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A Prototype Toolkit For Evaluating Indoor Environmental Quality In Commercial Buildings

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A PROTOTYPE TOOLKIT FOR EVALUATING INDOOR ENVIRONMENTAL QUALITY IN COMMERCIAL BUILDINGS

Prepared for: California Energy Commission
Prepared by: Center for the Built Environment

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CENTER FOR THE BUILT ENVIRONMENT

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PREFACE

The California Energy Commission Energy Research and Development Division supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

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A Prototype Toolkit For Evaluating Indoor Environmental Quality In Commercial Buildings is the final report for the Wireless Measurement Tools for a Better Indoor Environment project (contract number 500-10-048-6) conducted by Center for the Built Environment. The information from this project contributes to Energy Research and Development Division's Buildings End-Use Energy Efficiency Program.

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ABSTRACT

Measurement of building environmental parameters is often complex, expensive, and not easily proceduralized in a manner that covers all commercial buildings. Evaluating building indoor environmental quality performance is therefore not standard practice. This project developed a prototype toolkit that addressed existing barriers to widespread indoor environmental quality performance evaluation. A toolkit with both hardware and software elements was designed for practitioners around the indoor environmental quality requirements of the American Society of Heating, Refrigeration and Air Conditioning Engineers / Chartered Institution of Building Services / United States Green Building Council Performance Measurement Protocols. This unique toolkit was built on a wireless mesh network with a web-based data collection, analysis, and reporting application. The toolkit provided a fast, robust deployment of sensors, real-time data analysis, Performance Measurement Protocol-based analysis methods and a scorecard and report generation tools. A web-enabled Geographic Information System-based metadata collection system also reduced field-study deployment time. The toolkit was evaluated through three case studies, which were discussed in this report.

Keywords: Indoor Environmental Quality (IEQ); IEQ model; Occupant satisfaction; Acoustics; Field measurements; Indoor Air Quality (IAQ); Lighting; Thermal comfort

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

EXECUTIVE SUMMARY

Introduction

Conducting measurements in a systematic way is critical to understanding the energy and comfort performance of existing buildings and it is especially important in demonstrating the potential of modern low-energy and net-zero buildings. The need for evaluating performance beyond energy and water consumption has become increasingly relevant and pressing as standards and high performance building rating systems like Leadership in Energy and Environmental Design continue to push for better performing buildings. Indoor environmental quality parameters have a strong influence on energy consumption, both through design-related decisions and in the operation of the building. Setting energy benchmarks without corresponding indoor environmental quality benchmarks is shortsighted. The comfort of the occupants and their satisfaction with the indoor environmental quality should not be overlooked when the focus is on developing low-energy buildings.

Recent guidance exists regarding indoor environmental quality measurements from the Performance Measurement Protocol (American Society of Heating, Refrigeration and Air Conditioning Engineers / Chartered Institution of Building Services / United States Green Building Council, 2010), but there is limited guidance on how to perform all of these measurements to a satisfactory level within a constrained timeframe and budget. Additionally, there is currently a lack of guidance on how to summarize these indoor environmental quality evaluations for the purposes of benchmarking or rating systems. Overall evaluation of a building's indoor environmental quality for the purposes of a case study report, a competition review or a rating system review requires rolling up sub-evaluations into a concise performance evaluation. Such roll-ups are inherently subject to bias and interpretation, as both surveys and physical measurements offer a complex, interrelated picture of building performance.

Project Purpose

The goal of this project was to address the need for better methods and tools for evaluating building performance by accomplishing the following objectives:

1. Developing a hardware and software toolkit for facilitating the evaluation of indoor environmental quality performance in commercial buildings based on the American Society of Heating, Refrigeration and Air Conditioning Engineers/Chartered Institution of Building Services/United States Green Building Council Performance Measurement Protocol.
2. Evaluating the success of the toolkit through three case studies.
3. Exploring indoor environmental quality models as a method for rating indoor environmental quality performance.
4. Investigating paths to commercialization.

Researchers intended that the toolkit would simplify the process of building performance evaluation by tying together the multiple pieces needed to appropriately evaluate performance. Researchers hoped the toolkit would be a prototype for future cost-effective, commercially available toolkits. They planned to evaluate the tookit's success through three case studies that provided feedback on toolkit procedures and features from practitioners.

This project also aimed to provide critical feedback on the Performance Measurement Protocol in an effort to widen the appeal of indoor environmental quality evaluation to current practitioners and other potential interested parties such as Leadership in Energy and Environmental Design (LEED).

Project Results

A successful prototype toolkit (henceforth referred to as the Toolkit) was developed with both hardware and software components. The Toolkit hardware was designed to be easy to use, accurate and reliable. The wireless mesh network system was the key component to making sensor deployment and data collection fast. The density of wireless devices does not need to be high in an open plan office because there is little radio frequency interference. The density of devices required to maintain a robust network in a more challenging environment tended to align with the density of sensors that would be ideal for achieving good spatial coverage for performance measurement.

The indoor climate monitors in their prototype form proved the efficacy of a wireless universal multi-sensor platform. A wealth of data could be collected by configuring a set of monitors that combined covered the range of the six types of measurements necessary for indoor environmental quality assessment, even though the monitors were limited to four channels each. An advanced sensor platform was developed that supported up to eight sensors but was not completed in time for deployment in the case studies. These will be integrated into the indoor climate monitors by the Center for the Built Environment during ongoing support for Toolkit development.

Cost was the primary downside of using wireless sensors. Wireless sensors have come down in cost considerably in the past few years and traditional logger companies like Onset were offering wireless versions of their sensors. Onset's wireless sensors came at a premium of approximately $100 over their logging counterparts. Solutions with combined sensors on one wireless device were ideal and a four-channel wireless device from Onset was $220 at the time this report was written. That cost represented a reasonably priced solution for a building indoor climate monitor or Portable Underfloor Air Distribution Commissioning Cart devices ("Wireless HOBO Data Loggers & Sensors: ZW Series by Onset," n.d.). It seemed likely that these wireless devices could be made at quantity for reasonable cost. Consulting firms interested in the Toolkit suggested that an overall price of $10,000 was a reasonable target. A system with 20 indoor climate monitors could be built within this budget through a mixture of design/sensor changes and economies of scale.

The procedures involved in the Toolkit deployment were largely successful at reducing deployment overhead. All metadata was captured in the database and metadata/data relationships could be used during the analysis phase from defining device-related metadata (data describing data) at the time of deployment. The metadata must be recorded when the logger was placed in a traditional logging system and then it was associated with the specific file that was later downloaded from the device. This procedure generally took the form of a network of Excel or comma separated value files that must be assembled into one database, which could take a considerable amount of time. The web-enabled Geographic Information System/map-based metadata collection scheme of the Toolkit allowed users to input metadata digitally in a manner that was faster and more accurate than paper-based map/grid solutions.

The Toolkit web analysis and reporting components were designed to minimize the time it took to reach conclusions from data analysis. The Toolkit succeeded in providing a framework for quick analysis through a standardized method of retrieving, filtering and charting data. The Toolkit framework (including map-based metadata) decreased overall deployment and analysis time by at least an estimated factor of five compared to previous Center for the Built Environment projects. The implementation of scorecard summaries helped practitioners arrive at a conclusion more quickly.

The Toolkit was deployed and tested in three case studies in office buildings in California. Each case study led to improvements in both the hardware and software components of the Toolkit. Building performance issues discovered using the Toolkit are summarized below for each building.

WSP Flack + Kurtz Building:

- Daylight sensors did not seem to be working properly.
- Occupancy sensors and timers needed tuning.
- Temperature within the open plan office space was on the low end of the comfort range, resulting in cold complaints from occupants.
- Sound levels were high in the open plan area, leading to complaints from occupants.

Syska Hennessy Building:

- Lighting levels were low, which contributed to occupant complaints. The building did not have overhead lighting.
- Thermal comfort was largely maintained, although one chilled beam room was nearly always too cold according to the American Society of Heating, Refrigerating and Air Conditioning Engineers Standard 55.
- Sound levels were high, but occupant complaints focused on speech privacy rather than background noise.

199 Fremont Building:

- Sound levels were within the recommended limits during off-hours but some occupants still complained of heating, ventilating and air-conditioning related noise.
- Occupants complained of speech privacy acoustical issues.
- Occupants complained of poor indoor air quality, although measured carbon dioxide data suggested that there was not a major outdoor air intake problem. There could be other indoor air quality issues that the instrumentation did not measure.
- Lighting levels were within the recommended range although some occupants expressed dissatisfaction with visual comfort.

- Thermal comfort was largely maintained although setpoints varied widely and many zones had setpoints that were too cold according to the American Society of Heating, Refrigerating and Air Conditioning Engineers Standard 55. Occupants directly adjacent to windows may need personal fans to maintain comfortable conditions with high solar exposure.

Many of these issues were common and could be remedied with tuning. Acoustical changes tended to be more complex and expensive, often requiring the installation of acoustical panels or a sound masking system.

Project Benefits

This project developed a toolkit for evaluating indoor environmental quality performance in commercial buildings based on the American Society of Heating, Refrigeration and Air Conditioning Engineers/Chartered Institution of Building Services/United States Green Building Council Performance Measurement Protocol. The Toolkit was deployed and tested in three case studies in office buildings in California and proved to be effective. If the Toolkit was deployed more widely it could result in the diagnosis of indoor air quality issues and potentially could result in improved air quality in office buildings.

CHAPTER 1: Introduction

As standards and high performance building rating systems like Leadership in Energy and Environmental Design (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 (Olesen, 2012; REHVA (Representatives of the European Heating and Ventilation Association), 2011). Multiple studies have linked poor indoor air quality (IAQ) with sick-building-syndrome (SBS) (Fisk, 2000; Jones, 1999; Pawel Wargocki, Wyon, Sundell, Clausen, & Fanger, 2000). 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 (Fisk, 2000; M A Humphreys & Nicol, 2007; Leaman & Bordass, 2007; Lorsch & Abdou, 1994; Singh, Syal, Grady, & Korkmaz, 2010). Green building advocates also highlight the importance of IEQ in maintaining occupant comfort, suggesting that occupants (i.e., employee costs) represent the largest share of the operational costs of a building (Kats, Alevantis, Berman, Mills, & Perlman, 2003; Pyke, McMahon, & Dietsche, 2010; P Wargocki & Seppänen, 2006; Wilson, 2004).

Recent guidance regarding IEQ measurements from the Performance Measurement Protocol (PMP) (ASHRAE/CIBSE/USGBC (American Society of Heating, Refrigeration and Air Conditioning Engineers / Chartered Institution of Building Services / United States Green Building Council, 2010), the Performance Measurement Protocols: Best Practices Guide (BPG) (ASHRAE, 2012) , European standard EN15251 (CEN, 2007), and the REHVA Indoor Climate Quality Assessment guidebook (REHVA, 2011) 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 (Zimmerman & Martin, 2001)—lack of standard practice, presence of split incentives (between owner, designer, and contractor), a lack of standard indicators and benchmarks, and fear of liability—are largely still valid today. There exists a strong need for both hardware and software tools that make implementation of these IEQ guides more feasible, including:

- fast, robust deployment of sensors
- real-time analysis of data
- built-in PMP-based analysis methods
- scorecard and report generation tools

Previous studies have presented both hardware and software tools that have similar aims (Cao et al., 2012; Chiang, Chou, Lai, & Li, 2001; Choi, Loftness, & Aziz, 2012; Kim & Haberl, 2012), though none implement a completely wireless sensor network and a web-based analysis and reporting frontend with Geographic Information System (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 review 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 (Cao et al., 2012; Chiang et al., 2001; Chiang & Lai, 2002; Lai, Mui, Wong, & Law, 2009; Marino, Nucara, & Pietrafesa, 2012; Ncube & Riffat, 2012; Wong, Mui, & Hui, 2008) though none of these methods have been implemented in large-scale studies or evaluated outside of their own reports (Heinzerling, Schiavon, Webster, & Arens, 2013). This study implements the method described in (Marino et al., 2012) and with modifications that are described in (Heinzerling et al., 2013). A critical literature review of the IEQ models is reported in (Heinzerling et al., 2013).

This report is divided into three main chapters: (Chapter 2) *Toolkit hardware* outlines a prototype set of IEQ measurement tools that use a wireless mesh networking system; (Chapter 3) *Toolkit software* outlines an open-source, web-based analysis and reporting tool for evaluating IEQ performance data; (Chapter 4) *Case studies* presents the results of three case studies that used the toolkit described in the first two chapters; and then *Discussion* and *Conclusions*. The prototype toolkit described in this paper is here on referred to as the "Toolkit."

The aim of this report 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 case studies.

CHAPTER 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 research based 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 (unless otherwise noted) for a system including 20 Indoor Climate Monitors (ICMs – see section 2.2.1) and one Portable Underfloor Air Distribution Commissioning Cart (PUCC – see section 2.2.2).

Table 1: Toolkit Instrumentation Summary

Basic Level	Sensor/Instrument	Accuracy (±)	Quantity	Cost (per sensor)
Acoustics	Sound level meter	-	1	$1495
Indoor Air Quality	CO_2	30 ppm + 3% measured value	20	$65
Lighting/Daylighting	Illuminance	5%	20	$440
Thermal Comfort	Infrared temperature (surface temperature)	2 ˚C or 1.5% of reading	2	$345
	Thermistor (air and globe temperature)	0.056 ˚C	50	$9
	Anemometer (air speed)	0.075 m/s	20	$385
	Relative humidity	2%	20	$45
	Differential pressure	1%	1	$273
Wireless System	Mote + IO Board	-	20	$650[1]
	Embedded computer	-	1	$1000
	Tablet w/ 4G cellnet	-	1	$700

[1] Research level pricing at low volume

Basic Level	Sensor/Instrument	Accuracy (±)	Quantity	Cost (per sensor)
	Wireless router	-	1	$200
Total Cost (as implemented in the project described herein)				$36,508

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 IEQ measurement. 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) (Stephen Dawson-Haggerty, Jiang, Tolle, Ortiz, & Culler, 2010) that is detailed in section 3. Drivers for Johnson Controls Metasys, Siemens Apogee, and Automated Logic Controls have been used successfully to import BMS data in real-time. When BMS access is restricted, trend log data can be manually imported to sMAP.

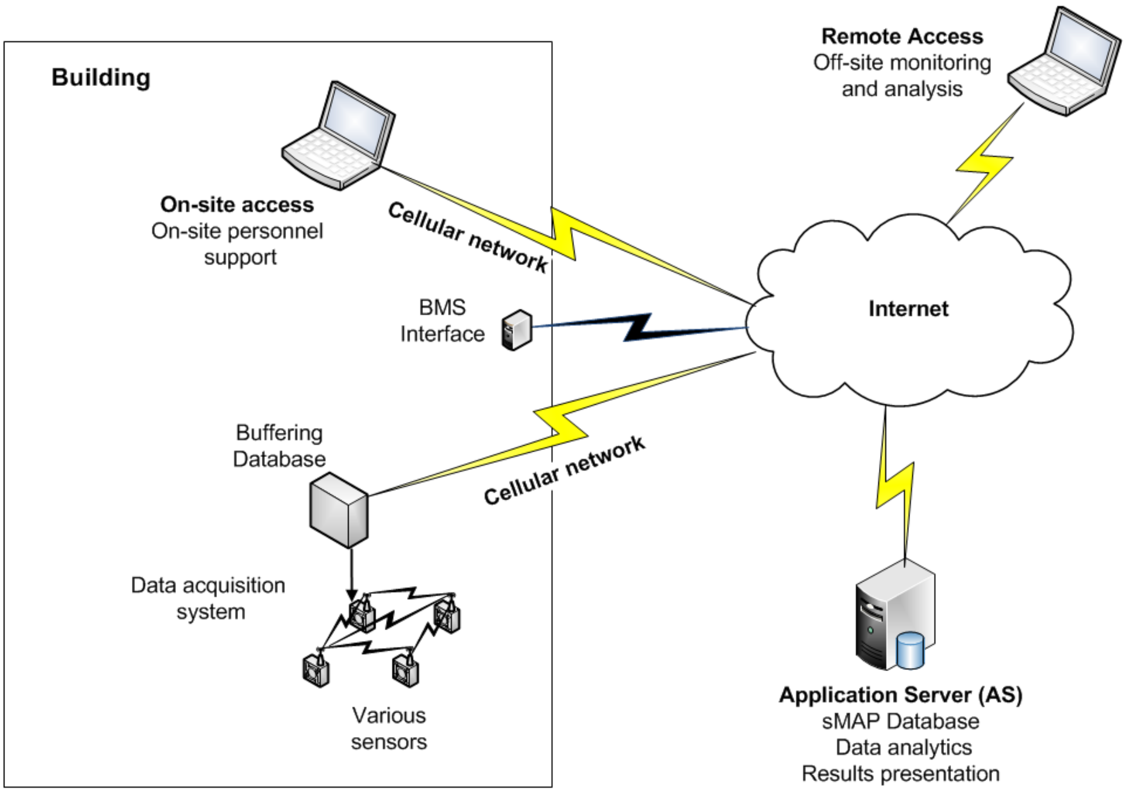

Figure 1: System Architecture

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 – Indoor Environmental Quality Monitoring Devices

The ICM was developed as part of a previous research project involving occupant comfort in buildings with operable windows (Paliaga, 2004). 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 carbon dioxide (CO_2) sensor were added to the device, and all sensors were wired to a new wireless enabled input-output board. The new ICM is a wireless device that is capable of sensing PMP-suggested thermal comfort, lighting, and indoor air quality parameters. This device is designed to be placed on an occupant's desk and to measure dry-bulb temperature, globe temperature, air speed, relative humidity, horizontal illuminance, and CO_2 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. Figure 2 and Figure 3 show the outside and inside of the ICM device respectively.

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.

Figure 2: ICM Device With CO_2, Illuminance, Globe, Air Velocity, Dry Bulb Temperature, and Relative Humidity

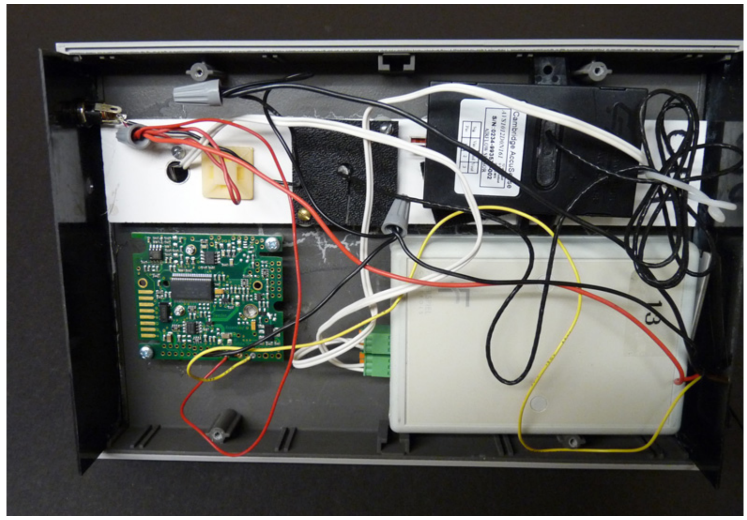

Figure 3: Inside View of the ICM Device

2.2.1.1 Wireless mote input/output (IO) board

The wireless motes input/output (IO) board provides a flexible means to connect up to eight (8) external sensors. The IO board is a custom design board to accommodate the NeoMote from Metronome Systems, Inc. An IO board with and without the mezzanine NeoMote is shown in Figure 4.

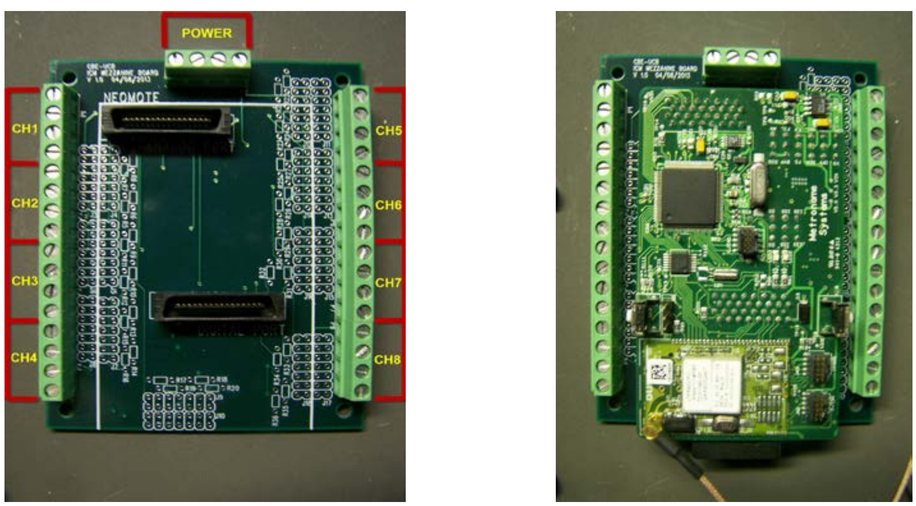

Figure 4: Photograph of IO board With and Without NeoMote

Each channel of the IO Board can accommodate 2-wire, 3-wire, or a 4-wire sensor. Figure 5 illustrates the typical wiring for each type of sensor.

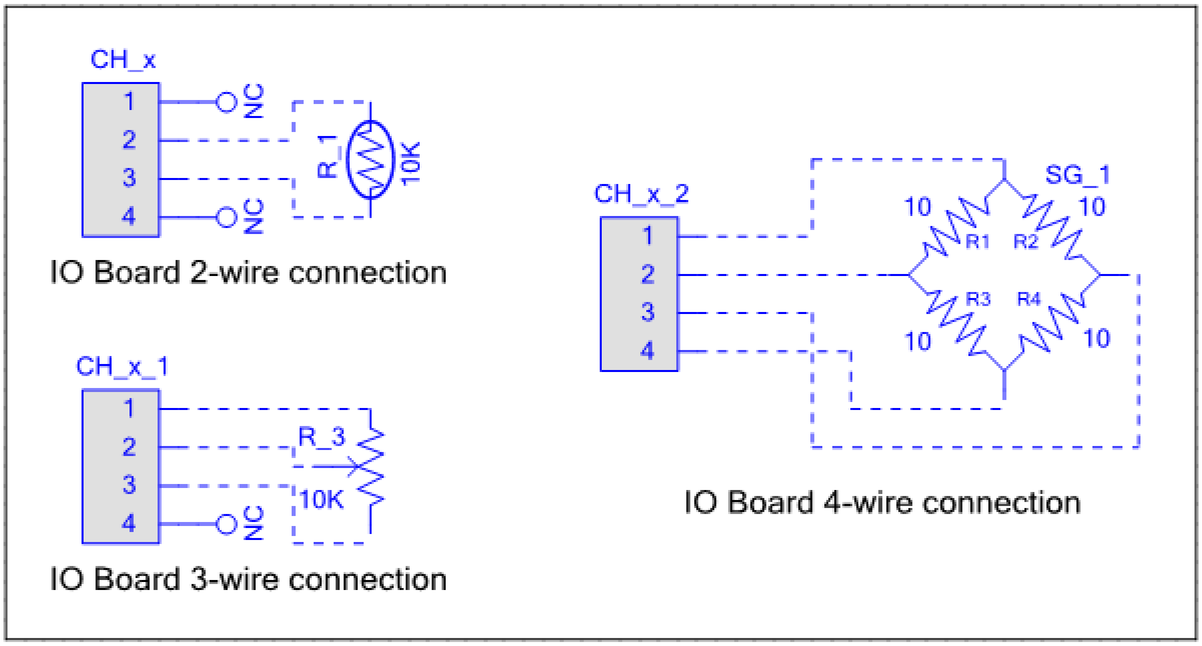

Figure 5: Typical Sensor Wiring

The NeoMote is a combination of a programmable system–on-a-chip (PSOC) from Cypress Semiconductor, Inc. and a SmartMesh IP wireless mote from DUST Networks (Linear, n.d.). The DUST Networks chip supports the latest generation of mesh-networking devices operating at 2.4 Gigahertz and includes on-board programming, low power for extended battery life, support of inter-integrated circuit (I^2C), and expanded IO.

