not different from the condition specified in the “Default” space-type row.
Table 4: Assessment conditions for objective measurements scorecard results (see [27] for more details)

<table>
<thead>
<tr>
<th>Space-type</th>
<th>Acoustics</th>
<th>IAQ</th>
<th>Lighting</th>
<th>Thermal Comfort</th>
</tr>
</thead>
<tbody>
<tr>
<td>Default (open plan office with intensive computer use and no sound masking)</td>
<td>dBA ≤ 40</td>
<td>CO₂ ≤ 700 ppm above outdoor CO₂</td>
<td>300 ≤ lx ≤ 2500</td>
<td>-0.5 ≤ PMV ≤ 0.5</td>
</tr>
<tr>
<td>Open plan office with intensive computer use and sound masking</td>
<td>dBA ≤ 45</td>
<td>“”</td>
<td>“”</td>
<td>“”</td>
</tr>
<tr>
<td>Open plan office with intermittent computer use and no sound masking</td>
<td>“”</td>
<td>“”</td>
<td>500 ≤ lx ≤ 2500</td>
<td>“”</td>
</tr>
<tr>
<td>Open plan office with intermittent computer use and sound masking</td>
<td>dBA ≤ 45</td>
<td>“”</td>
<td>“”</td>
<td>“”</td>
</tr>
<tr>
<td>Conference room - televideo conference</td>
<td>dBA ≤ 30</td>
<td>“”</td>
<td>“”</td>
<td>“”</td>
</tr>
<tr>
<td>Lobby / stairway</td>
<td>dBA ≤ 50</td>
<td>“”</td>
<td>100 ≤ lx ≤ 2500</td>
<td>“”</td>
</tr>
<tr>
<td>Private office</td>
<td>“”</td>
<td>“”</td>
<td>500 ≤ lx ≤ 2500</td>
<td>“”</td>
</tr>
</tbody>
</table>

From the scorecard we have a general idea of how the space is performing, but without further information it is difficult to interpret the specifics of the performance and what steps might be taken to improve performance. The subsequent sections will break down the different subjective and objective measurement scores and highlight lessons learned from the case study.

4.1.1 Acoustics

Acoustics is the first category that jumps out as low-performing, with 29% occupant satisfaction and a 20% objective measurement score. While correlating the objective and subjective scores is enticing, these scores represent different aspects of acoustical quality. The survey complaints relate primarily to speech privacy, whereas the objective measurements are only looking at background noise levels (see Figure 10). While the boxplot analysis of background noise level (dBA) provides a limited measure of acoustical performance, it is unable to predict the occupant dissatisfaction with speech privacy that drives their complaints (Boxplots are [minimum, 1st quartile, median, 3rd quartile, maximum]. Outliers are computed using 1.5 * interquartile range). Follow-up measurements of speech privacy using the procedure outlined in [43] could provide clues on how to best mitigate the speech privacy issues, though there are limited solutions in an open plan environment that already uses sound-masking.
4.1.2 Lighting

The lighting survey results (65% satisfied) suggest a medium level of dissatisfaction, though better than the objective measurement score (45) would suggest. The intent of the subjective and objective measures align better in lighting than in acoustics. The survey questions cover a broader range of concerns, including amount of light and sources of visual discomfort, than the objective measurement, which for this case study is solely illuminance (amount of light); however, the major source of dissatisfaction was amount of light. The written responses suggest that the desk-lighting strategy (there are no overhead lights in the office space) does not provide enough light for many tasks.

There were four ICM devices with illuminance meters that were placed on desks in the work-plane though not directly under the desk-mounted light. These devices continuously measured work-plane illuminance for the study period. The scorecard result shows that 45% of the measurements that were taken during operational hours (weekdays, 6:00 - 18:00) met the IESNA recommended illuminance level for an open office plan with intensive computer use (300 lx) [44]. The question of how much under this recommended light level the measurements were can be analyzed by looking at the underlying data. An “average-day time-series plot” is one Toolkit method for reducing a large quantity of data (e.g. continuous illuminance measurements from 4 locations over 2 weeks). This method divides daily data into hourly bins, then averages those bins across all days in the study period, resulting in an “average-day” of hourly illuminance levels (Figure 11). This chart allows users to select the IESNA recommended level, which is 300 lx in Figure 11, represented by the shaded portion of the chart. One device (ICM05) is more influenced by daylight levels in the space, though its maximum average illuminance level is still not very bright (600 lx). This chart shows that illuminance levels are quite low when daylight is not present, though a more detailed study would need to be conducted to determine the relative contributions of electric light and daylight (see Discussion section for further information).
4.1.3 Thermal comfort