The introduction of the PSOC allows each wireless mote to be reconfigurable to accommodate different sensors with software. The PSOC is a system on a chip that includes a variety of analog hardware modules such as op-amps, analog to digital converters (ADC), current and voltage digital to analog converters (DAC), and analog multiplexers on the same silicon. Analog interfaces for most sensors can be implemented in software.

Each analog channel is fed via an eight channel analog multiplexer through a programmable gain amplifier (PGA) to a 20-bit ADC. The ADC is capable of sampling each channel at a rate up to 46 samples/sec. The ADC can be configured to map the input range to be ±6.144 volt (V), ±2.048V, ±1.024V, ±0.512V, ±0.254V, ±0.128V, ±0.061V. The PGA has a selectable gain ranges of 1x,2x,4x,8x,16x,24x,48x,50x.

The IO board operates with a supply voltage of 9V-30V. Each channel can be wired to provide the supply voltage, 5V, 3.3V. Up to 2 channels can supply a software configurable voltage output with a range of 0-1.020V or 0-4.080V. The output has a resolution of 4mv and 16mv respectively. Up to 2 channels can be configured to source or sink current with a range of 0-31.875µA, 0-255µA, or 0-2.04mA. These are programmable at a resolution of 0.125µA/bit, 1µA/bit, and 8µA/bit respectively.

The PSOC and the IO Board can be configured and programmed to read any sensor via serial binary single-ended data and control, I^2C, or serial peripheral interface (SPI) digital interface protocols.

The NeoMotes are capable of updating all eight channels of data every 10 seconds.

2.2.1.2 Thermal comfort sensors

The ICM measures dry-bulb temperature using a radiation-shielded thermistor (a resistance-based temperature measurement device). Both the globe temperature sensor and the dry-bulb temperature sensor use thermistors that are accurate to 0.1 degrees Celcius (C) with 1percent interchangeability. Each thermistor was calibrated using a dry or wet-well temperature calibration unit while connected to the wireless IO 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 (Paliaga, 2004). Additional theory behind the globe temperature sensors are available in (Benton, Bauman, & Fountain, 1990; Fountain, 1987; Michael A. Humphreys, 1977). Currently, operative temperature is computed as the average of mean-radiant temperature (MRT) and dry-bulb temperatures. MRT is computed from globe temperature using correction factors for the globe size, emissivity, and air speed. Future work will add the ability to compute other thermal comfort parameters including Standard Effective Temperature (SET).

2.2.1.3 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 (light levels) and luminance (glare and reflectivity) measurements of areas with potentially problematic glare. 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. Future implementations of the Toolkit web application aim to include luminance analysis methods similar to those provided by (Konis, 2012).

Horizontal illuminance is measured using a Licor Photometric sensor that has cosine correction and is accurate to ±5 percent. An amplification circuit was 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 that is accurate to ±2 percent to obtain calibration coefficients of reasonable relative accuracy.

2.2.1.4 Indoor air quality sensor

Indoor air quality is a complex science and accurate measurement techniques are typically difficult and expensive. For typical commercial buildings that do not have specific outdoor air quality problems (particulate matter [PM_{10}, $PM_{2.5}$ – 10 and 2.5 micron diameter particles], ozone, or air-toxics non-attainment problems), the primary method for managing IAQ is to guarantee an adequate outside airflow rate (ANSI (American National Standards Institute)/ASHRAE, 2010a). 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 (ANSI/ASHRAE, 2010a). 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 complex and require access to multiple mechanical spaces in a building. CO_2 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. ASHRAE Standard 62.1 (ANSI/ASHRAE, 2010b)and the European Standard 15251 allows the control of outdoor airflow rate as a function of the CO_2 concentration (CEN, 2007). Ozone, volatile organic compounds (VOCs), and $PM_{2.5}$ and PM_{10} were also considered, though reasonably priced sensors were deemed to be too inaccurate to provide valuable IAQ performance evaluation.[2] The PMP suggests that CO_2 measurement is a highly inaccurate, but nevertheless potentially useful tool for diagnosing ventilation issues. Persily (Persily, 1997) provides details on the connection between CO_2 measurement and IAQ and how to appropriately interpret CO_2 measurement as an indicator of IAQ.

The ICMs provide the opportunity for making multiple local CO_2 measurements in one zone, whereas most buildings with CO_2 sensors have only one sensor per zone. A CO_2 module with 1 percent repeatability and 3 percent 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 CO_2 measurement in a building will be 400 parts per million (ppm) (baseline outdoor level). The sensors were spot checked against an EGM-4 CO_2 sensor by PP Systems that has an accuracy of less than 1percent and found to be within 50 ppm.

2.2.2 Portable Underfloor Air Distribution Commissioning Cart

The PUCC was designed to be a portable and wireless alternative to a previously Center for the Built Environment (CBE) designed Underfloor Air Distribution (UFAD) commissioning cart (Webster, Bauman, & Anwar, 2007). 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 6 is a photograph of the PUCC.

[2] Recently, less inexpensive units appear to be becoming available making these measurements possible in the near future

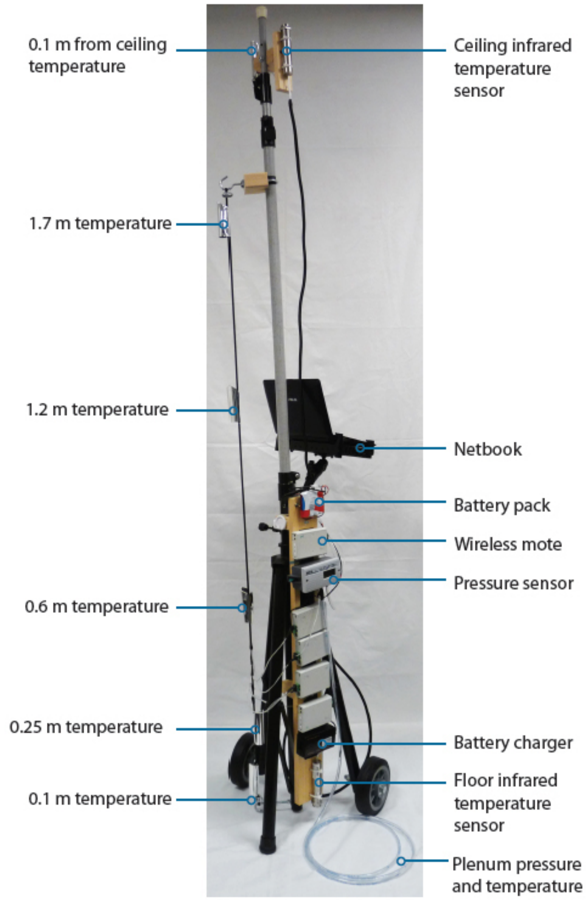

Figure 6: Portable UFAD Commissioning Cart

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 (model) meter has the add-on capability if such analysis were deemed appropriate in the future.

Chapter 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 sMAP system and Django web application software (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 ("Django 1.4," n.d.). 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 (Stephen Dawson-Haggerty et al., 2010). sMAP has three major components that are shown in Figure 7.

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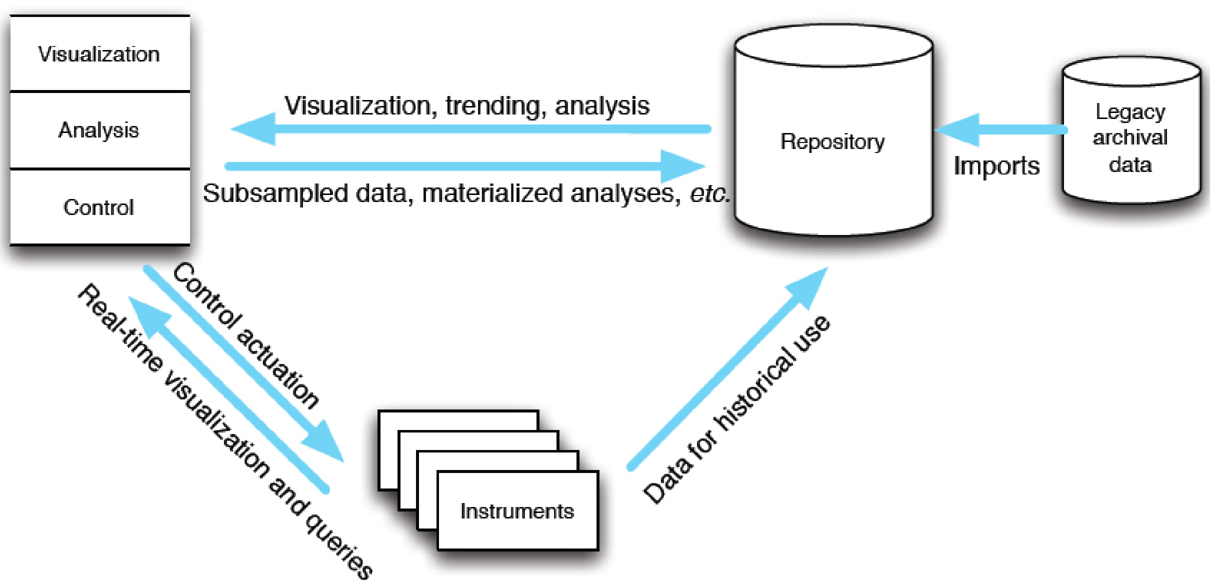


Figure 7: sMAP Components and Data exchange Paths (S. Dawson-Haggerty, n.d.)

1. Instrument drivers: A library of instrument drivers is available to enable the connection of devices to sMAP through Hypertext Transfer Protocol (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). 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 Hypertext Markup Language (HTML) and Javascript. The frontend is used for three main tasks: (1) setup and collection of sensor data and metadata, (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 8.

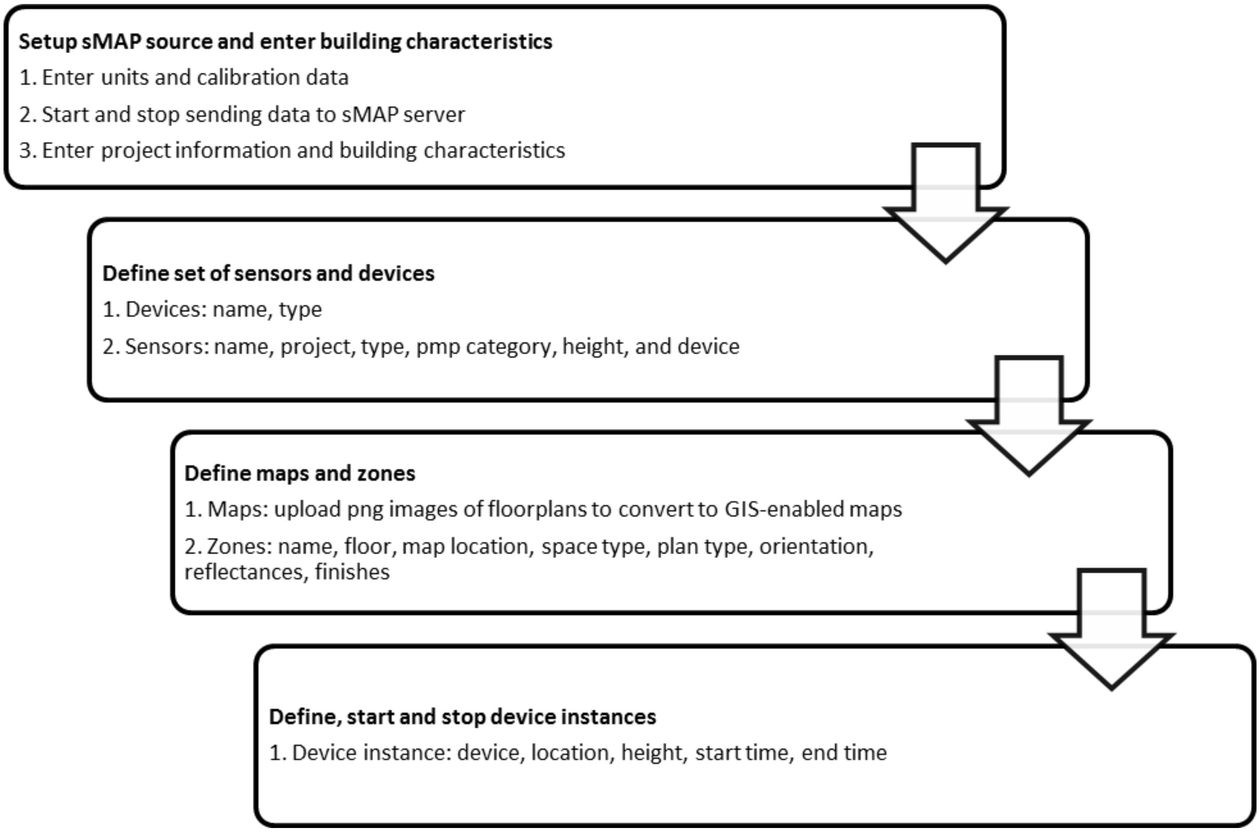


Figure 8: Overview of Project Setup

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 ("MapTiler - Map Tile Cutter. Overlay Generator for Google Maps, Google Earth (KML SuperOverlay).," n.d.) with the Olwidget framework for OpenLayers ("Welcome to olwidget's documentation! — olwidget 0.48 documentation," n.d.). These tools allow users to draw zones (Figure 9) and specify testing locations on a GIS-enabled floor plan map (Figure 10) that is also used for data analysis.

Figure 9: Users Can Draw and Edit Zones on a GIS-Enabled Floor Plan

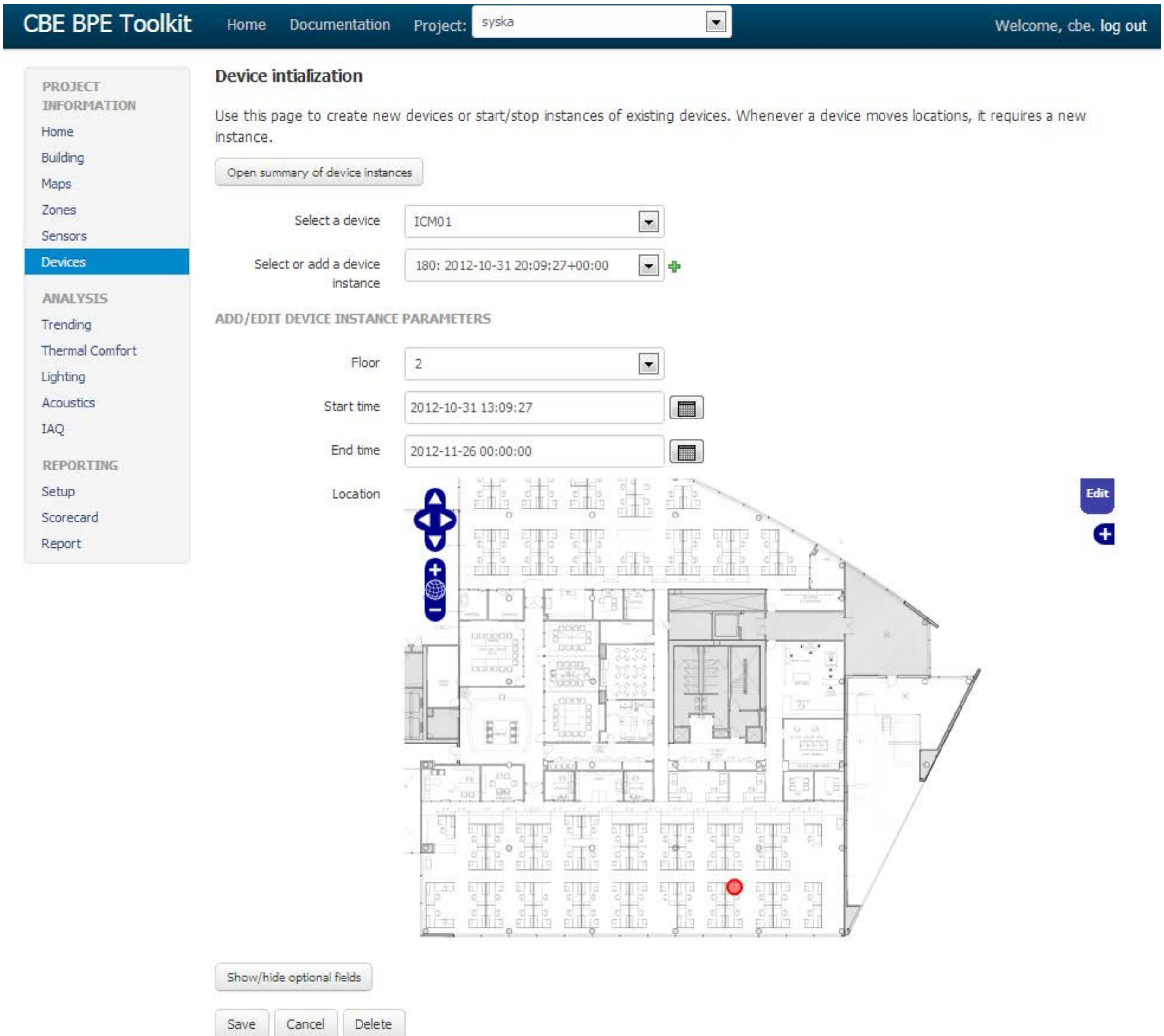


Figure 10: Toolkit Webpage for Adding a New Device Instance (Measurement)

3.2.2 Real-Time Analysis Of Sensor 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

Analysis method	IEQ categories	Description
Trending	All	The trending application allows real-time trend analysis of any data stream (e.g., BMS or wireless).
Setpoint analysis	Thermal comfort	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 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.
Comfort zone analysis	Thermal comfort	The Toolkit comfort zone analysis webpage allows users to analyze the comfort data from the Toolkit 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 Predicted Mean Vote (PMV) and operative temperature.
Stratified systems analysis	Thermal comfort	Stratification refers to the increasing temperature gradient of the air in a space that is conditioned by a stratified system: i.e., a UFAD or displacement ventilation system (DV). The Toolkit includes two analysis types for analyzing stratification data: room-air stratification and comfort zone analysis – stratification.
Whole test-period analysis	Acoustics	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 that 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.

Analysis method	IEQ categories	Description
Time-slices analysis	Lighting, IAQ	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.
Performance summary model analysis	All	The performance summary model analysis is used to determine what percentage of measured values fall within certain classes. See (Heinzerling et al., 2013) for more details.

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 (Heinzerling et al., 2013). 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.

Chapter 4:
Case Studies

4.1 WSP Flack + Kurtz

4.1.1 Background

The San Francisco office of WSP Flack and Kurtz (WSPFK) is located at 405 Howard St. in a mid-rise development designed by Studios Architecture (see Figure 11). Their offices are located in sections of the fifth and sixth floors and are serviced by a UFAD system. The building earned a LEED- Existing Building (EB) Platinum rating and an EnergyStar score of 94. WSPFK is a collaborating partner on this project and provided use of their space as a test bed for the Toolkit. The study period dates were September 26 – October 11, 2012. The goals of this case study were as follows:

- Provide training to a collaborating partner on Toolkit operation
- Provide a complete test of the Toolkit software and hardware
- Obtain feedback from trainees on Toolkit operation and software analysis tools
- Provide feedback to WSPFK on IEQ performance of their offices. This information will also be used to help satisfy a LEED-EB Measurement and Verification (M&V) credit for the space.

Figure 11: 405 Howard St. Building

Figure 12: ICM on Desktop

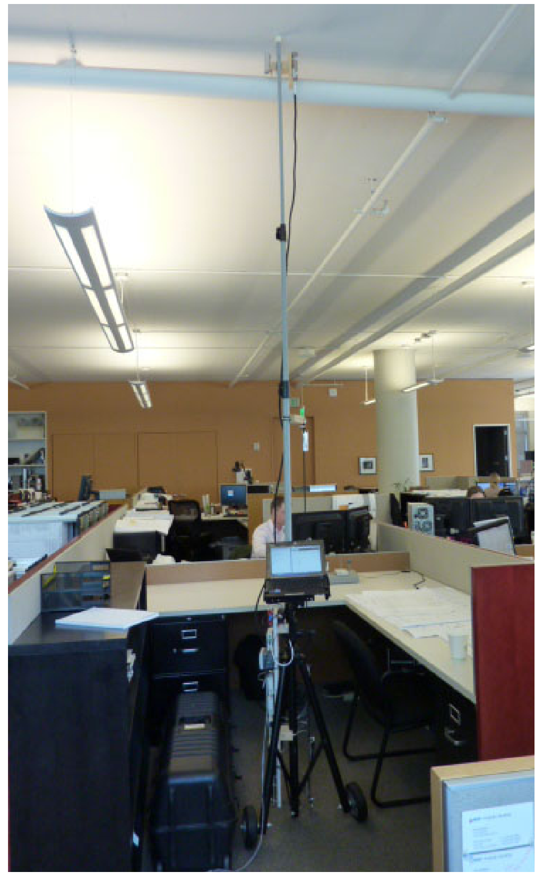


Figure 13: PUCC Deployed in Open Plan Cubicle Space

This chapter begins with an overview of the steps required to deploy the Toolkit. The subsequent sections detail the background information and analysis of each IEQ category for the WSPFK offices. The analysis is written to highlight certain features of the Toolkit, with an emphasis on presenting a complete example of the analysis process a potential user may take. Consistent with this goal, all graphs are screenshots from the actual Toolkit webpage—though the reader should keep in mind that all graphs are interactively zoomable and clickable, which cannot be captured in a screenshot.

4.1.2 Toolkit Setup

A summary of the steps involved in setting up the Toolkit for deployment is provided below along with approximate time to complete the task. The steps are divided into two sections: (1) completed off-site before deployment and (2) completed on-site during or after deployment.

Steps completed off-site before deployment:

- (2 hours) Create a zoning diagram of the spaces to be measured: this step generates the spatial metadata that is necessary for filtering options in the Toolkit analysis web pages. Figure 14 shows the zoning diagram for the sixth floor. This zoning diagram is typically based on thermal zones, though other zoning types (lighting/acoustics) could also be defined. Zone definition is primarily useful for dividing the building up into smaller areas that can be analyzed individually or grouped together by shared traits (e.g. orientation). To the extent that the zones can align with zones defined by the thermostats in the spaces, the zones will align with control points in the BMS, which allows a more detailed analysis of a space. Once zones are defined, they are input into the Toolkit using the "Zones" webpage.

- (15 minutes) Align a standard grid over the zoning diagram. A grid serves two main purposes: it provides a structure for locating device placement at a fine resolution and secondly it links this grid location to the larger zone. Printouts of the gridded zoning diagram are useful as backup documentation during the field tests for locating Toolkit devices that have been placed.
- (5 minutes) Define the sensors and devices that are to be used for the study. This step is completed using the "Sensors" webpage of the Toolkit. This project used the default set of sensors, so there was no extra configuration to complete.
- (5 minutes) Define the units and calibration coefficients for the sensors. This step is completed using the "sMAP Setup" webpage of the Toolkit. This project used the default set of sensors, so no extra work was required to define these units and calibrations.
- (1 hour) Choose locations to deploy sensors. For this project, our representative at WSPFK chose the locations based on spatial diversity, minimizing disruptions, and areas that needed measurement for the LEED-EB M&V credit.

Steps completed on-site during or after deployment:

- (10 minutes) Unpack wireless base station and setup communications.
- (5 hours for full deployment) Deploy the ICM devices and plenum motes in the chosen locations (see Figure 12). Because the devices are wireless mesh networked, they take some time to fully develop a mesh network and begin to send data back to the base station. This process can be accelerated by resetting the mesh devices when placing them. This project involved sensors placed on two floors, though the mesh network established itself robustly between the floors within an hour of sensor placement, with most sensors establishing connection within the first 5 minutes of placement.
- (1-3 minutes per device instance, 49 device instances) Initialize the device instances during placement. This step is ideally performed at the time of device placement using the Toolkit "Device Instance" webpage, though for this project, it was done after the sensors were placed. Subsequent case studies have employed an iPad touch screen device with cellular connection that allows the user to move around the building with an easy-to-carry/use internet device for connection to the Toolkit. In lieu of entering device instances during placement, device locations were recorded on the paper gridded zoning diagram. Device instances were created after deployment using the Toolkit "Device Instance" webpage.
- (10 minutes per reading, 17 readings) Use the PUCC to measure thermal stratification and underfloor plenum pressure (see Figure 13). There is not a predefined set of locations for PUCC measurements. In general, the user tries to get a good temporal and

spatial resolution of measurements (e.g. one measurement every 25 feet (ft) done over the course of the day). In cases in which solar radiation is a factor, the PUCC measurements are typically done in a manner that follows the solar load (e.g. start in the east and work around the building toward the west).

- (10 minutes per reading, 10 readings) Use the sound level meter to measure background noise levels throughout the space.
- (2 hours) Retrieve devices and pack them up at conclusion of the study.

The total time spent preparing the Toolkit, deploying the sensors, recording metadata, taking measurements, and retrieving and packing the sensors was approximately 17 hours, or roughly two working days. For further discussion of the Toolkit deployment at WSPFK see Section 5.1.

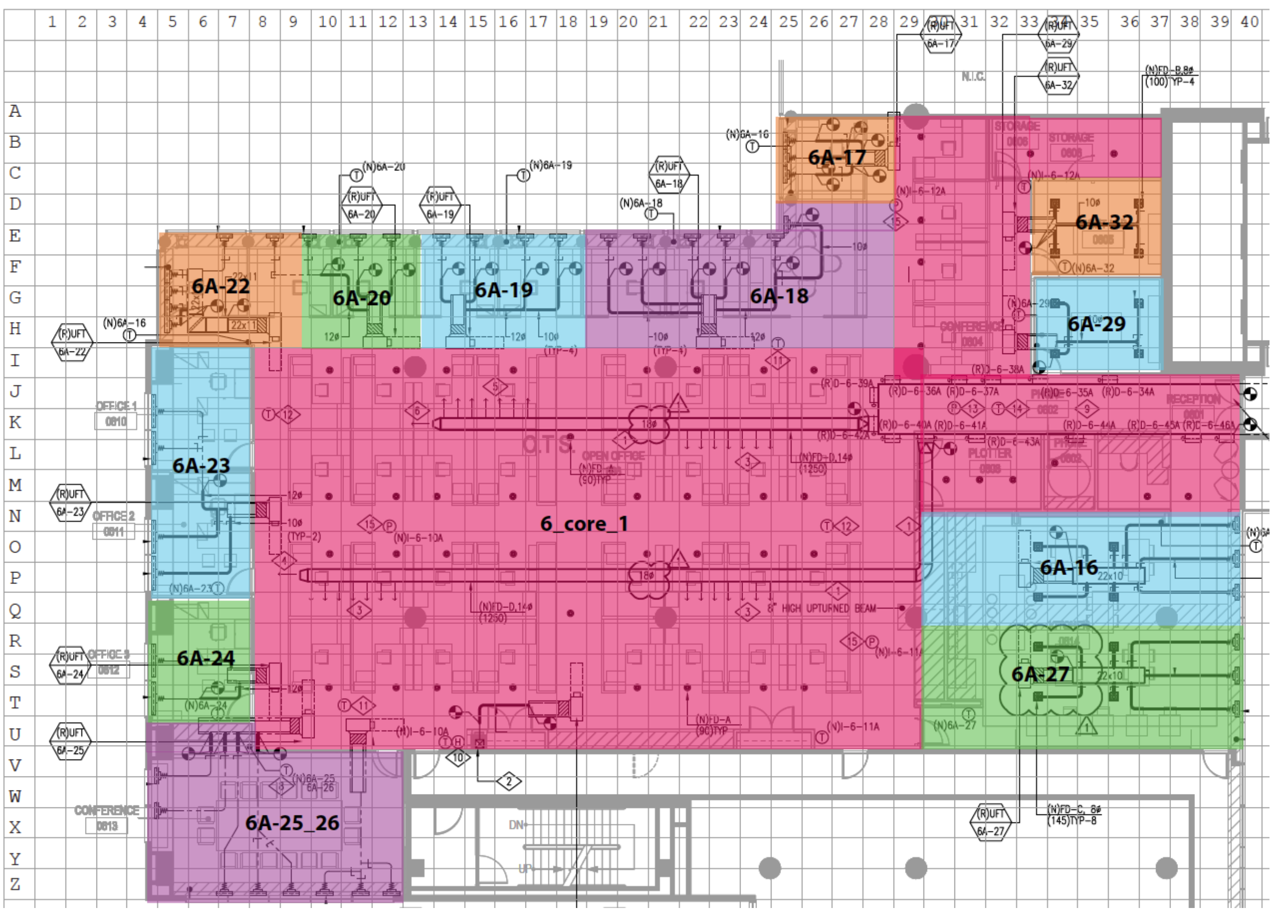


Figure 14: Zoning and Grid Plan for 6th Floor of WSPFK Offices

4.1.3 Thermal Comfort

The space occupied by the WSPFK offices is serviced by a UFAD system; thus, both ICM devices and the PUCC were used to study the spaces. Additionally, BMS data was collected for the study period for the air handling units (AHUs) and the underfloor fan terminals (UFTs). The process of analyzing the data from these two devices is presented in the next three sections.

4.1.3.1 Zone temperature setpoint analysis

A simple method for analyzing thermal comfort in a space is to look at the thermostat readings in a zone and determine how well the space is being controlled to the setpoint temperature. However, this method is typically used on a per-zone basis through trend review. The Toolkit setpoint analysis feature provides a more complete summary of how the entire space is performing by analyzing all zones for a certain time range. Figure 15 shows a histogram representing the percent of readings (15 minute data over entire study period for hours of 6:00AM-6:00PM) that are a certain deviation from a setpoint range of 72-74 degrees Fahrenheit (F) for all UFTs serving the fifth and sixth floors of the WSPFK spaces. A fixed setpoint range was used because we were unable to obtain the specific zone setpoints that may have been adjusted. The building manager suggested that most zones were set between 72-74 degrees F. Thus, the negative side of the histogram refers to times when the zone temperature was below 72 degrees F and the positive side of the histogram refers to times when the zone temperature was above 74 degrees F. The bins are defined as *lower bound ≤ x < upper bound (x is between the upper and lower bounds)*. The majority of readings were within the setpoint range, though the distribution is skewed to the cold side, suggesting overcooling.

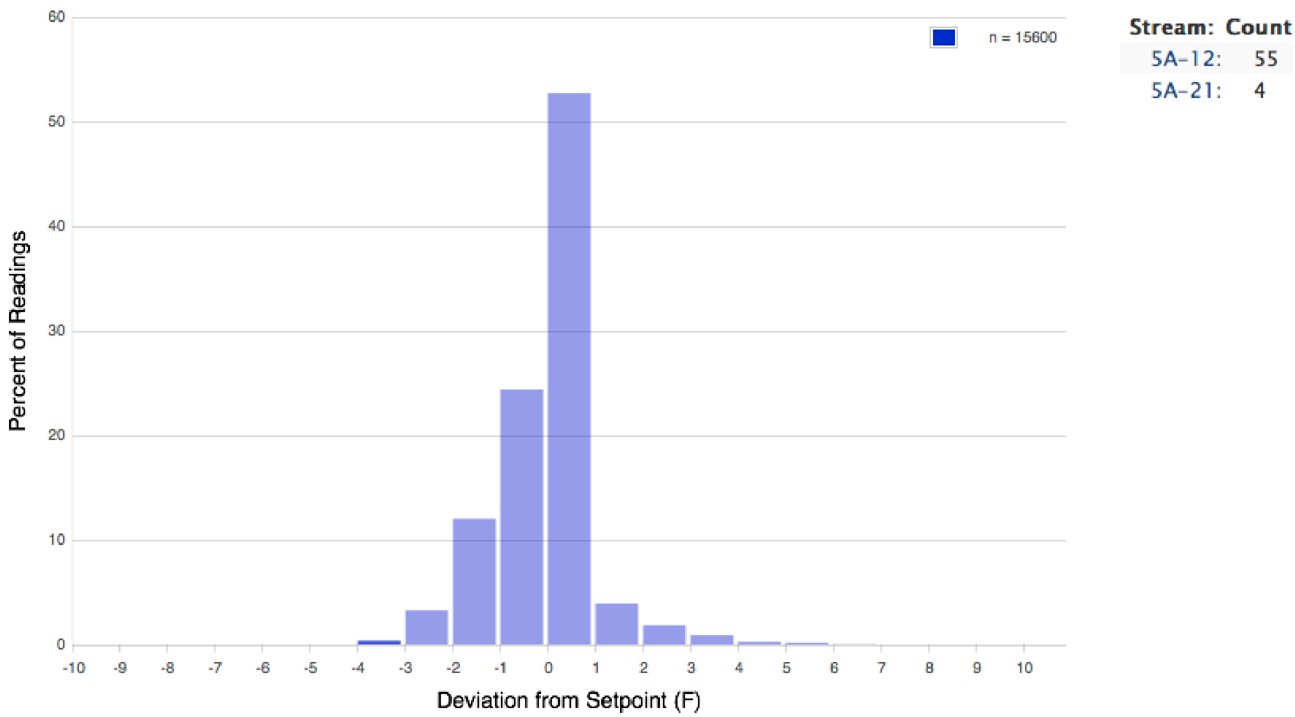


Figure 15: Zone Temperature Setpoint Analysis for all Fifth and Sixth Floor Underfloor Fan Terminals for Entire Study Period

Another important element of setpoint analysis is to search for potential problematic zones. By clicking on the histogram bars, we get a list of the fan terminals that comprise that bin of data and how many readings were in that bin. In Figure 15, the coldest bin (-4 to -3 degrees F) has been clicked, showing two potentially problematic overcooled zones: 5A-12 with 55 readings and 5A-21 with four readings. Fifty-five readings, over 15-minute periods, represents around 14 hours (or two workdays) of time with this deviation from setpoint, over a 2-week period. This represents a small portion of 15,600 total readings from all fan terminals over this period, but nearly 10 percent of the readings of this single fan terminal. Figure 16 shows the trend of the 5A-12 fan terminal speed percent and the thermostat reading for that zone. The temperature hovers below 70 degrees F. The red line shows the 69 degrees F line, which represents 3 degrees F below a nominal 72 degrees F setpoint. The readings below this line fall into the histogram bin highlighted above. The fan speed trend is a constant 30 percent, which represents the minimum airflow for the fan terminals during operational hours. The fact that the fan speed trend does not ever change, including during non-operational hours could indicate a problem with the control point, though the consistent low temperature is also consistent with a minimum airflow from the fan terminal. This fan terminal serves the WSPFK president's office and is set a bit lower (70 degrees F heating, 73 degrees F cooling) than the other zones, but these setpoints do not explain why the zone hovers below 70 degrees F.

On the warm end of the histogram, we can look at one of the zones in which we also have an ICM placed: 5A-1. This is a corner southern zone with two glass exposures. Figure 17 shows the trends of the BMS fan speed percent and thermostat for this zone, along with the dry bulb temperature of the ICM located in that zone for the week of 10/1-10/5/2012. The ICM data is 30 second data, while the BMS data is 15-minute data, which helps explain why the BMS thermostat does not show some of the highest temperatures that are reported by the ICM. Additionally, despite radiation shielding, the ICM dry-bulb temperature may be influenced by direct sun if the ICM device itself heats up and radiates up through the shielding, whereas the thermostat is placed on an interior wall that does not see direct sun. The fan speed trend shows expected behavior: zero percent during non-operational hours, 30 percent minimum flow when air temperature is below setpoint, and ramping up airflow to 100 percent when temperature rises above setpoint. For each day during this week, the fan terminal was unable to cool the space down to setpoint once the temperature rose above setpoint during the late morning or early afternoon. This problem may be caused by a fan maximum setting that is too low, and/or high terminal unit inlet temperatures due to temperature rise in the plenum.

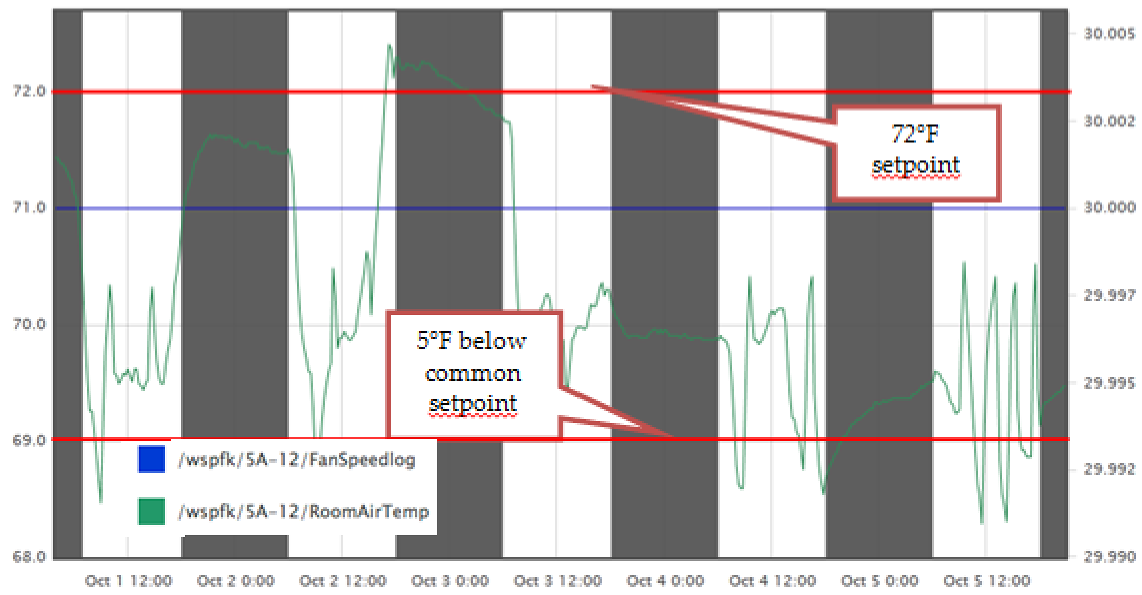


Figure 16: Fan Terminal 5A-12 Air Speed Percent and Thermostat Reading for Week of 10/1-10/5/2012

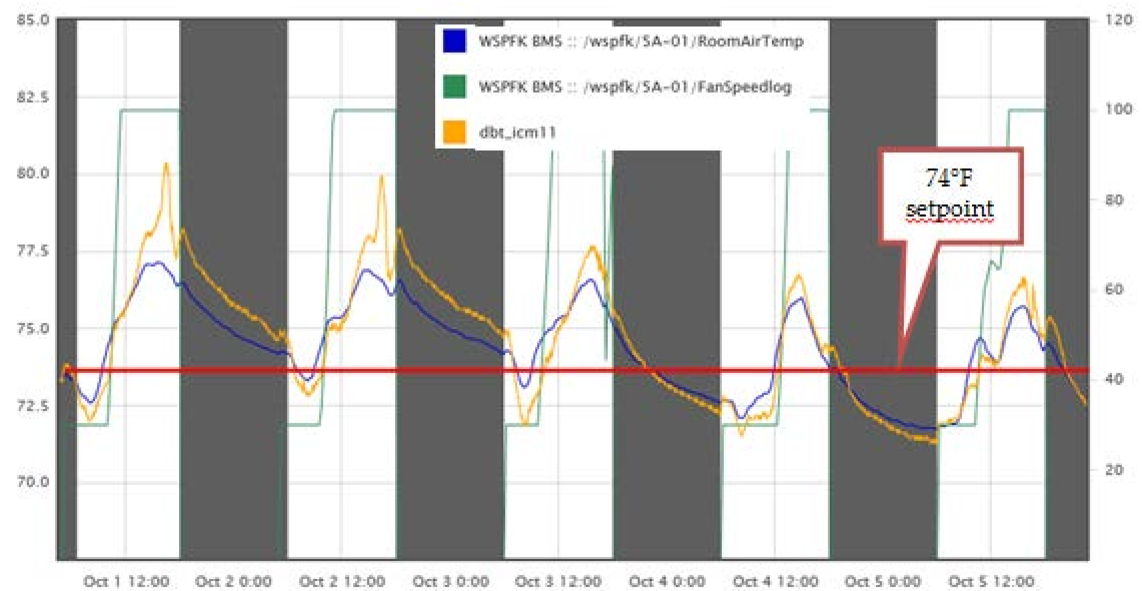


Figure 17: Fan Terminal 5A-1 Air Speed Percent and Thermostat Reading, With ICM11 Dry-Bulb Temperature for Week of 10/1-10/5/2012

While each box could be studied individually to assess proper operation, the setpoint analysis feature of the Toolkit allows the user to quickly narrow down potential problems. The next few sections analyze ICM and PUCC data, which provide further detail into the thermal comfort conditions of the measured spaces.

4.1.3.2 ICM thermal comfort data analysis

For this case study, only four anemometers were used. This limitation arose because of the limited number of channels available on the wireless motes. Future case studies will use newer motes that are capable of handling all ICM sensors. Because air speed was not measured for each ICM, MRT was assumed to be close to the "globe" temperature measured by the ping pong ball sensor on the ICM. Trend analysis of the four anemometers shows that for a typical day, the air speed averaged below 50 feet per minute (fpm), suggesting that this approximation is reasonable. Also assuming low air speed, operative temperature was computed as the average of globe and dry-bulb temperature.

One of the primary struggles in the analysis of a large amount of data is the process of breaking down the data into meaningful charts. For ICM thermal comfort data, we are primarily interested in how the data aligns with the comfort boundaries defined in ASHRAE Standard 55 (the "comfort zone"). For this analysis, a metabolic rate (met) of 1.1 (seated, typing) and a clothing value (clo) of 0.8 were chosen to define the comfort boundaries. Not everyone in the office was wearing the same level of clothing, though a visual survey suggested that the average clothing value in the office was reasonably around 0.8 clo. Once the comfort boundaries are set, the comfort analysis function of the Toolkit was used to determine how comfortable the conditions in the building were. To start, all hourly values for the operational hours of the entire study period are given in Figure 18. The operational hours are weekdays 6:00AM – 6:00PM. This figure provides the ability to quickly see how well the building is controlling to comfortable conditions and if there are any patterns. We see that the building is within the comfort zone 78 percent of the time and that the average predicted percentage dissatisfied (PPD) is 8.3 percent. The majority of the values fall along the lower boundary of the comfort zone, suggesting possible overcooling. However, there are also some instances in which the temperatures were close to the upper boundary of the comfort zone. Another way of looking at this set of data in its entirety is to average hourly data across the days in the study in order to obtain an "average day." Figure 19 shows the average day data for each ICM in the study (13 points each representing 6:00AM to 6:00PM).

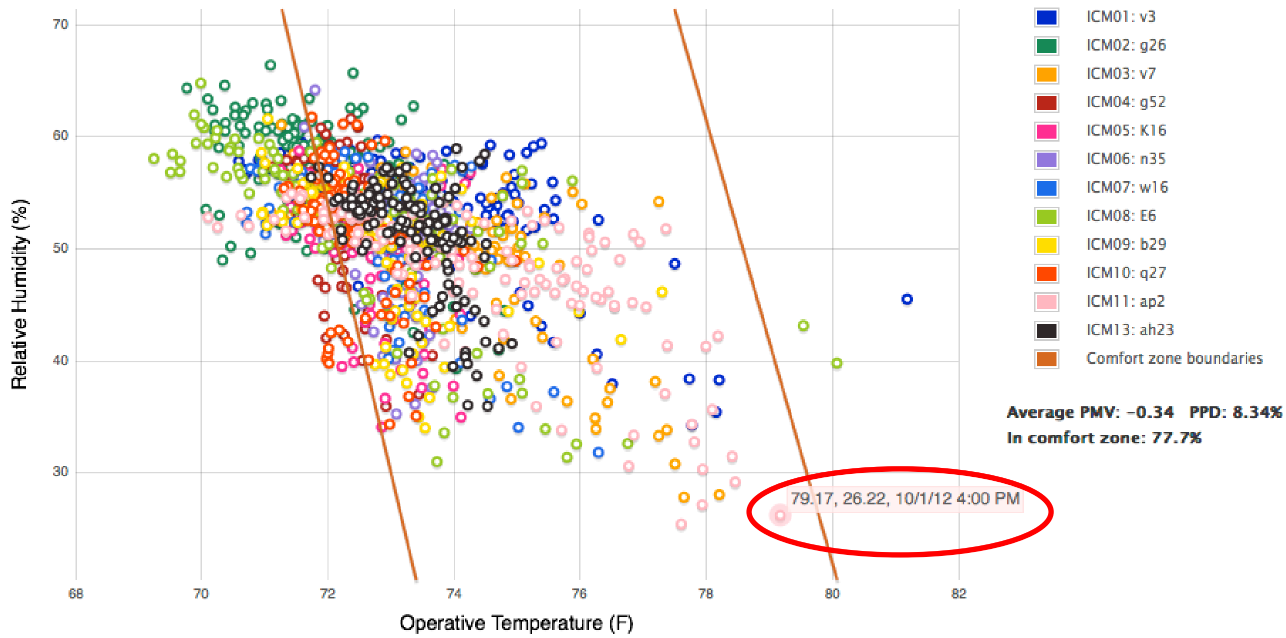


Figure 18: Hourly ICM Thermal Comfort Data from 9/27/12 - 10/10/12 for Weekdays 6AM-6PM

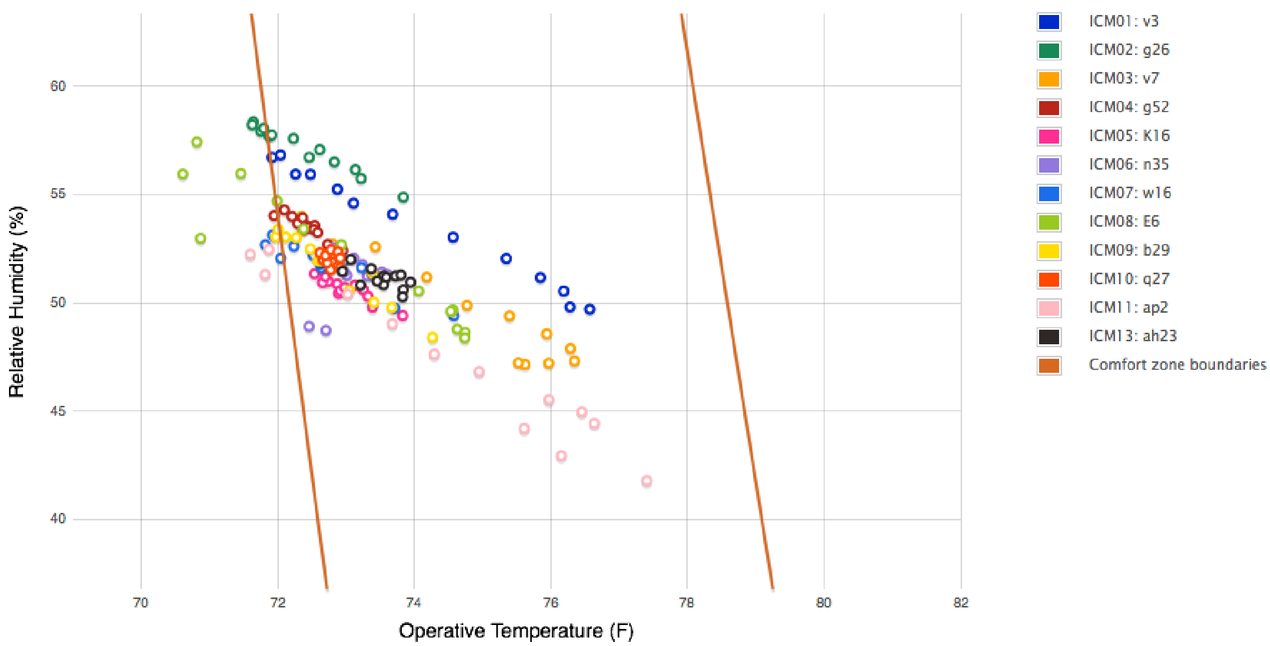


Figure 19: Average of Hourly Values Across All Days in Study Period, Representing an "Average Day"

From these charts there are a couple of questions to investigate:

1. What parameters contribute to the observed temporal variations within and between ICMs?

2. Which spatial parameters (windows, orientation, and interior/perimeter) contribute to the observed variation between ICMs?