The thermal comfort subjective (65% satisfied) and objective measurement (62) scores align well. The survey results do not offer a clear indication of reasons for dissatisfaction because of a small sample size. Thermal comfort is the only IEQ category with a widely used satisfaction model (Predicted Mean Vote-PMV and Predicted Percentage Dissatisfied-PPD). While there is disagreement concerning the applicability of the PMV/PPD model [45], it offers a good starting point for predicting occupant satisfaction with specific environmental conditions. The PMV/PPD is quite sensitive to changes in metabolic rate (met) and clothing levels (clo), which makes it difficult to apply the model accurately to a whole-building environment in which there are widely varying clothing insulation and metabolic levels. A web-based interactive comfort tool integrates with the Toolkit to provide a quick way of analyzing comfort data under a wide range of comfort parameter values [46]. Figure 12 shows average-day data for operational hours for all 12 ICMs that measured operative temperature and relative humidity. There are 13 points for each of the ICMs, totaling 156 points on the chart that summarize the thermal comfort conditions over the study period. The user can dynamically alter the position of the comfort range (blue shaded area) by changing any of the parameters on the left side of the screen or by clicking on a data point. It is important to note that because each data point has a different mean radiant temperature, the compliance boundary is different for each point, and thus changes each time a different data point is clicked. When a point is not clicked, the average of all the points (representing the average air temperature, mean radiant temperature, air speed, clothing level, metabolic rate, and relative humidity) is shown (the red point in Figure 12) along with the comfort boundary defined for that average point. The cluster of points on the cold side of the boundary is from a conference/training room conditioned with chilled beams. This space also stands out in the summary map of thermal comfort scores shown in Figure 13 as the room with the lowest score (9). In Figure 13, zones are colored according to the total percent of time the zone was in the comfort zone (with 1.1 met, 0.8 clo). The dots represent the ICM locations and users may click on a dot to get the score for that particular ICM.
Figure 12: ICM thermal comfort data plotted on psychrometric chart of thermal comfort tool
4.1.4 Indoor air quality

Both the objective and subjective measures indicate high indoor air quality. Acceptable indoor air quality is defined as air in which there are no known contaminants at harmful concentrations as determined by cognizant authorities and with which a substantial majority (80% or more) of the people exposed do not express dissatisfaction (From ASHRAE 62.1-2010). Perceived IAQ is capture by occupant assessment. The only objective measurement, CO₂ levels, is a proxy measurement for outdoor air flow rate and occupant generated pollutants. The limitations of IAQ subjective and objective measures are discussed further in the Discussion section.

5 Discussion

Indoor environmental quality has both subjective and objective dimensions. Satisfaction surveys are inexpensive and effective even if humans are not able to sense several dangerous physical parameters (e.g. radon or carbon monoxide) and do not always uncover potential problems or energy impacts (e.g. energy wasted by over-lighting or improper economizer operation). Objective measurements can help fill gaps in subjective assessment methods and pinpoint design, construction, and operational issues, though their use in summary scorecards require an understanding and clear communication of their limitations. Many of the scoring systems looked at in a literature review done for this topic [27] use subjective and objective measurements to evaluate IEQ performance but provide limited guidance on proper interpretation of the results obtained through an application of their systems. The intent of this paper is to present a novel IEQ data collection and analysis toolkit while also presenting a thorough discussion of its limitations and how to interpret the summary scorecard it provides.

5.1 Toolkit hardware and software

As a collection of off-the-shelf sensors connected to a wireless mesh system, the hardware prototype represents a system that could be improved in both cost and size while sacrificing some flexibility and accuracy. We have found the wireless mesh network model to work well within buildings and to be a good match for this type of temporary sensor deployment by being both unobtrusive and quickly...
deployed. As more applications move to the cloud, there is less reason to invest effort in standalone
desktop collection, storage, and analysis applications for building data. We have found that current open-
source web-platform software offers powerful capabilities for custom-built analysis, while also creating
opportunities for continued development through the open-source community.

We have found that compared to other field studies we have performed (e.g. [47,48]), the use of wireless
sensors and GIS-based metadata collection reduces the combined deployment and analysis time by at
least a factor of four. The sensors for this case study were completely deployed, actively sending data, and
capable of analysis within two hours of unpacking the Toolkit. The steps of retrieving, organizing and
aligning sensor data are removed through the Toolkit’s dual-database system (GIS-based metadata
corresponding to iMAP-based time series data). The steps of aggregating, charting, and analyzing the
data are considerably more efficient and greatly simplified through the use of the web-based analysis and
reporting application that is tailored to the PMP.

5.2 Objective/subjective measurement and corresponding scorecard
limitations

The PMP served as the primary guidebook for measurement types, techniques, and interpretation of
results. The PMP is an imperfect guidebook and there were many lessons learned during the project,
which are described in further detail in [49]. Kim provides a more extensive critique of the PMP,
highlighting many of the same issues we discovered [18,50]. Limitations, lessons learned, and comments
regarding the Toolkit measurements are broken down into IEQ categories below.

5.2.1 Acoustics

The Toolkit currently only measures background noise level (dBA) though future case studies plan to
employ the speech privacy method of [43]. Acoustical measurements are expensive and the links between
measured values of background noise, speech privacy, and reverberation time and occupant satisfaction
have not been well-established. We think that acoustical quality is best assessed by occupant satisfaction
surveys, with measurements used only in situations in which the problem is otherwise not easily
identified or understood. Thus, scorecard focus of acoustical performance should be on survey results
rather than objective measures.