In order to address question 1, we need to consider how the outdoor weather affects the indoor environment. The daily outdoor temperature averages associated with this time period are given in Figure 20 (solar radiation was not available for this project). Clearly October 1st and 2nd were uncharacteristically warm days and by hovering over the points in the comfort chart, we see that most of the points toward the upper end of the comfort boundary are from those days (the red-circled hovered point in Figure 18 is 10/1 at 4:00PM), suggesting that the system had difficulty keeping the setpoint during this high load period.

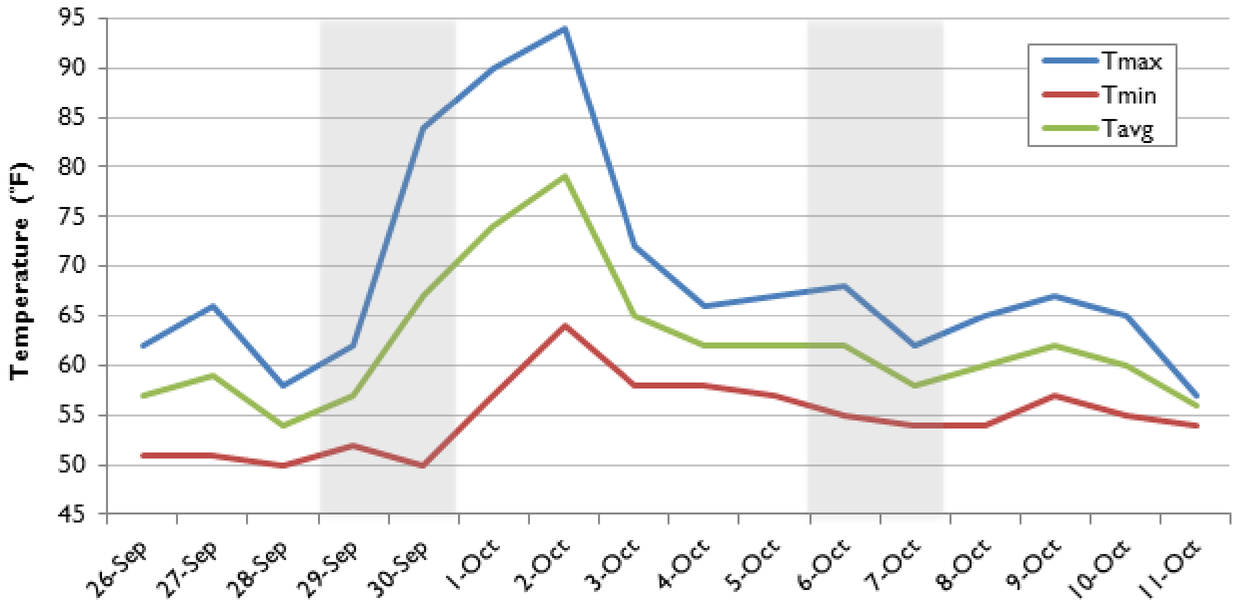


Figure 20: Daily Outdoor Air Temperatures in Downtown San Francisco for Study Period (Weekends are Shaded)

At this point in the analysis, it would be helpful to drill down into a couple of days' worth of data. With temporal filtering we can look at two charts, the first (Figure 21) showing a hot day (October 2nd) and the second (Figure 22) showing a "normal" day (September 27th) for the study period.

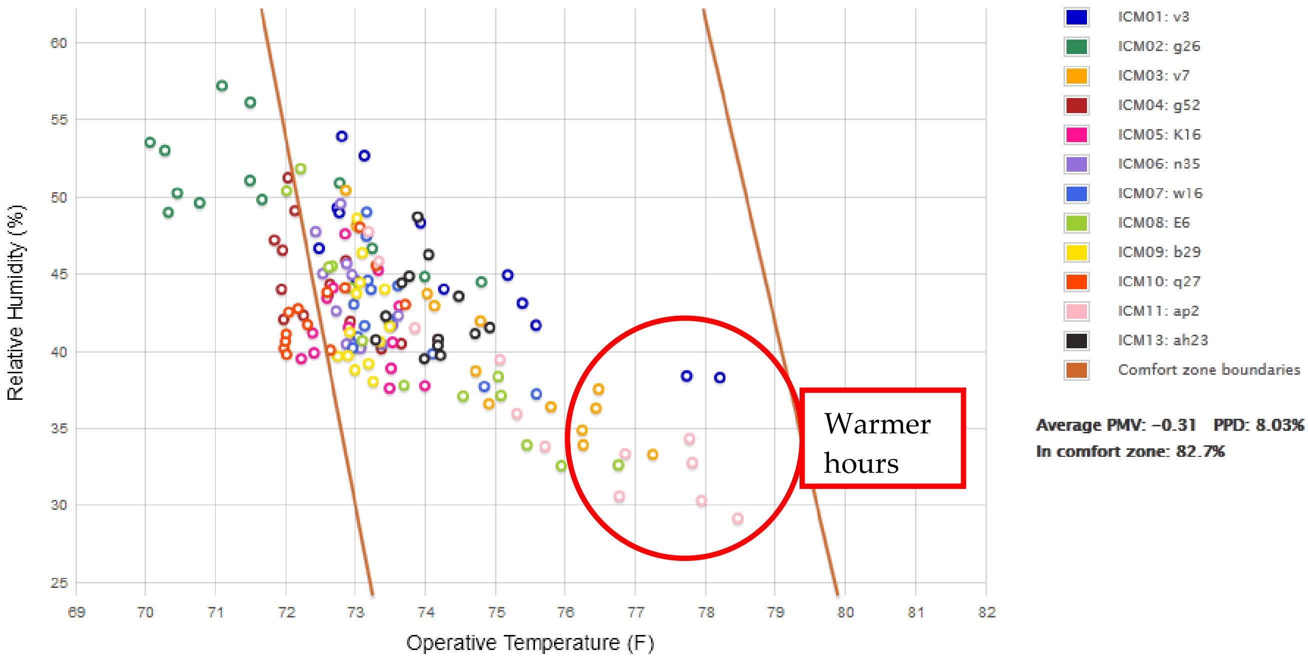


Figure 21: Hourly ICM Thermal Comfort Data for Hot Day – 10/2/12

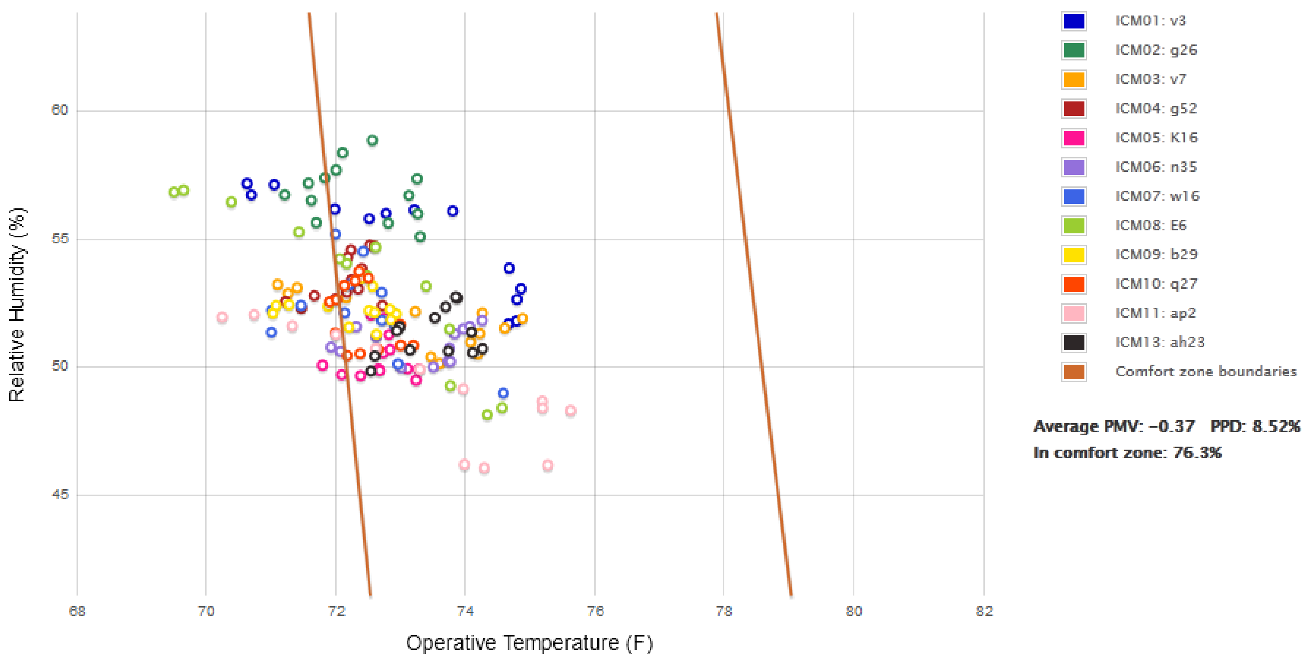


Figure 22: Hourly ICM Thermal Comfort Data for "Normal" Day – 9/27/12

From these two charts, we can see that the percent in the comfort zone is actually higher on the hot day, further suggesting that building is likely overcooling during low-load days. We can also notice that ICM01, ICM03, and ICM11 have the highest operative temperature values on both days. ICM01 is directly in front of a northwest window, ICM03 is in a conference room, and ICM11 is in southwest perimeter office. None of these devices are in the interior and all have loads that help explain their variation (solar in the case of ICM01 and ICM11, and people for ICM03).

In addition to looking at temporal variations in the data, we are interested in determining spatial variation. One way to quickly summarize the data spatially is to aggregate by zone or orientation, which combines the results of devices that are in the same zone or orientation respectively. Figure 23 shows the hourly ICM comfort data aggregated by orientation and averages across days in the study. This chart is very similar to the one in Figure 19 except it narrows the data even further by binning into orientation. From this chart we can see that the core maintains a tighter set of conditions than the perimeter zones. Additionally we can see that north and south orientations are less tightly controlled, tending to be cold in the morning and warm in the afternoon. The two zones in the south and the one zone in the north are corner sections of the building with two exposures of glass. This double exposure helps explain why these zones have a more difficult time maintaining consistent conditions.

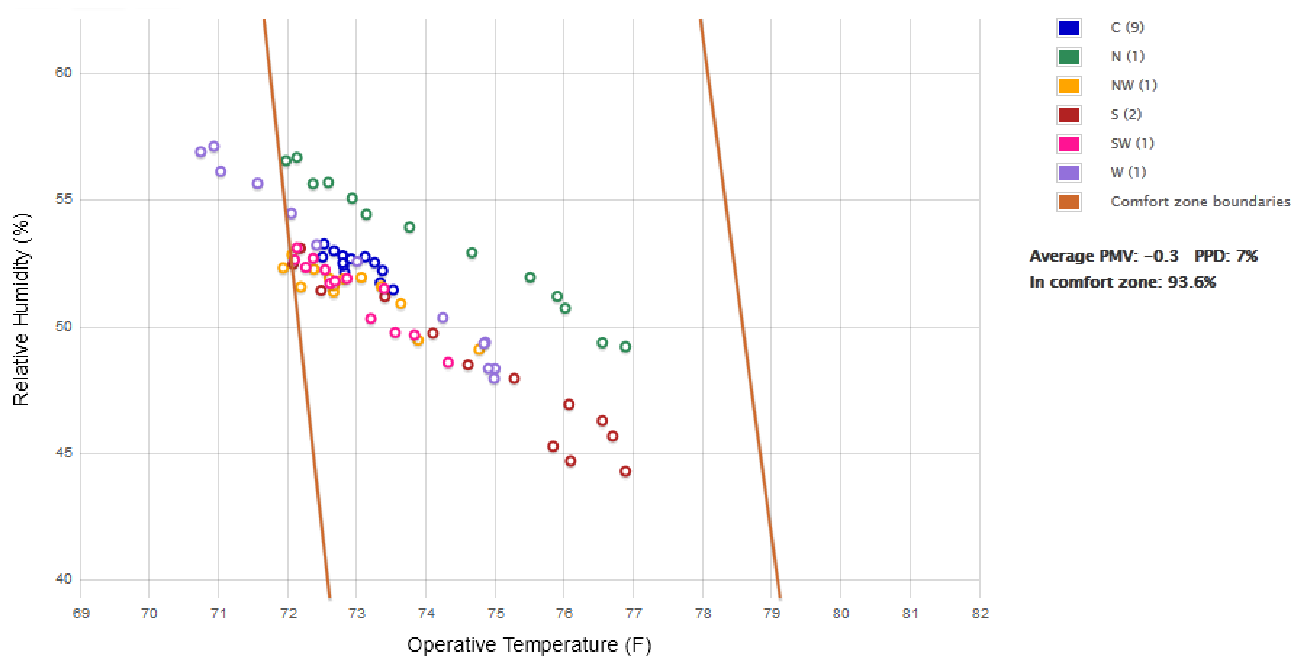


Figure 23: ICM Thermal Comfort Data Aggregated by Orientation for Entire Study Period, Showing "Average Days"

The ICM comfort zone analysis shows that the building tends to fall nicely into the comfort zone for a clo of 0.8 and met of 1.1. The analysis also shows that most of the hours during the day lie along the lower end of the comfort boundary, suggesting possibility for increased setpoints. However, the western zones would need to be monitored closely if setpoints were raised to ensure that they maintained comfortable conditions in the late afternoon.

To summarize the overall thermal comfort performance of the spaces for the time period measured, we can use the thermal comfort performance summary model. Figure 24 shows the summary model based on the assessment class conditions of the "proposed" PMP model discussed in Heinzerling et al (2003). All ICM thermal comfort data (15 minute resampled/averaged) for weekdays 6:00AM – 6:00PM was used in the analysis. For thermal comfort, all space types have the same class I condition, which is that the PPD is less than or equal to 10 percent, indicating compliance with the PMV/PPD model of ASHRAE Standard 55. Assessment class 2 represents any PPD above 10 percent. In the proposed model case, the percent-persons-*satisfied* (100-PPD) is computed instead of PPD. Figure 25 shows the distribution of percent-persons-satisfied for the two assessment classes of the default space type data. Looking at the class 2 distribution, with the exception of a few outliers, the space conditions *should* satisfy 80 percent or more of the occupants 100 percent of the time.

Figure 24: Thermal Comfort Summary Performance Model of Entire Study Period and All ICMs

Figure 25: Distribution of the Data for Each Assessment Class for the Default Space Type Shown in Figure 24

4.1.3.4 Portable Underfloor Commissioning Cart analysis

The PUCC was used to analyze the performance of the UFAD system at the WSPFK offices. The practitioner involved in this case study completed a total of 13 cart measurements. Each measurement lasts about 10 minutes in order to allow the sensors to stabilize in the space. The last two minutes are then averaged to provide the final stable readings at each height. All measurements were taken on 10/9/2012 and 10/10/2012.

The two main variables we are concerned with when using the PUCC, is the average occupied zone temperature and the occupied zone stratification (i.e., temperature difference between foot and head height). Figure 26 shows a scatterplot of occupied zone stratification against average occupied zone temperature of each cart measurement, aggregated by zone. In zones where multiple measurements were taken, those measurements were aggregated (averaged). The parentheses next to the zone names in the legend of the chart indicate how many measurements were taken in the zone. The beige box represents the comfort zone defined by the clo and met values specified by the user.

The average occupied zone temperature is well below the comfort zone for most of the measurements, again suggesting overcooling during this measurement period. The occupied zone stratification was generally on target though typically lower than ideal (3 degrees F). Ideal stratification can indicate high ventilation effectiveness. The one point that has negative stratification is a perimeter zone that was under the influence of direct sun during the measurement and is discussed in more detail for Figure 29.

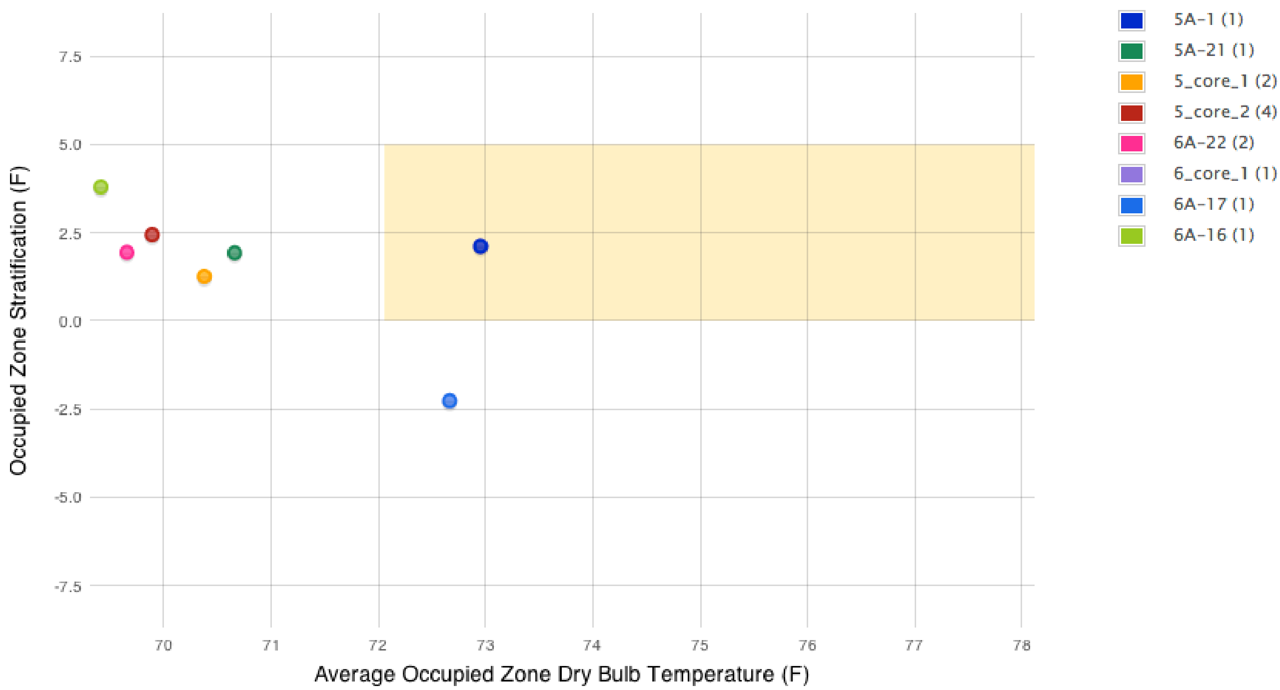


Figure 26: Comfort/Stratification Summary Chart of Cart Measurements Aggregated by Zone

Room-air-stratification (RAS) charts provide a further level of detail for analyzing stratified systems. Figure 27 displays a room-air-stratification chart for the cart measurements taken in interior zones. The lines (stratification profiles) represent temperature measurements at each height on the PUCC (-10 inches represents the temperature of the underfloor plenum). At each height we can gather information about how the system is operating. In the underfloor, we see that the supply air temperature in the plenum varies from 64 degrees F to 68.5 degrees F. These floors are served by four AHUs that vary the supply air temperature throughout the day. Looking at the building management system, the data for these four air handlers shows that supply air temperature ranged from 55 degrees F to 65 degrees F with two of the four air handlers in sync, but not necessarily with the other two handlers (Figure 28). These supply air temperature differences help explain some of the differences in observed underfloor air temperature. There is also heat gain that occurs as air stays in the plenum, which can also create thermal differences in the plenum. As is evident by the last measurement (2012-10-10 14:39 g53), the colder the underfloor air temperature, the greater the occupied zone stratification is. By the time the air reaches thermostat height (48"), the temperatures begin to converge around 70-71 degrees F. Even the temperature directly below the ceiling (152") is still quite cool, at 72 degrees F, suggesting overcooling. Because of the limited temporal distribution of the cart measurements, the ICM data provide a better picture of overall comfort in the space, but the cart measurements align with the general trend of the ICMs—temperatures tend to be near the lower bound of the comfort boundary. These lower temperatures are a common problem with UFAD systems: stratification in the occupied zone causes a cooler temperature than the 48" thermostat indicates, yet the setpoints are set as they would be in an overhead mixed system.

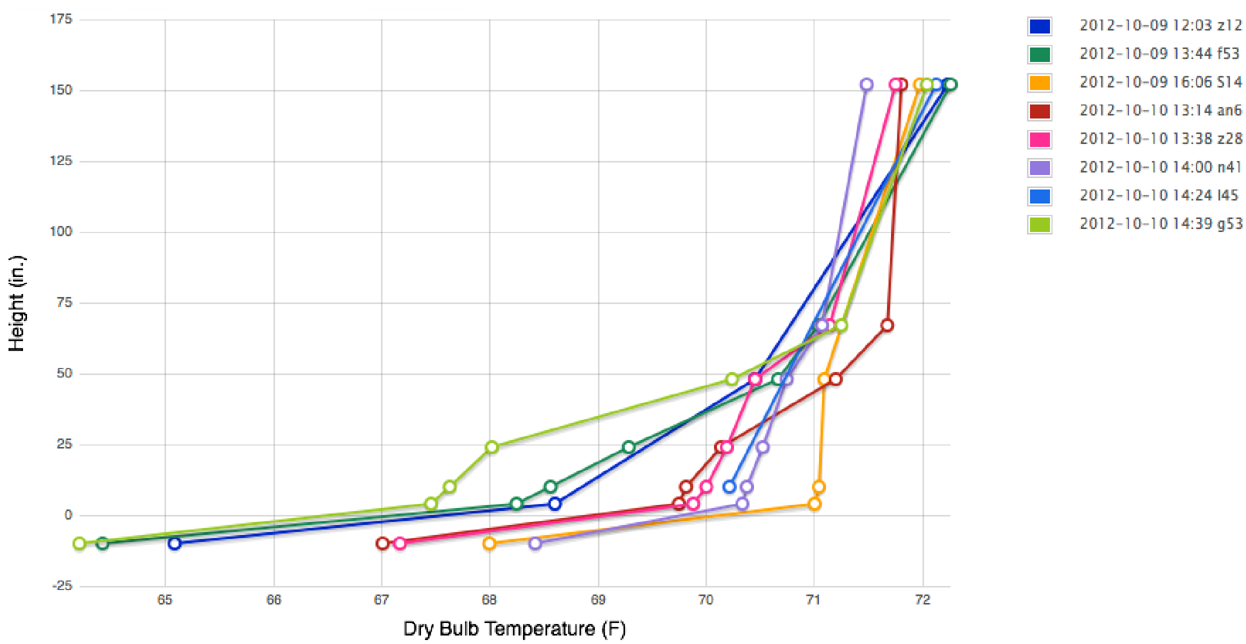


Figure 27: Room-Air-Stratification Chart for Interior Cart Measurements

The perimeter cart measurements are shown in Figure 29. In these measurements, the underfloor air temperature probe was not placed in the underfloor, so those measurements can be ignored. There were very few perimeter measurements taken, but there is more variability shown in these measurements than those in the interior. The atypical profile (2012-10-10 15:12

A28) results from a sun-bathed space. The sun shining on the floor warmed the floor causing a high temperature at 4″, leading to a negative stratification.

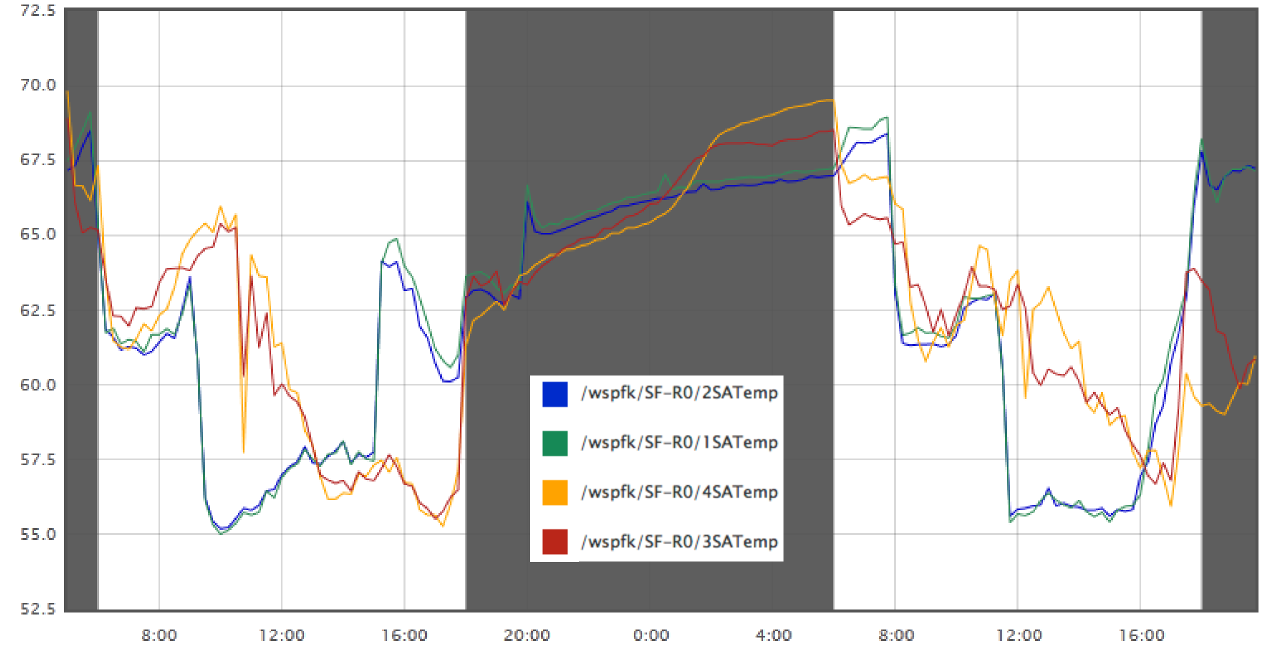


Figure 28: Air Handling Units Supply Air Temperature for 10/9 - 10/10/2012 (Non-Operational Hours are Grayed Out)

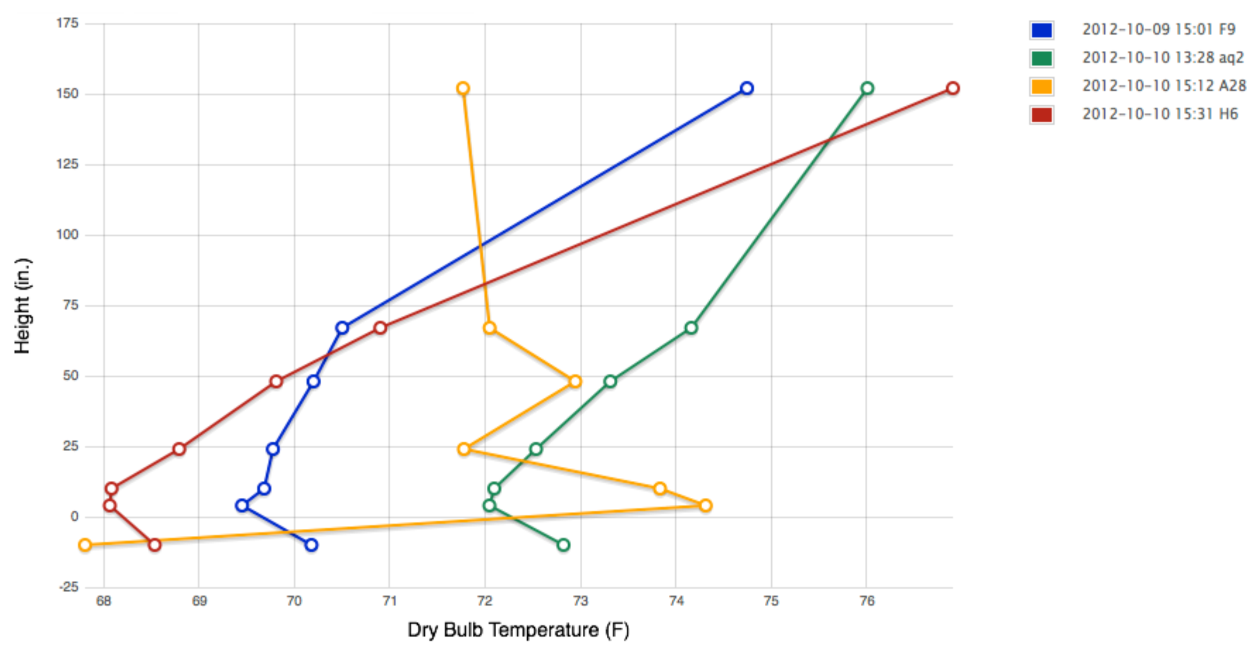


Figure 29: Room-Air-Stratification Chart for Perimeter Cart Measurements Aggregated by Zone

4.1.4 Lighting

The office has daylighting features, including auto-dimming perimeter light fixtures controlled by light-sensors and motion detectors. There were two interest raised by the tenant related to LEED M&V verification:

- The lighting schedule is working correctly.
- The daylighting controls are working to maintain the lighting level throughout most of the day. Sometimes the reflection off of the adjacent buildings will flood the lighting level on a sensor, but when that happens, usually a blind is dropped to compensate.

Four ICMs were recording illuminance continuously over the study period. With only four illuminance meters, spatial density was limited, providing a limited picture of lighting performance. Additionally, because no manual testing of lights was completed, it is not possible to distinguish between daylight and electrical light. Manual testing of lights at night could help separate the influence of daylight from electrical light during the day, as well as confirm that electric lighting provides sufficient light levels at night. The addition of solar sensors on the ICMs would also help to distinguish between the two.

There are two main ways of visualizing the long-term data from the ICMs: (1) a summary analysis of the entire study period (or any multi-day period) or (2) a detailed analysis of a day at a time. The first method takes hourly data across each day in the study period (weekdays only) and provides a boxplot for each hour showing the distribution of values for that hour over the whole study period. This method is similar to the "average day" feature for the comfort zone analysis discussed in the last section except instead of providing the average, it provides a boxplot distribution. Figure 30 shows this style of analysis for one of the illuminance meters in the sixth floor core zone. From this chart we can get a lot of information about how the light levels varied in time over the course of the study period. The red line indicates the Illuminating Engineering Society of North America (IESNA) recommended minimum illuminance level for an open plan office with intensive computer use. We can see that the lights appear to be off most days from midnight to 6:00AM. There are a few outliers, indicating that it is possible someone was working late one or two days. We can also see that there is greater variation in the evening, which suggests a variation in time of departure for the occupants. Lastly, we can see that for the occupied hours, the light levels are near the recommended level, though often fall below that level in the morning. There are relatively few outliers, suggesting that the operation of the building is fairly consistent between days and appears to have reasonable light levels for an interior zone when considering the accuracy of the sensor. Because this is an interior zone, we can assume that when the light levels begin to drop significantly at 6:00PM, this is the result of interior lights turning off on a schedule rather than the loss of daylight in the space. A higher spatial density of measurements or lighting controller data could enhance the analysis and interpretation of lighting performance in this space.

The second method of lighting analysis involves looking at single days. A user can cycle through hourly data a day at time, looking for outliers or anomalies, such as the lights being on at night. Figure 31 shows the hourly data that corresponds with the circled outliers in Figure 30. In this case, the outliers happened within the same 24-hour period. Note that the data in

Figure 32 starts at 6:00AM and ends at 5:00AM the following day. The hours that align with the outliers are circled. Again, the red line indicates the IESNA recommended minimum illuminance level for this space-type, which is an open-plan office with intensive computer use (30 fc). The chart shows that the light level remains higher than expected for most of the early morning hours but does drop down from 1:00AM – 3:00AM.

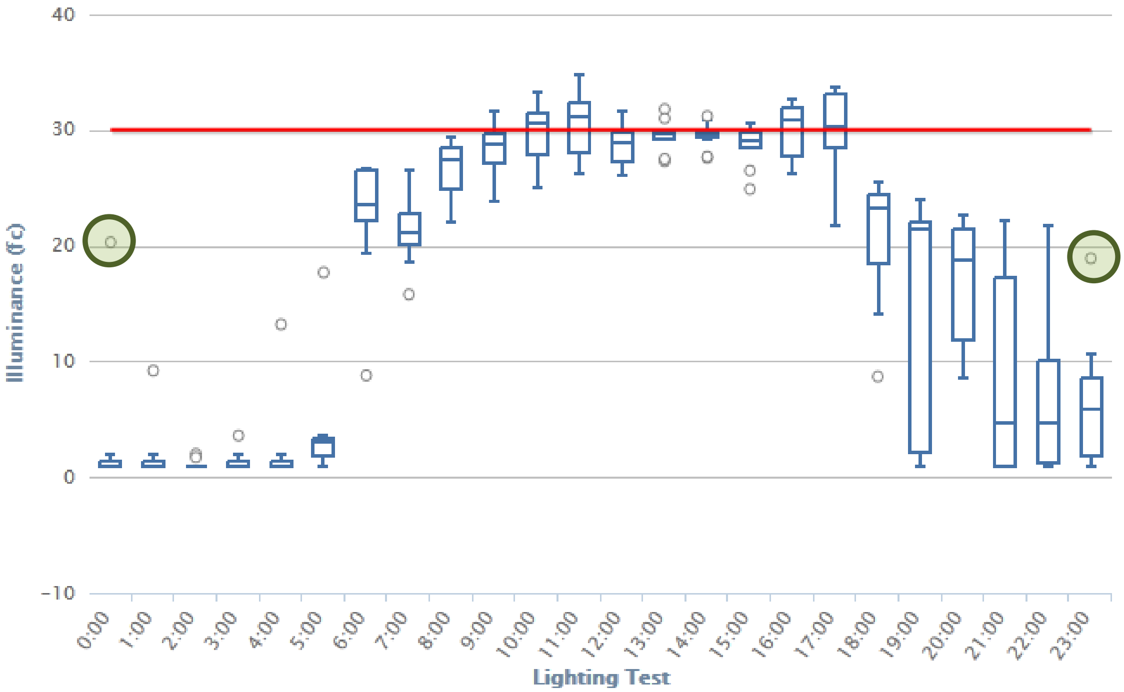


Figure 30: "Average Day" Boxplots of Hourly Light Levels Across Study Period Weekdays for ICM05 in the Sixth Floor Core Zone

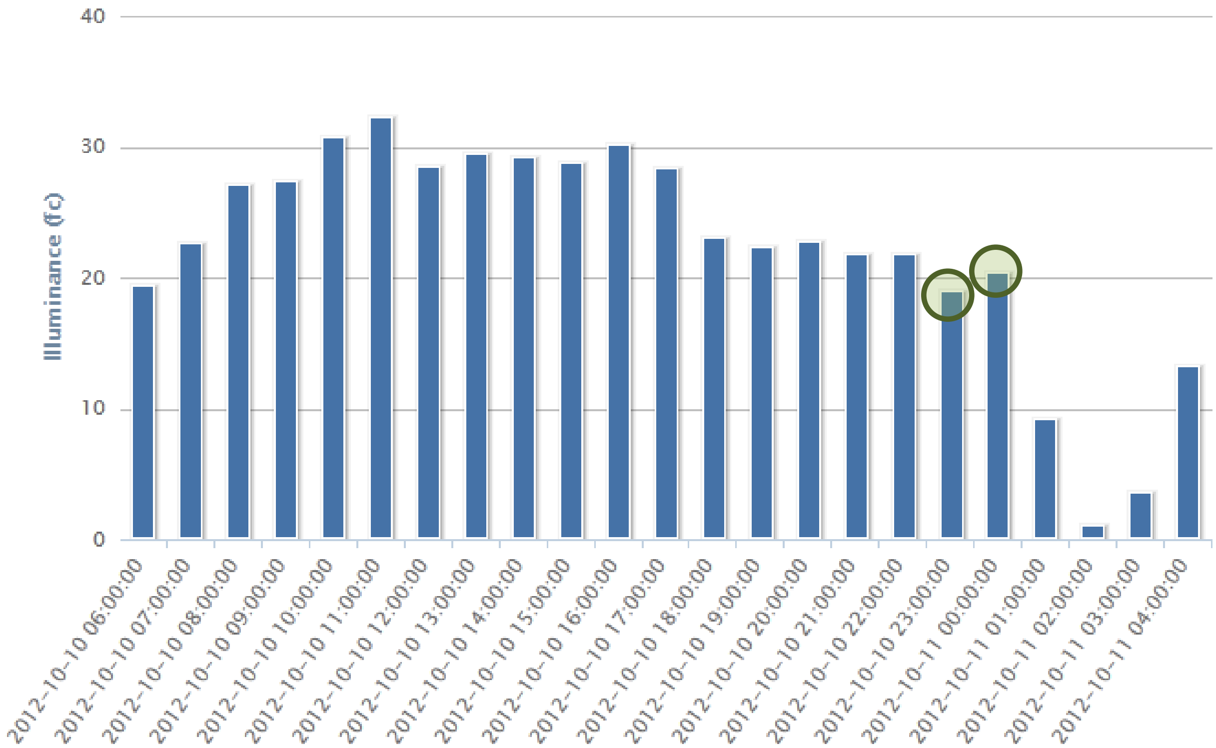


Figure 31: Hourly Light Levels for Sixth Floor Core Zone ICM05 for Thursday 10/10/2012

Figure 32 and Figure 33 show the boxplot "average day" analysis for two perimeter zones on the sixth floor. ICM09 (Figure 32) was placed on a bookshelf approximately 10 ft from a southwest-facing window. As the afternoon sun gets low enough to penetrate deep into the building, the illuminance values rise dramatically (the maximums are cut off in order to keep a reasonable scale). ICM08 (Figure 33) was placed on a bookshelf directly next to a west-facing all-glass corner of the building. The light levels are considerably higher in this zone than in other parts of the building, far exceeding the minimum recommended light level for this space.

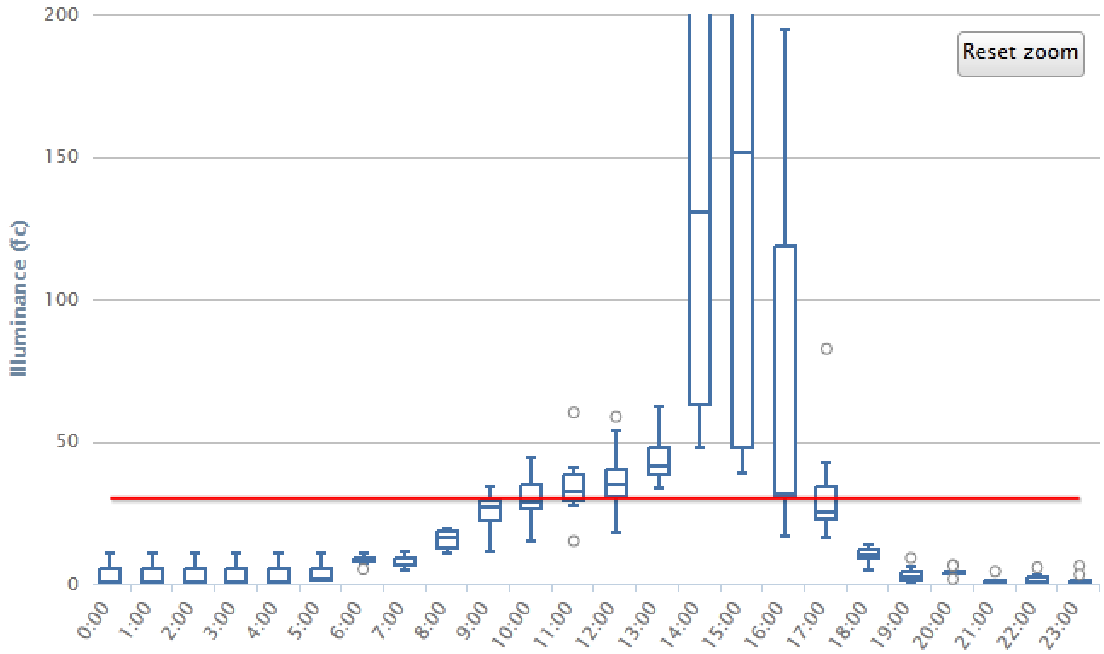


Figure 32: Hourly Light Levels Across Study Period Weekdays for ICM09 in the Sixth Floor Perimeter Zone 6A-17

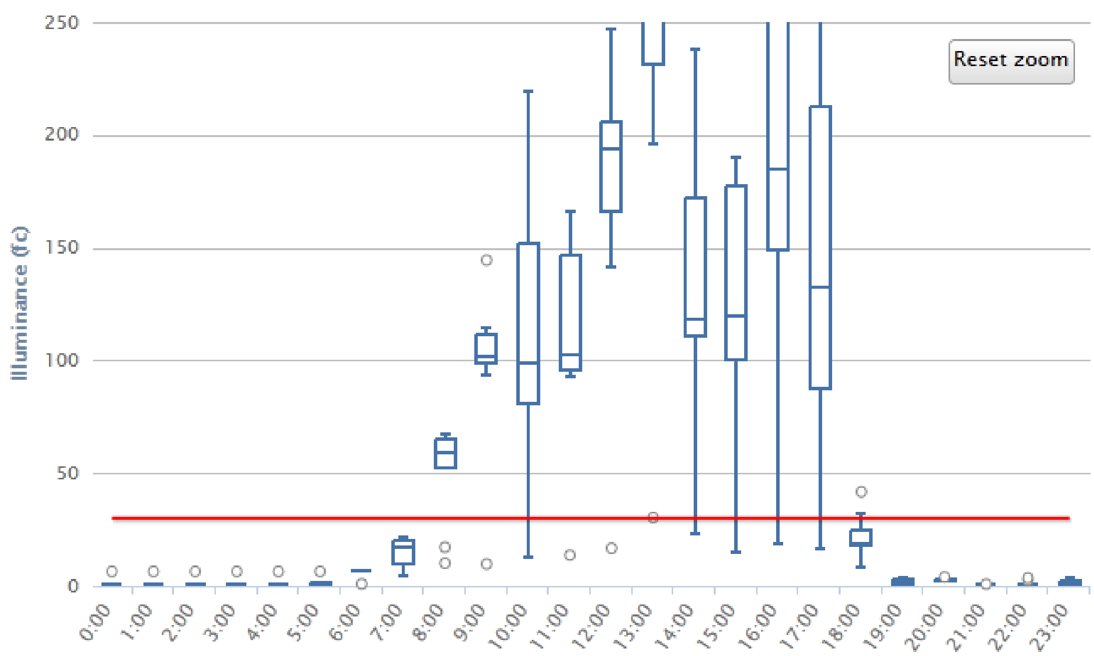


Figure 33: Hourly Light Levels Across Study Period Weekdays for ICM08 in the Sixth Floor Perimeter Zone 6A-22

To summarize the performance of the lighting system we can look at the lighting performance summary model. Figure 34 shows the results of the model when applied to all illuminance sensors during weekdays of the study period from 6:00AM – 6:00PM. All of the illuminance meters were placed in the same space-types, which was the default for the study. The illuminance level needed to be above 300 lux (lx) [28 foot-candles(fc)] in order to meet assessment class 1 and comply with PMP recommendations. The spaces monitored reached this level nearly 70 percent of the time, suggesting that there is a significant portion of time during which light levels may be too low for occupant comfort. Unfortunately, the lighting performance summary model does not capture overlighting because we were unable to obtain zoned electric lighting data (or solar gain data) to correlate high light levels with electric light operation. In the absence of this additional lighting data, we can study the distribution of data for each assessment class in Figure 35. Here we clearly see that the median light level (37 fc) for assessment class 1 is near the cutoff of the class (28 fc) though the upper quartile is quite a bit higher, with multiple extreme outliers. The median for assessment class 2 (22.6 fc) is only slightly below the class 1 cutoff, suggesting light levels are generally quite close to the recommended level (as suggested by the detailed analysis above).