5.2.2 Lighting

The case study described here only collected illuminance data, though future case studies plan to employ
HDR photography for capturing luminance data. Luminance data is key to understanding complaints
about glare. Light level is an important parameter to capture, though future measurement procedures need
to include methods for separating electric light from daylight. One way to estimate this separation is to do
manual tests of electric light during night time (at different brightness levels if dimmable fixtures are
installed). Unlike acoustics, in which objective measurements serve to support subjective findings,
lighting survey results do not necessarily capture all important lighting performance issues, such as over-
lighting or improper daylight control operation. Therefore, both objective and subjective measurements
are necessary to fully evaluate lighting performance.

5.2.3 Thermal comfort

The Toolkit measures all required parameters for estimating thermal comfort satisfaction except for
personal factors (clothing and metabolic rate), which can be estimated and recorded in the web-based
interface. The PMV/PPD method is quite sensitive to clothing level and metabolic rate and small
adjustments to these parameters can result in starkly different performance scores. For example, if most of
the data falls on the edge of the comfort zone, moving the comfort zone slightly could result in most of
the data falling outside of the comfort zone (and subsequently a significantly lower score). Ranges of
clothing and metabolic rate, forming overlapping comfort zones need to be more easily evaluated to
provide a more robust assessment of thermal comfort in the range of conditions that exist in a particular
space (especially differences in men/women clothing levels). Current work on the interactive thermal comfort tool [46] is focused on these enhancements.

5.2.4 **Indoor air quality**
The Toolkit currently only measures CO\(_2\) levels for estimating indoor air quality. Future case studies plan to measure outdoor air ventilation rate using differential pressure. Subjective assessment of IAQ only partially describes IAQ and is often conflated with thermal conditions (e.g., occupants tend to associate cool and dry conditions with high IAQ [51]). However, extensive IAQ objective measurement is high-cost with limited accuracy. Therefore, we believe that the PMP rightly focuses on verifying proper ventilation rates as the primary objective measurement of IAQ. However, outdoor air rates are difficult to measure accurately, though efforts are underway to develop a cheap tracer-gas method similar to ASTM Standard E741-11 [52]. Until measurements beyond CO\(_2\) are included in the Toolkit, interpretation of IAQ performance will remain very limited.

5.3 **Path toward commercialization**
Commercialization of a product is a complex task with many players. This section is not intended to serve as an exhaustive analysis of the feasibility of commercializing the Toolkit, but rather a short discussion of some of the immediate needs on a path toward commercialization. The primary driver toward commercialization is ensuring that features add value for the users. A primary barrier to IEQ measurement as standard practice has been unclear value for owners. With decreased hardware costs and labor costs associated with data collection and analysis, we feel that IEQ measurement systems such as the Toolkit have potential to generate market interest. Future work showing connections between occupant satisfaction with indoor environmental quality and productivity and retention rates would help drive market feasibility. Other avenues toward improving market feasibility include required IEQ monitoring in high performance building rating systems, as well as solutions that enhance the workflows of building operators and commissioning agents. To move toward these goals, the primary steps involve improving ease-of-use, reliability, and cost of the Toolkit. While the first two steps will happen as a result of increased use and further development from our group, the third step requires interest from a hardware manufacturer. We believe that ICM and PUCC wireless devices could be made at quantity for reasonable cost. Consulting firms interested in the Toolkit suggested that an overall price of $10,000 would be a reasonable investment for the purposes of IEQ performance evaluation. Given the rapidly falling price of wireless sensors, we feel that a system with 20 ICMs could be built within this budget if a limited number of anemometers and illuminance meters (the two most expensive sensors) were included. Borrow/rental programs like Pacific Gas and Energy’s tool lending library [53] could also be another feasible route for getting this type of system into the marketplace.

6 **Conclusions**
A toolkit with both hardware and software elements was designed for practitioners around the requirements of the Performance Measurement Protocols. This toolkit was evaluated through three case studies, one of which was reported here. The main conclusions of the work are:

- The wireless mesh network system creates a robust internet-connected series of low-power sensors and devices that are quickly deployed and provide real-time data immediately after deployment.
- The ease of deployment and built-in analysis and reporting methods allows practitioners to diagnose IEQ issues quickly and provide a summary of performance.
- The GIS-based web-enabled metadata collection system combined with PMP-based analysis and reporting reduced deployment and analysis time by at least a factor of four for our projects.
- The open-source application platform can be used by anyone and improved by the community or adapted to other uses.
• The decreasing cost of wireless equipment and sensors, as well as the significantly reduced labor costs of quick deployment and analysis makes such systems cost-feasible even at relatively small economies of scale.
• A path toward commercialization could be viable with hardware manufacturing support and support from building rating systems and relevant standards.

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