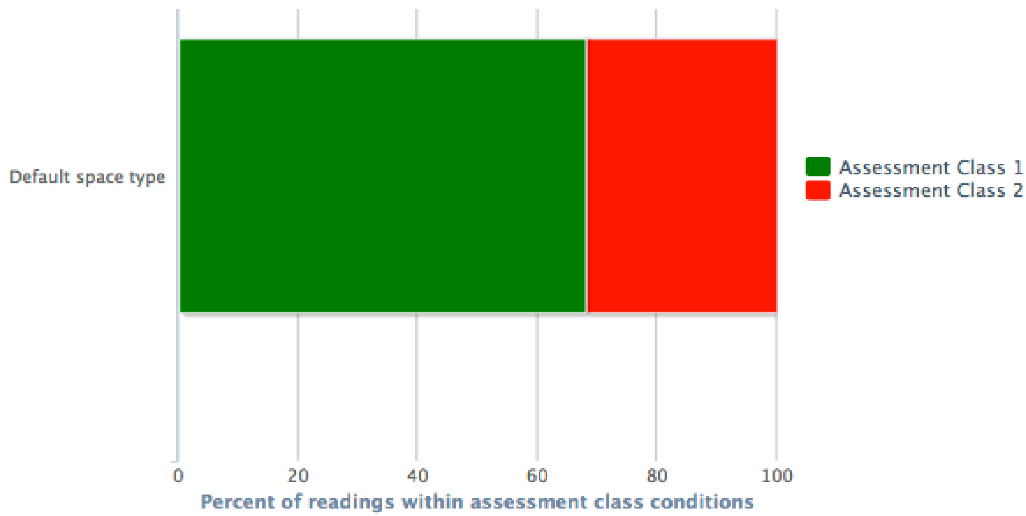


Figure 34: Lighting Performance Summary Model for All Illuminance Sensors

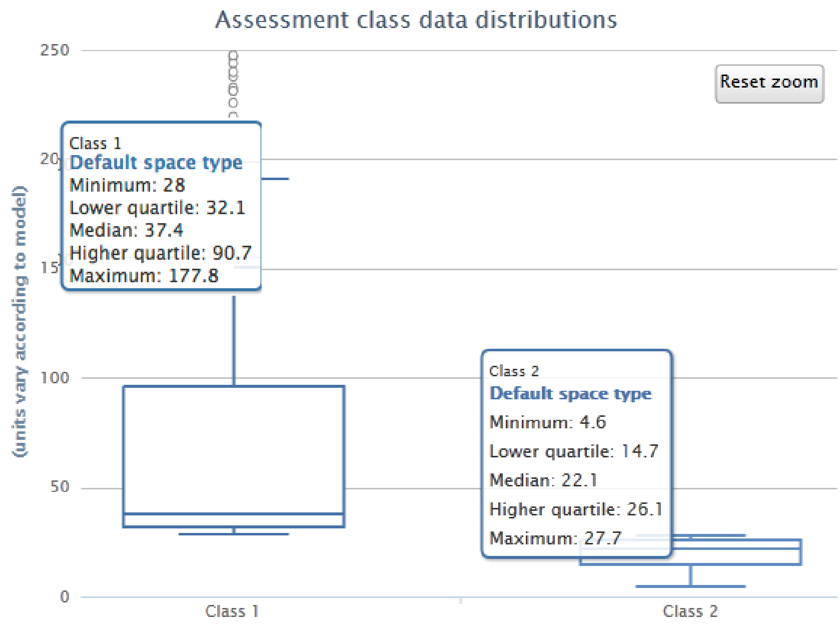


Figure 35: Assessment Class Data Distributions for Lighting Performance Summary Model

4.1.5 Acoustics

The purpose of the acoustics testing was to determine the background noise level in different spaces and how noise level varied over the course of a day in the open-office portion of the office. Background noise level was assessed with A-weighted sound level pressure measurements. Proper protocol involves taking a 5-10 minute reading in a space without talking or other non-background noises present (e.g. a lawnmower outside) and taking the 90th percentile of the readings over that measurement period as the background noise level. For this case study, the protocol was not well communicated to the practitioner using the system and thus the resulting data is not meant to represent an accurate picture of the background noise levels for the WSPFK office. However, the data do provide a general picture of noise levels in the office spaces and how they compare to recommended levels.

One long-term reading (7 hours) was conducted on 10/9/2012 and a series of short-term readings were conducted on 10/10/2012 and 10/11/2012. Figure 36 shows the boxplot summary sound level measurements for each half hour from 8:00AM – 3:30PM for the open office portion of the fifth floor. These measurements represent A-weighted sound pressure levels averaged every five minutes and summarized over each half-hour period. The ASHRAE/Acoustical Society of America (ASA)/ANSI/European Committee for Standardization (CEN) recommended (green – 35 decibel A-weighted (dBA)) and maximum (red – 40 dBA) background noise level for an open-plan office space without sound masking is shown on the chart. Background noise level is correctly measured without any activity in the space, but with the heating, ventilating, and air-conditioning (HVAC) system running. A long-term test such as the one in Figure 36 does not appropriately measure background noise level, but does provide a picture of how noise level varies over the course of a day. Clearly the noise level does not vary much in this office space and is approximately 10 dBA above the maximum recommended background noise level.

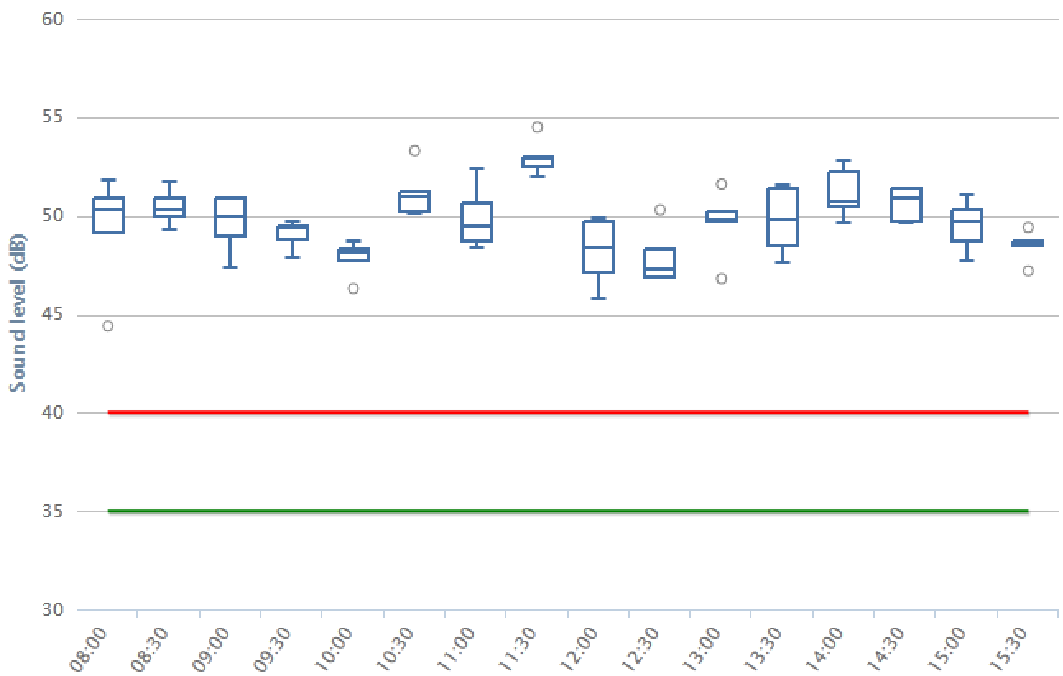


Figure 36: Long-Term level Test on 10/9/2012

Short-term tests (5-minute averages) were taken in two conference rooms and in the open-plan office on the sixth floor. The tests taken in the open-plan office were consistent with the levels shown in Figure 36. Figure 37 shows the short-term tests taken in the two conference rooms. Because these conference rooms were empty during the measurement, they represent actual background noise levels. While one of the conference rooms fell squarely in line with the recommended background noise level of 30-40 dBA for conference rooms, the other conference room aligned more closely with the open-plan spaces. BMS data for the fan-powered boxes in these conference rooms would be needed to determine air flow levels at the times of these tests.

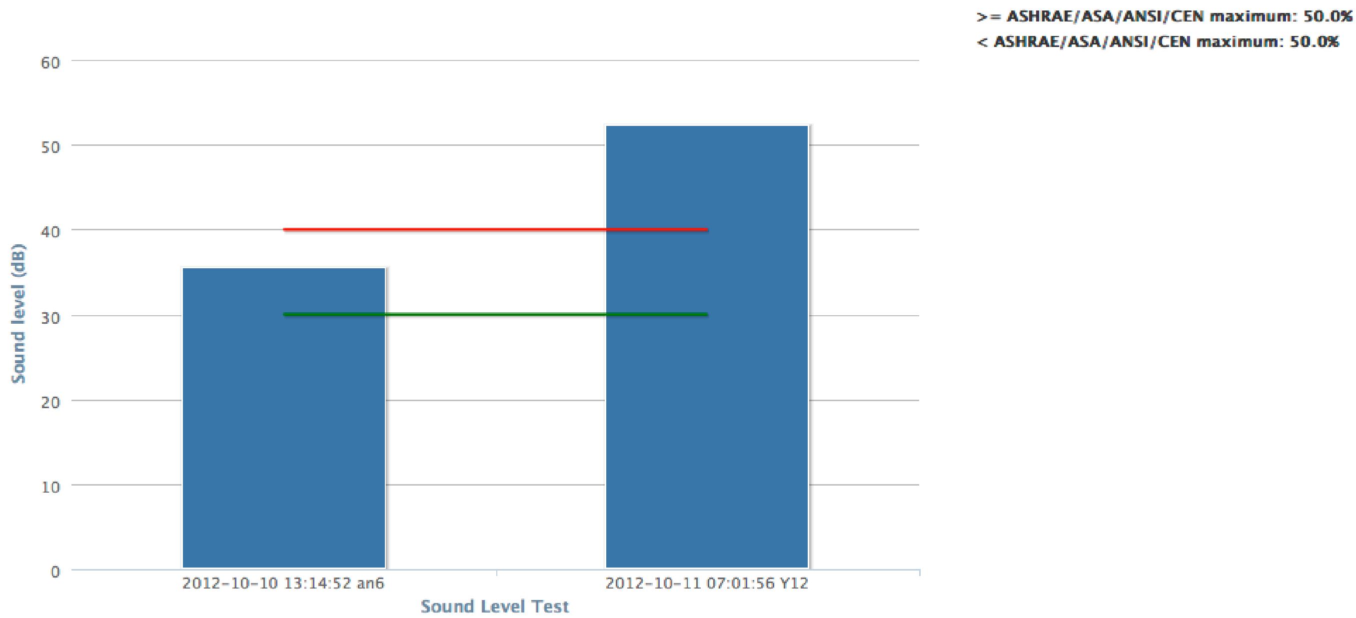


Figure 37: Short-Term Sound Level Tests for Conference Rooms

For this case study, a limited number of spaces were measured for background noise level, providing an incomplete picture of the overall office space acoustical performance. As mentioned before, the lack of complete coverage resulted from the lack of a clear protocol communicated to the practitioner using the sound level meter. Future case studies used the complete protocol outlined in the basic level of the PMP. Because the appropriate protocol was not followed, the acoustics performance summary model shown in Figure 38 is not a true characterization of compliance with PMP recommended background noise levels. We show it here only as an example of how the space might be characterized with this model. Assessment class 1 is defined as having a background noise level less than or equal to 40 dBA and assessment class 2 is anything above that level. The short-term tests taken on 10/10/2012 were used as the dataset for the model.

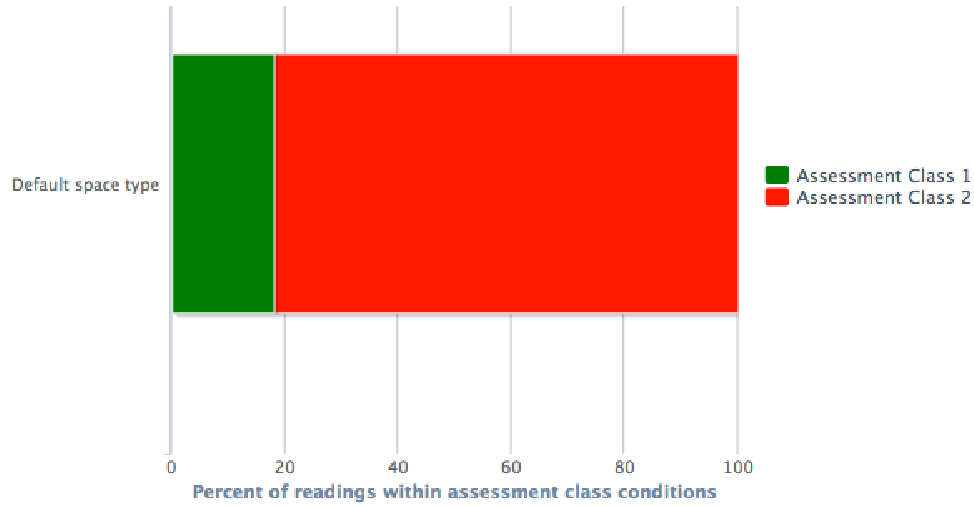


Figure 38: Acoustics Performance Summary Model for Short-Term Tests Taken on 10/10/2012

4.1.6 IAQ

For this case study, indoor air quality was evaluated solely on the basis of CO_2 measurement, which as mentioned previously is merely a proxy for outdoor air flow rates, not quality. The PMP states that CO_2 levels should not exceed 700 ppm above outdoor levels for more than 2 hours. Outdoor CO_2 levels were not monitored for this study, though a National Oceanic and Air Administration (NOAA) monitoring station in San Francisco measured an average CO_2 level of 390 ppm for the study period dates (US Department of Commerce, n.d.).

There were nine CO_2-enabled ICMs placed throughout the office continuously monitoring CO_2 levels throughout the entire study period. The analysis tools available in the Toolkit for IAQ are similar to those available for lighting and acoustics. Figure 39 shows a boxplot analysis of the hourly CO_2 levels across days in the study period for a core zone on the fifth floor. The median values of CO_2 are typically quite low and similar across the day except during the morning hours. The rise in CO_2 levels in the morning is mostly explained by the addition of occupants to the space, but is also the result of the economizer not fully opening during the morning. The BMS data shows that on a typical day during this study period, the economizer dampers begin to open around 9:00AM and throttle to 100 percent by 11:00AM. There are two outliers on most hours of the day, which correspond to the two warm days of the study period (10/1-10/2/2012). On these days the economizer was closed after 11:00AM and ventilation rates decreased to minimum outdoor air. Figure 40 shows the operational hourly data for the same core zone ICM on 10/2/2012, showing that CO_2 levels peaked in the late afternoon. The largest outlier is highlighted in green on Figure 39 and its corresponding data point is highlighted in Figure 40.

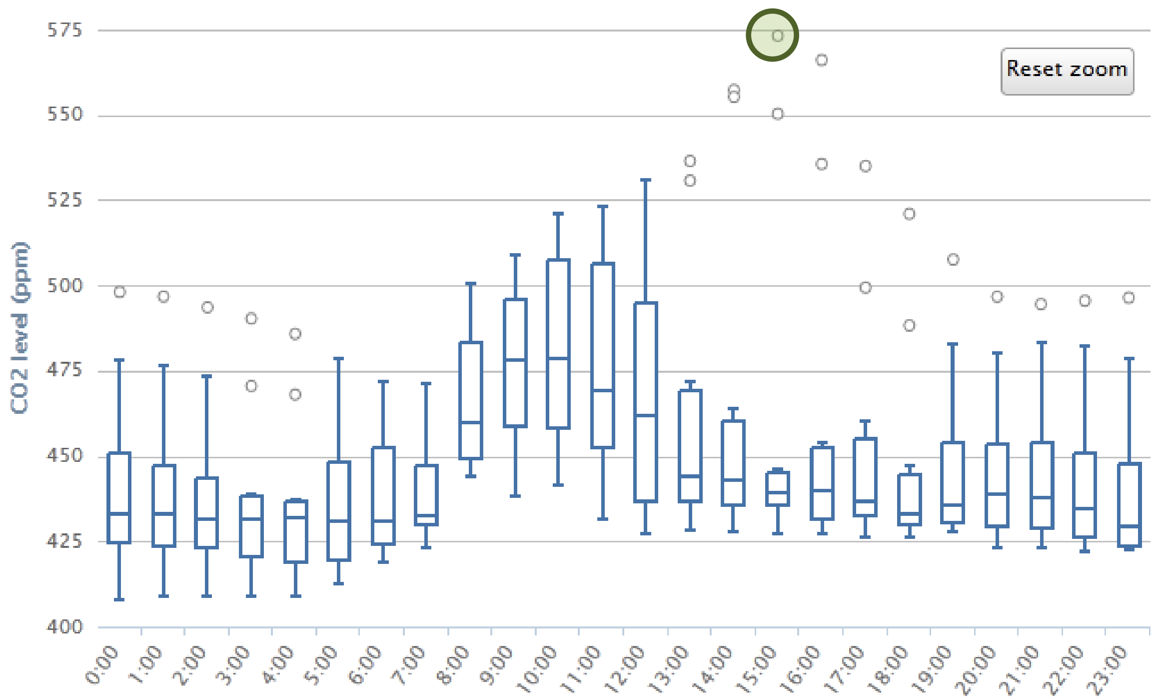


Figure 39: Hourly CO_2 Levels Across Study Period Weekdays for ICM12 in a Core Zone Cubicle on the Fifth Floor

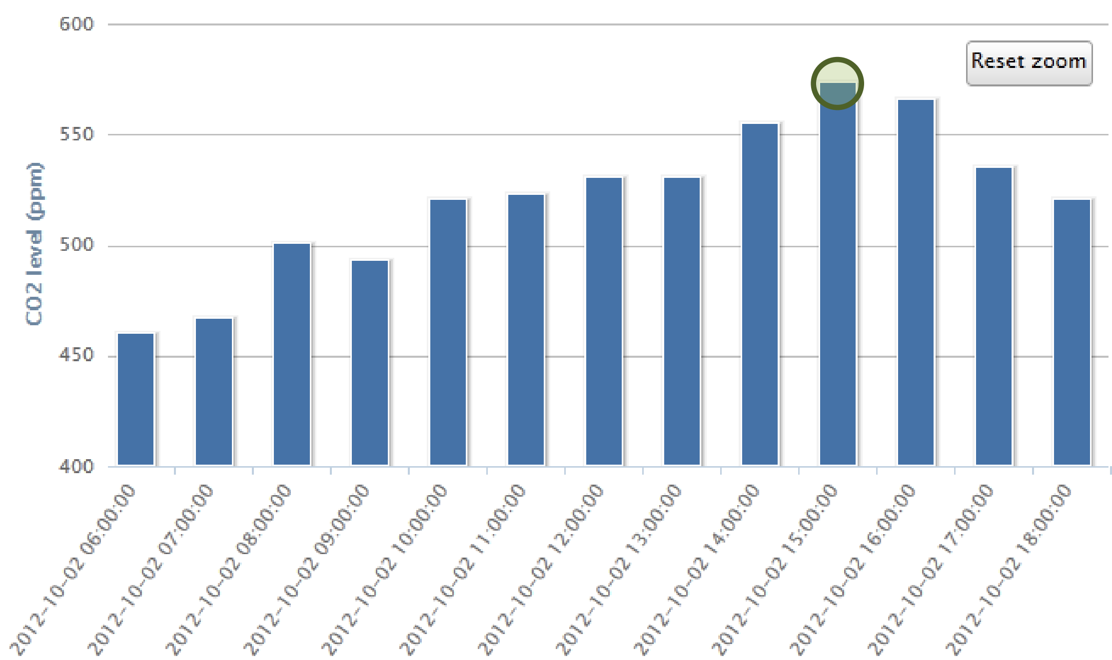


Figure 40: Hourly CO_2 Levels on 10/2/2011 for ICM12 in a Core Zone Cubicle on the Fifth Floor

Figure 41 shows the boxplot analysis of the hourly CO_2 levels across the study period for an ICM in a conference room in the fifth floor. With the exception of a couple of outliers at 9:00AM, the pattern of CO_2 levels is similar to the core zone data discussed above. Figure 42 shows the operational hourly data for the day in which one of those outliers occurred (10/1/2012). In this case, the outlier happened on a hot day that likely coincided with a large gathering in the conference room leading to a spike in CO_2 level at 9:00AM, though levels stabilized shortly after.

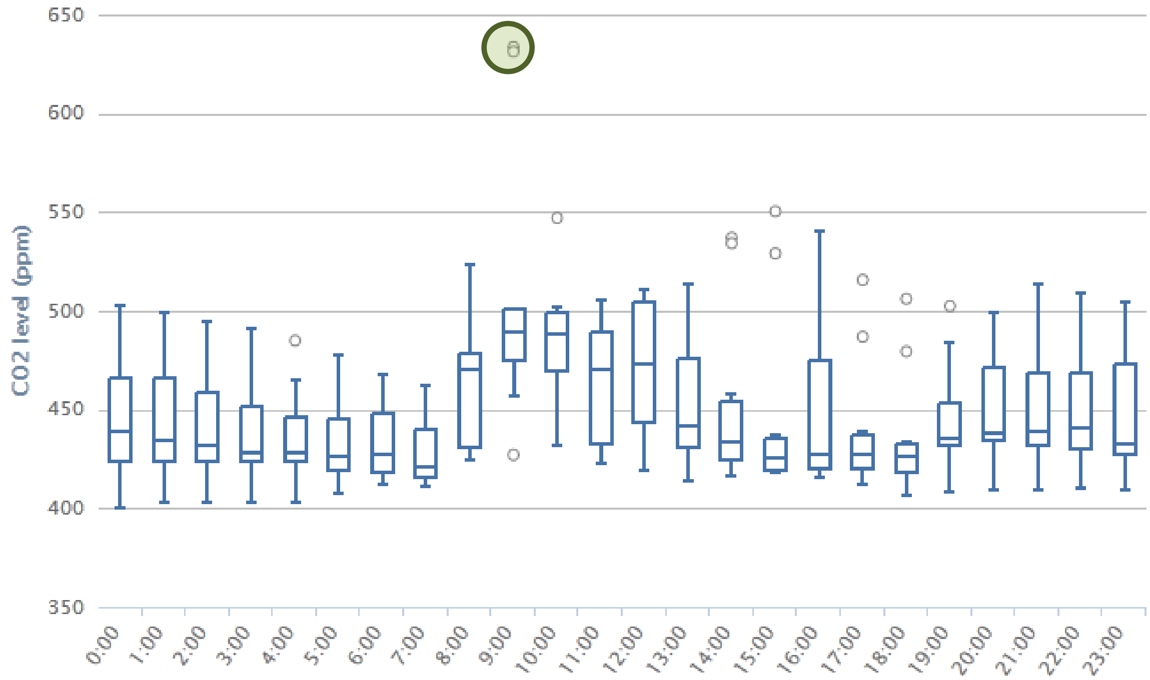


Figure 41: Hourly CO_2 Levels Across Study Period Weekdays for ICM15 in a Conference Room on the Fifth Floor

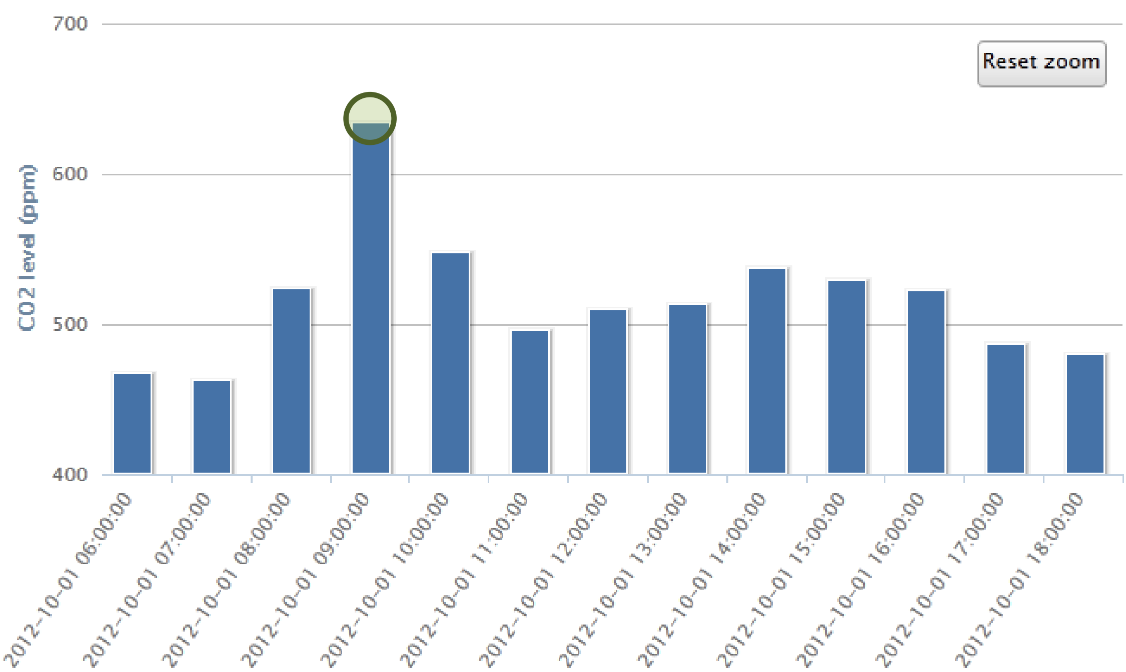


Figure 42: Hourly CO_2 Levels on 10/1/2012 for ICM15 in a Conference Room on the Fifth Floor

None of the CO_2 levels measured in the study approached the 700ppm above outdoor concentration, suggesting good ventilation, which is consistent with the high frequency of economizer operation in the San Francisco climate. The IAQ performance summary model confirms 100 percent compliance with the proposed model limits. In future work we would like to include VOCs, PM_{10}, and $PM_{2.5}$ for more detailed evaluation of indoor air quality.

4.1.7 Survey Results

A CBE survey was given to the occupants at WSPFK and 50 responses (out of 114, 44 percent) were collected. The summary results are provided in Figure 43, where percentages represent the percent of occupants satisfied. While overall satisfaction with the building was high, individual IEQ satisfaction scores were considerably more variable. The next few sections detail the survey results of the acoustics, IAQ, lighting, and thermal comfort categories.

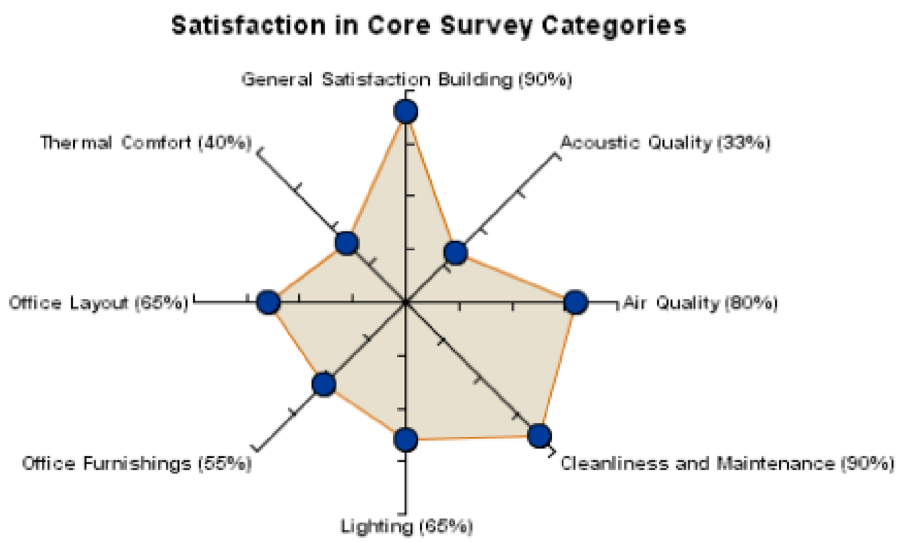


Figure 43: CBE Survey Summary Results

4.1.7.1 Acoustics

The acoustics satisfaction score was quite low, falling into the 27th percentile of the CBE survey benchmarking database. Occupants complained about both sound privacy and noise level, with overhearing other person's phone conversations as the largest source of dissatisfaction. This low satisfaction with acoustics is common in open-plan offices. This building is particularly challenging because of high exposed concrete ceilings and a UFAD system. The UFAD system does not produce much HVAC noise to mask other noises and is often coupled with a sound-masking system that is not present in this building. One respondent suggested that providing wireless phone headsets would allow them to take long phone calls away from the open-plan area.

4.1.7.2 IAQ

The IAQ satisfaction score was the highest among the IEQ categories, corresponding to the 90th percentile of the CBE survey benchmarking database. There were no comments concerning air quality, though 6 percent of respondents (3 people) were slightly unsatisfied with air quality.

Unfortunately these respondents did not provide further information concerning the nature of their dissatisfaction.

4.1.7.3 Lighting

The lighting satisfaction score was relatively low compared to the rest of the benchmarking database, falling into the 36th percentile. The occupant complaints however primarily concerned the lighting controls: occupancy sensors and daylighting sensors. Occupants were largely satisfied with both the amount of light and the visual comfort (glare, reflections, contrast), though complained about occupancy sensors not seeing them, timers being too short, and daylight sensors not working. Unfortunately, the systems designed to save lighting energy are the primary cause of dissatisfaction among occupants. Occupant satisfaction could likely be improved with a tuning of occupancy sensors and timeouts (the amount of time the lights stay on after an occupant has been sensed). Additionally, according to our observations as well as comments in the survey, the perimeter lights do not dim or turn off when sufficient daylight is available, suggesting a problem with the daylight harvesting controls.

4.1.7.4 Thermal comfort

The thermal comfort satisfaction score was relatively low and corresponded to the 50th percentile of the CBE survey benchmarking database. Thirty eight percent of the 50 respondents were dissatisfied with the temperature, with all but two of 18 respondents who responded to further questions complaining that the building was too cold. There was not a dominant source for this discomfort, though high air movement and drafts from vents were cited the most (28 percent and 22 percent respectively). The cold complaints are consistent with the measured data that showed that the building was controlling to the colder end of the comfort range.

4.1.8 Case Study Conclusion

The WSPFK case study provided important feedback on the Toolkit as well as insight into building operation, performance, and occupant satisfaction. The primary issues found during the case study included:

- Daylight sensors do not seem to be working properly
- Occupancy sensors and timers need tuning
- Temperature within the open plan office space is on the low end of the comfort range, resulting in cold complaints from occupants
- Sound levels are high in the open plan area, leading to complaints from occupants

These issues are common among buildings—the first three items are easily tuned, while the fourth requires potentially more complex solutions and investments (sound masking, wireless headsets, sound-absorptive panels).

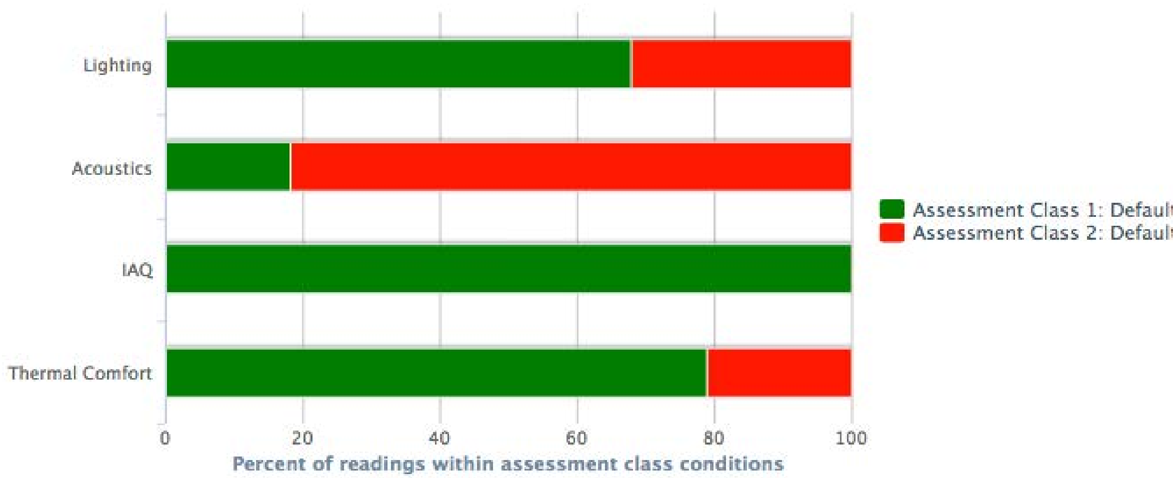
Figure 44 shows the Toolkit scorecard results, displaying the scores from the survey and the measured data. The survey results did not exactly match the measured results (with the exception of lighting), though with the exception of thermal comfort, they matched relative to one another. Thermal comfort stands out as the largest discrepancy between subjective and objective measures. Part of this discrepancy can be explained by the fact that the IEQ model uses a fixed clothing and metabolic rate corresponding to a fixed comfort range. If the clothing level is lowered from 0.8 to 0.7 clo, the measured thermal comfort score drops from 79 to 30, highlighting how close most of the data is to the bottom end of the comfort range (as the clothing level is reduced, the comfort range shifts up) and how sensitive the model is to the clothing and metabolic rate assumptions.

IEQ Model: PMP

Scorecard

Category	Survey	Measured
Energy		
Water		
Thermal Comfort	40	79
Lighting	65	68
Indoor Air Quality	80	100
Acoustics	33	18

IEQ Indices



Environmental Quality Indices
Default: 56

Figure 44: Scorecard for WSPFK Study With the PMP IEQ Model

This study was not meant to provide a detailed comparison of subjective and objective measures. In order to appropriately align such measures, a more detailed survey protocol that aligns objective measurements with occupant responses in both space and time (such as "right-now" surveys) would need to be conducted. That said, there is promising alignment between the general occupant survey and the results obtained from applying the PMP-based IEQ model to the objective measurements. Many more case studies would need to be performed in order to assess whether this alignment occurred through chance or through a statistically significant relationship.

4.2 Syska Hennessy

4.2.1 Background

A case study was performed on a small section of a major office building complex in Los Angeles, California. The tenants of the space, Syska Hennessy, 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 square meters (m^2) (23,633 ft^2) gross floor area, 1 floor
- UFAD system, with one section of chilled beams
- CO_2 demand-controlled ventilation

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.

Figure 45 shows the floor plan of the space divided into colored zones with the dots representing locations where measurements were taken and the type of measurement taken. "Cart" refers to the PUCC. There were 15 ICM devices placed, 13 cart measurements taken, and 8 sound-level measurements taken to provide good coverage of the office space.

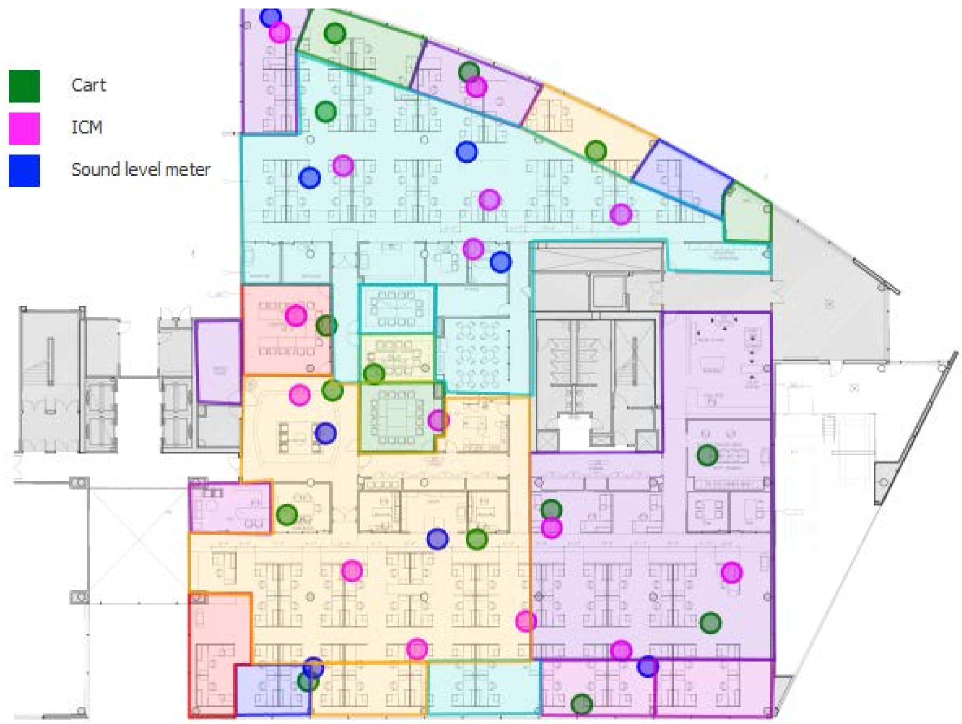


Figure 45: Floor Plan Divided into Zones Showing Where Measurements Were Taken

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 46 shows a screenshot of the scorecard webpage for the case study building.

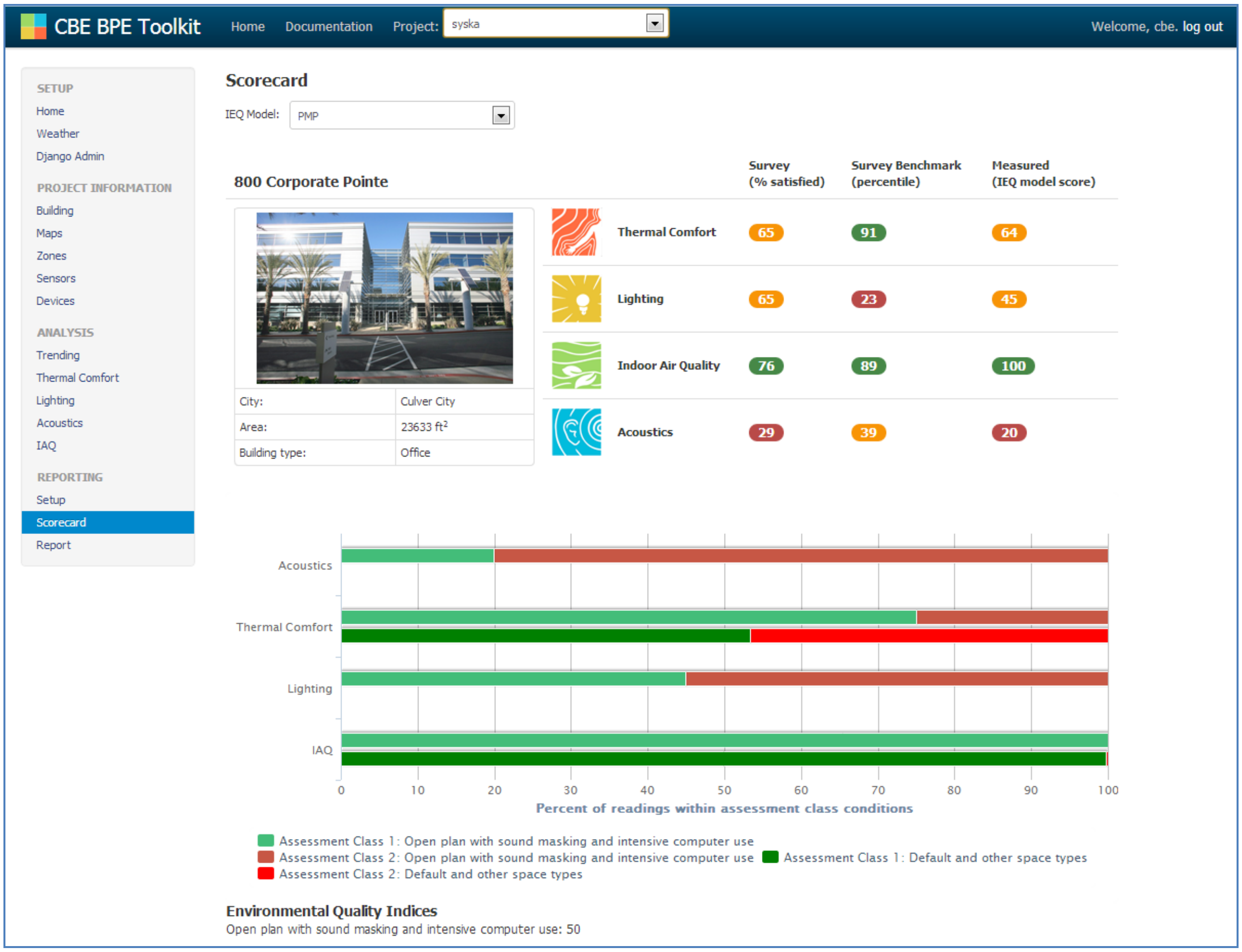


Figure 46: Scorecard Webpage for Case Study Building

Scorecards, as described in (Heinzerling et al., 2013), 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 CBE Survey (CBE, 2008) was conducted with a 20 percent response rate (17 out of 85), which is lower than the typical 50 percent response rate needed to ensure a representative sample. 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. The scorecard in Figure 46 suggests 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 (Marino et al., 2012). 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 3. The “"“ symbol in Table 3 means that the condition is not different from the condition specified in the “Default” space-type row.

Table 3: Assessment Conditions for Objective Measurements Scorecard Results (see (Heinzerling et al., 2013) for More Details)

Space-type	Acoustics	IAQ	Lighting	Thermal Comfort
Default (open plan office with intensive computer use and no sound masking)	dBA ≤ 40	CO_2 ≤ 700 ppm above outdoor CO_2	300 ≤ lx ≤ 2500	-0.5 ≤ PMV ≤ 0.5
Open plan office with intensive computer use and sound masking	dBA ≤ 45	"	"	"
Open plan office with intermittent computer use and no sound masking	"	"	500 ≤ lx ≤ 2500	"
Open plan office with intermittent computer use and sound masking	dBA ≤ 45	"	500 ≤ lx ≤ 2500	"
Conference room - televideo conference	dBA ≤ 30	"	500 ≤ lx ≤ 2500	"
Lobby / stairway	dBA ≤ 50	"	100 ≤ lx ≤ 2500	"
Private office	"	"	500 ≤ lx ≤ 2500	"

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.

4.2.2 Acoustics

Acoustics is the first category that jumps out as low-performing, with 29 percent occupant satisfaction and a 20 percent 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 47). While the boxplot analysis of background noise level (dBA) provides a limited measure of acoustical performance, they are 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, a standard method for identifying outliers). Follow-up measurements of speech privacy using the procedure outlined in (Salter & Lawrence, 2012) 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.

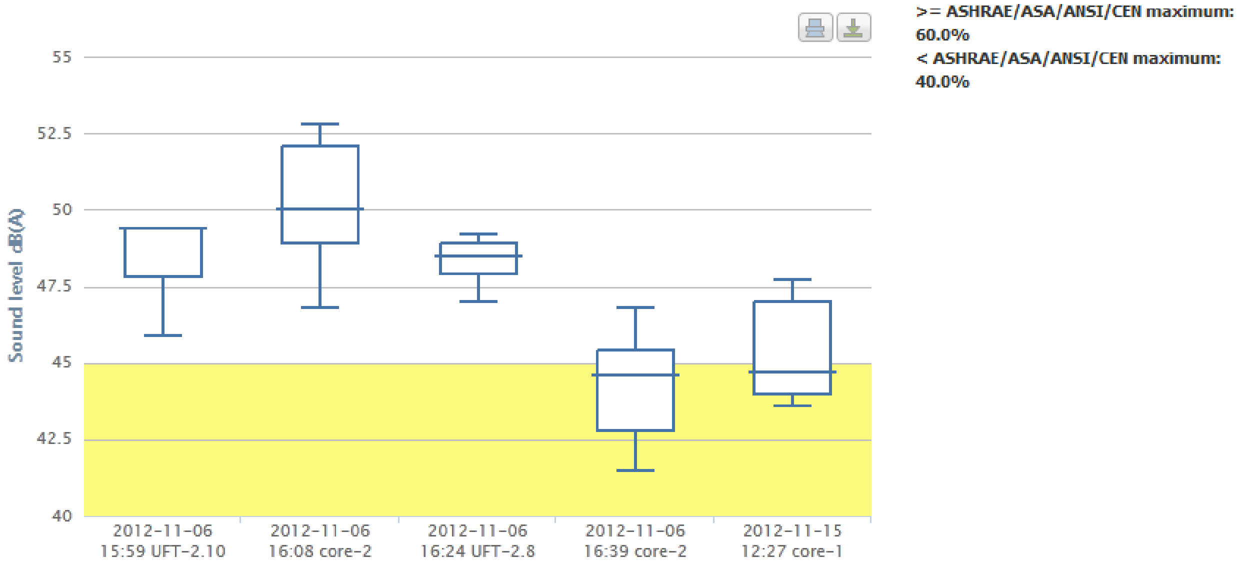


Figure 47: Boxplots of Background Noise Level Measurements Taken during the Case Study. Yellow Represents Recommended dBA Range for Open Plan Office With Sound Masking.

4.2.3 Lighting

The lighting survey results (65 percent 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 that 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 percent 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) (IES, 2000). 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 bins daily data into hourly bins, and then averages those bins across all days in the study period, resulting in an "average-day" of hourly illuminance levels (Figure 48). This chart allows users to select the IESNA recommended level, which is 300 lx in Figure 48, 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).

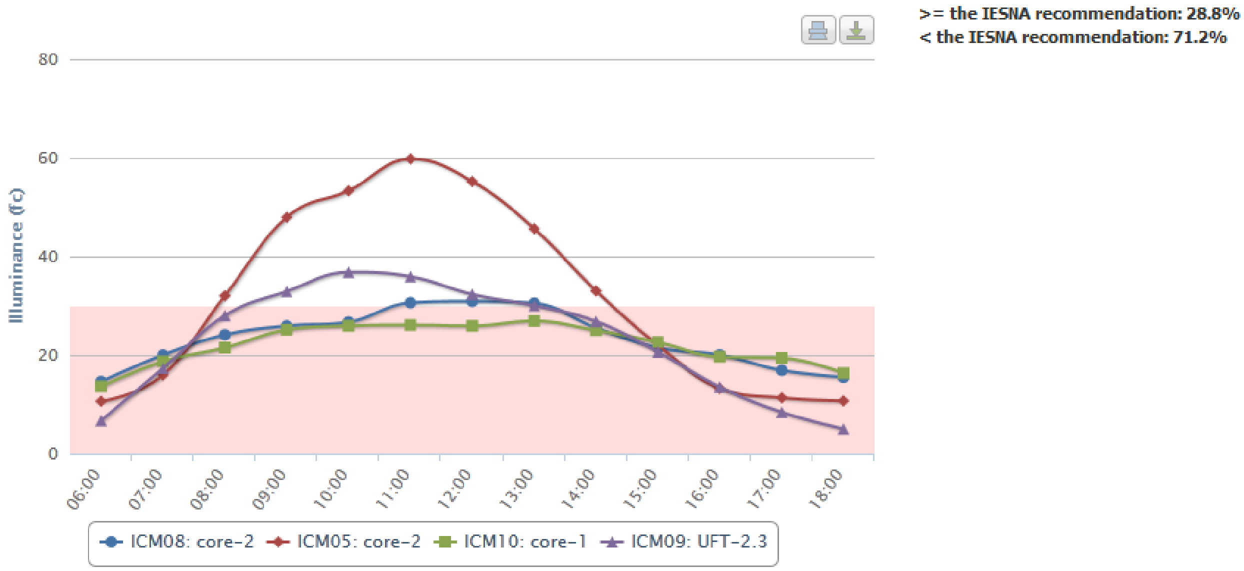


Figure 48: Average-Day Time-Series Plot for Illuminance Levels Over Study Period

4.2.4 Thermal Comfort

The thermal comfort subjective (65 percent 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 (PMV and PPD). While there is disagreement concerning the applicability of the PMV/PPD model (Arens, Humphreys, de Dear, & Zhang, 2010), it offers a good starting point for predicting occupant satisfaction with specific environmental conditions. The PMV/PPD is quite sensitive to changes in met and 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 method of analyzing comfort data under a wide range of comfort parameter values (Hoyt, Schiavon, Moon, & Steinfeld, 2012). Figure 49 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. It is important to note however that because each data point has a different operative temperature, the compliance boundary is different for each point, but only shown for the conditions chosen on the left. 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 50 as the room with the lowest score (9). In Figure 50, 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.

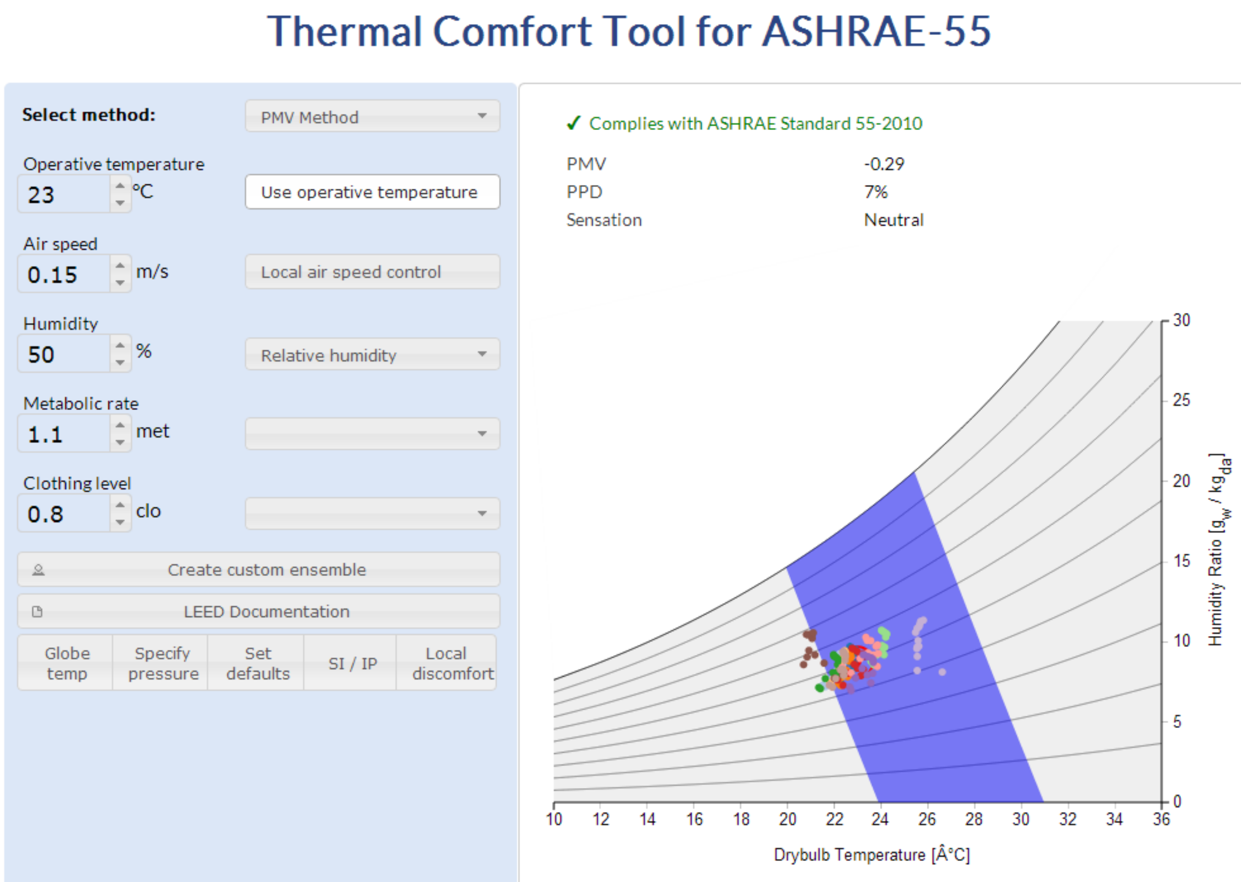


Figure 49: ICM Thermal Comfort Data Plotted on Psychrometric Chart of Thermal Comfort Tool

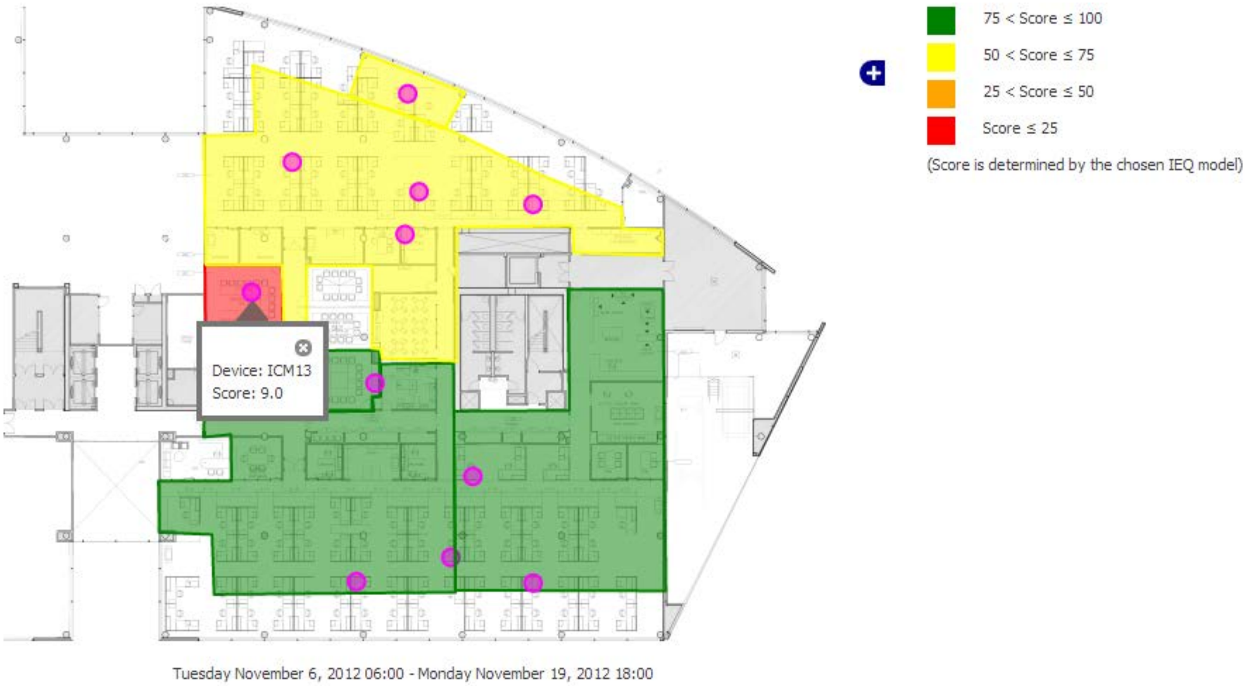


Figure 50: Map of ICM Thermal Comfort Scores

4.2.5 Indoor Air Quality

Both the objective and subjective measures indicate high indoor air quality. IAQ is a complex combination of factors that are not fully captured by both the subjective and objective measures. The only objective measurement, CO_2 levels, is a proxy measurement for ventilation. The limitations of IAQ subjective and objective measures are discussed further in the Discussion section.

4.3 GLL Real Estate (199 Fremont, SF)

4.3.1 Background

A case study was performed on one floor of a major office building complex in San Francisco, California. The study period lasted two weeks: June 7 – June 21, 2013. The tenants of the space are a major insurance company. The design mechanical engineer for the building helped to run the study and was trained on the Toolkit before deployment. The study was designed to test the Toolkit and obtain feedback on usability and operation. The characteristics of the studied space are:

- 15,000 square feet (sf), 1 floor
- Variable air volume (VAV) air distribution system
- Occupant adjustable thermostats

The case study results presented here are not meant to be exhaustive, but rather highlight aspects of the Toolkit that have not been highlighted in the previous two case studies.

Figure 51 shows the floor plan of the space divided into colored zones with the dots representing locations where measurements were taken. The pink dots represent ICMs and the blue dots represent sound level meter measurement locations.

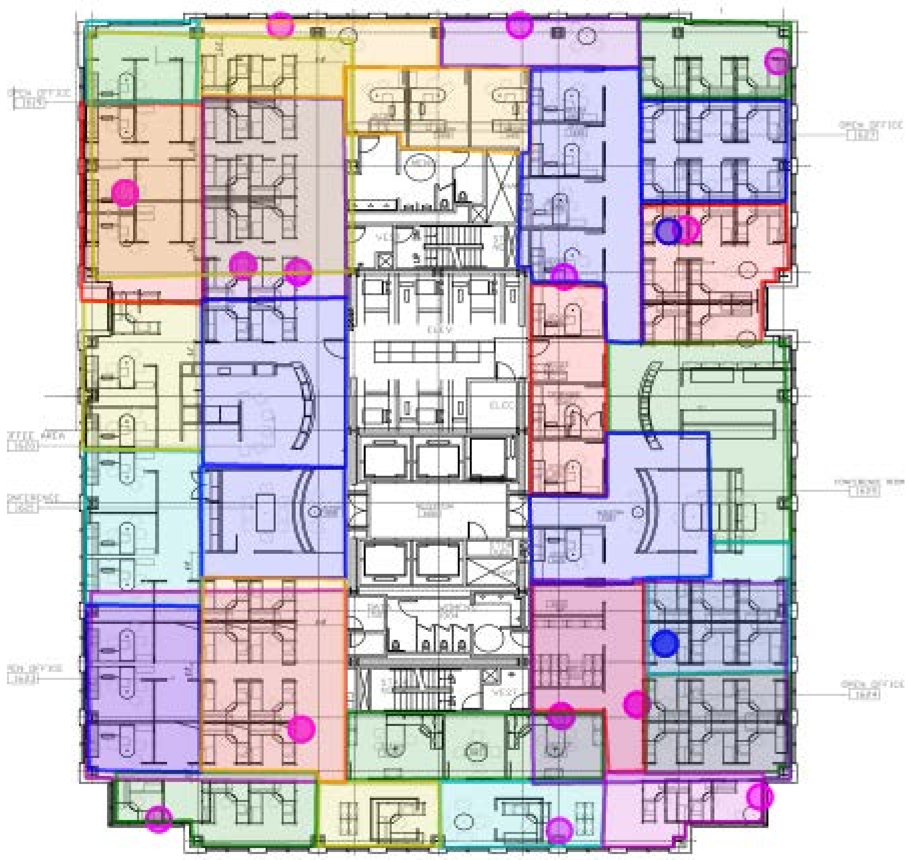


Figure 51: Device Map of 199 Fremont

A CBE survey was conducted over the course of three weeks surrounding the measurement period. Unfortunately, only 18 respondents responded out of 60 (30 percent response rate). Because of the low response rate, the survey results are not necessarily indicative of the overall opinion of the space. The overall results of the survey and a summary of the physical measurements are presented in the scorecard in Figure 52.

199 Fremont Office Building

199 Fremont Office Building	Survey Benchmark (percentile)	Survey (% satisfied)	Measured (IEQ model score)
Thermal Comfort	62	33	78
Lighting	22	60	96
Indoor Air Quality	31	40	100
Acoustics	21	27	50

City:	San Francisco
Area:	462000 ft^2
Building type:	Office

Figure 52: IEQ Scorecard for 199 Fremont

4.3.2 Acoustics

The survey results (27 percent satisfied, 21st percentile) suggest dissatisfaction with acoustics. The occupants' primary complaints were overhearing neighboring conversations and people talking on the phone. These complaints are common for an open office layout and relate primarily to speech privacy, which our acoustical measurements did not determine. Three occupants complained of HVAC mechanical noise, which relates to background noise, which the Toolkit measures with a sound level meter. For this study, the first two background sound level measurements were made during normal operating hours (11:40AM and 11:45AM), and the other four measurements were taken before or after normal operating hours. Thus, the first two measurements include background conversation noise and the last four measurements only include the background noise of the HVAC system. The measurements were taken as the Leq_{95} (the 95th percentile of all readings during this 5 minute period) of a 5 minute period of 1 second readings. The last three measurements were the only measurements to fall within the ASHRAE/ASA/ANSI/CEN recommended range of background noise level for an open plan office without sound masking, the lowest being during the afternoon (5:40PM).

As a small sample of acoustical measurements across the floorplate, these measurements do not indicate a major problem with background noise levels, though the higher sound level reading in zone VAV32 suggests the potential for further investigative measurements in that area.

Ideally the locations of the three occupants who complained about HVAC noise could be measured again to determine if there was a zone specific problem (e.g. a noisy diffuser or VAV box directly above an occupant's desk).

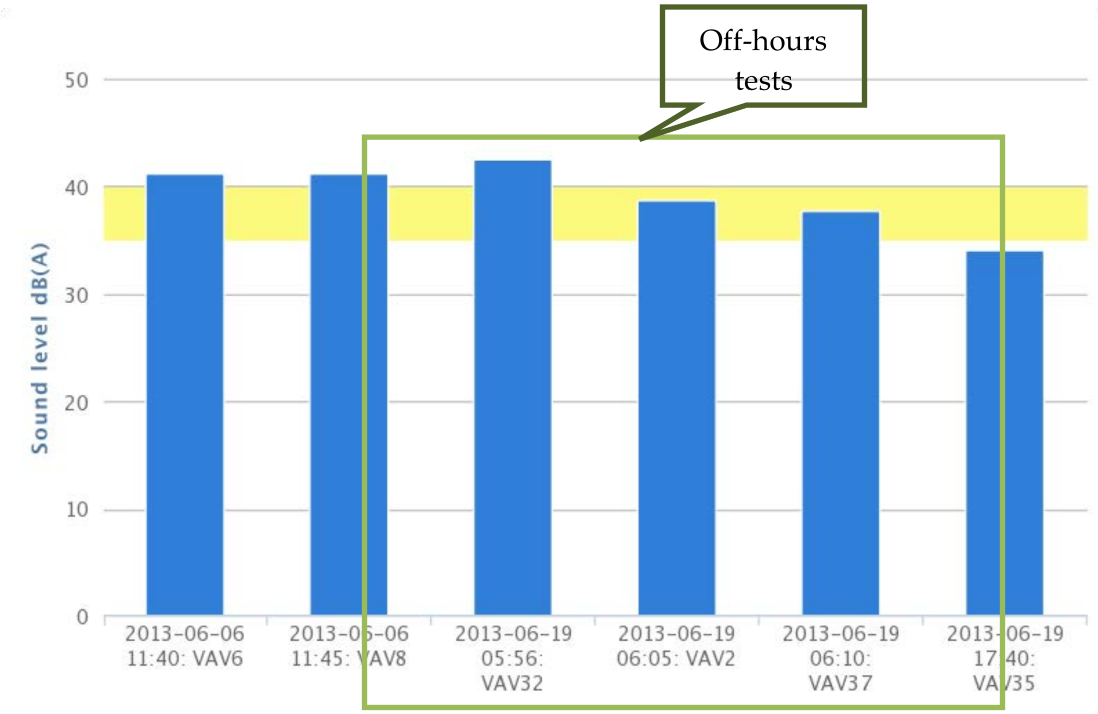


Figure 53: Background Sound Level Measurements for 199 Fremont

4.3.3 IAQ

The survey results (40 percent satisfied, 31st percentile) suggest dissatisfaction with IAQ. IAQ is difficult for occupants to perceive and is often conflated with thermal comfort. The written survey comments suggest a potential problem with allergens in the building (sneezing) and a perception that the air filters are not replaced often enough. This floor does not have a dedicated economizer but is supplied outside air via a dedicated outside air system from central system for the upper floors.

The measured results suggest that there is not a serious problem regarding outdoor air flow. The CO_2 levels in the space never rose above 900 ppm and typically peaked around 750 ppm during the day (see Figure 54), resulting in a IAQ score of 100. The Toolkit's inability to measure IAQ beyond CO_2 highlights, a weakness in its ability to match measured results with occupant satisfaction. A more in-depth study would be required to better understand the occupants' perception of poor IAQ in the space.

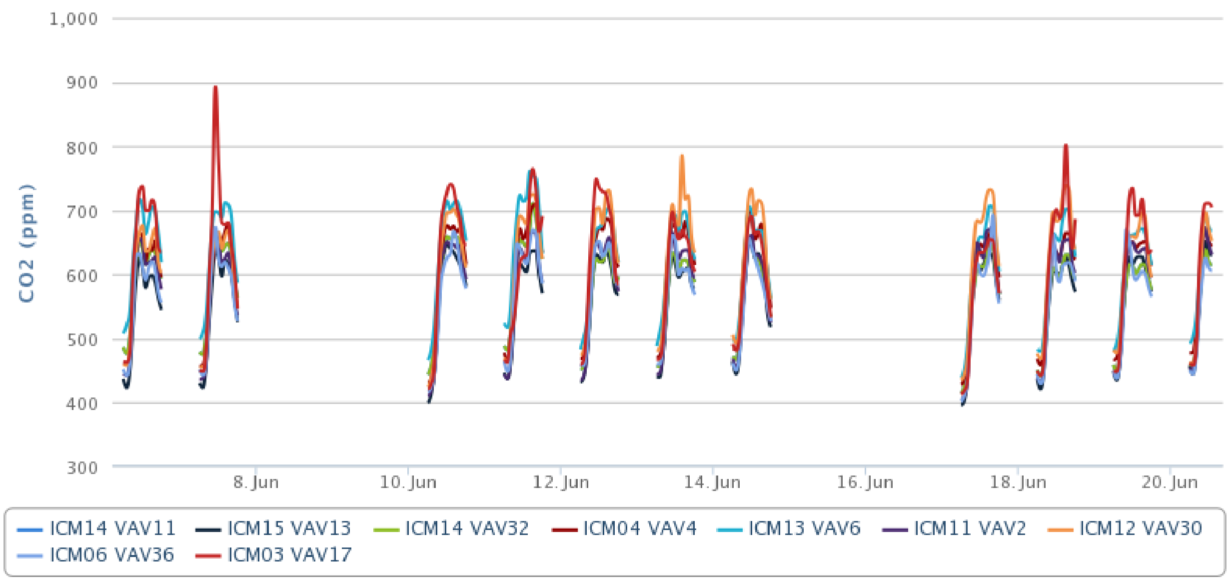


Figure 54: CO_2 Levels During Study Period

4.3.4 Lighting

The survey results for lighting (60 percent satisfied, 20th percentile) were the highest in terms of percent of occupants satisfied. The measured score was 96, indicating that nearly 100 percent of occupied hours were characterized with a light level at or above the IESNA recommended level. The occupants did not provide written feedback on what may have been an issue with regards to light quality, though only one occupant indicated dissatisfaction with both light level and visual comfort. Figure 55 shows how the light levels varied over the course of one week. ICM 05 was placed on top of a filing cabinet shaded from a light source, which is consistent with the lower light levels recorded. However, the light levels are still above the recommended light level (28 fc) for almost the entire week. All light sensors were placed in the core of the building to provide an indication of illuminance under electric light rather than sunlight. Neither the measured results nor the survey results point to any serious problem with the lighting quality in the space.

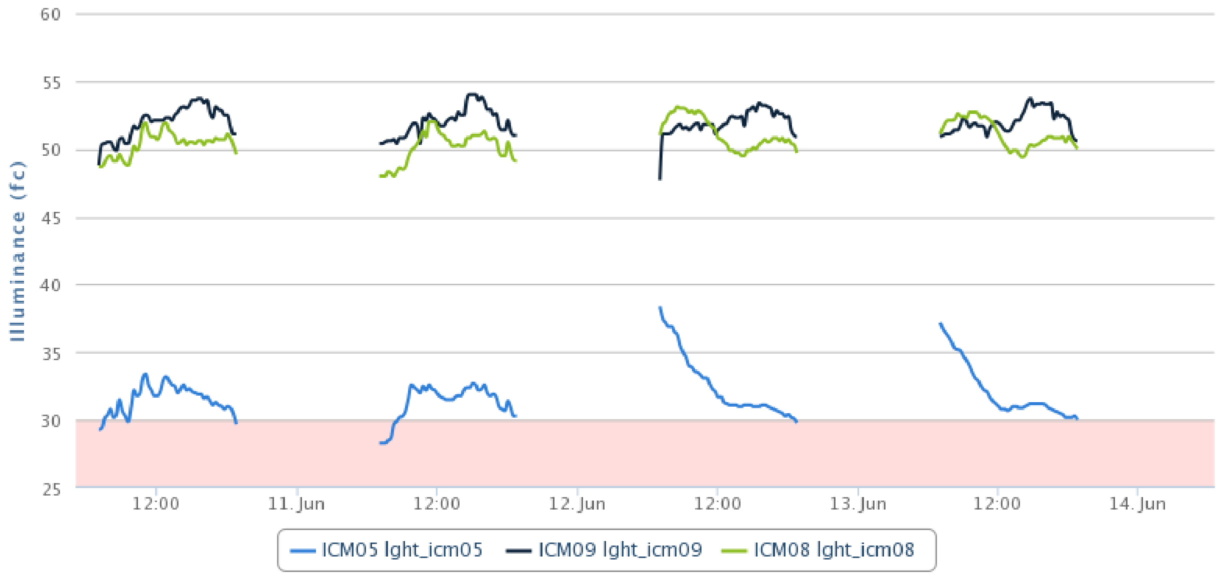


Figure 55: Light Levels During the Study Period

4.3.5 Thermal Comfort

The survey results for thermal comfort (33 percent satisfied, 62nd percentile) indicate potential issues with the thermal comfort conditions of the space. With a small sample of occupants, 33 percent of whom indicated a neutral response, it is difficult to extend these survey results as a broad measure of thermal comfort in the space.

The measured results score (78) suggests that the building is largely controlling to conditions that meet ASHRAE Standard 55 comfort conditions. Figure 56 shows the average day thermal comfort results for all ICMs over the study period. Each dot represents an average hourly value (averaged each day over the two-week study period) and is colored according to the thermal sensation scale. Some of the dots are light blue indicating slightly cool conditions and some are yellow, indicating slightly warm conditions. The operative temperature readings for the same average day results are shown on a time series chart in Figure 57. This time series chart shows that the operative temperature is kept stable during the day between 70 and 75 degrees F with the exception of three zones: VAV2, VAV3, and VAV10. Each of these three ICMs were placed next to windows and their readings are consistent with their location relative to the sun (VAV2 and VAV3 are in the northwest section of the building—peaking in the afternoon, and VAV10 is in the southeast—peaking in the morning). In these instances, the globe temperature is significantly higher than the air temperature, indicating high solar load. This could result in significant discomfort for occupants that are directly next to the windows during these times of day. The survey responses indicate that some occupants are too hot and others are too cold, which could be a factor of where the occupants sit (cold in the interior and hot at the perimeter).

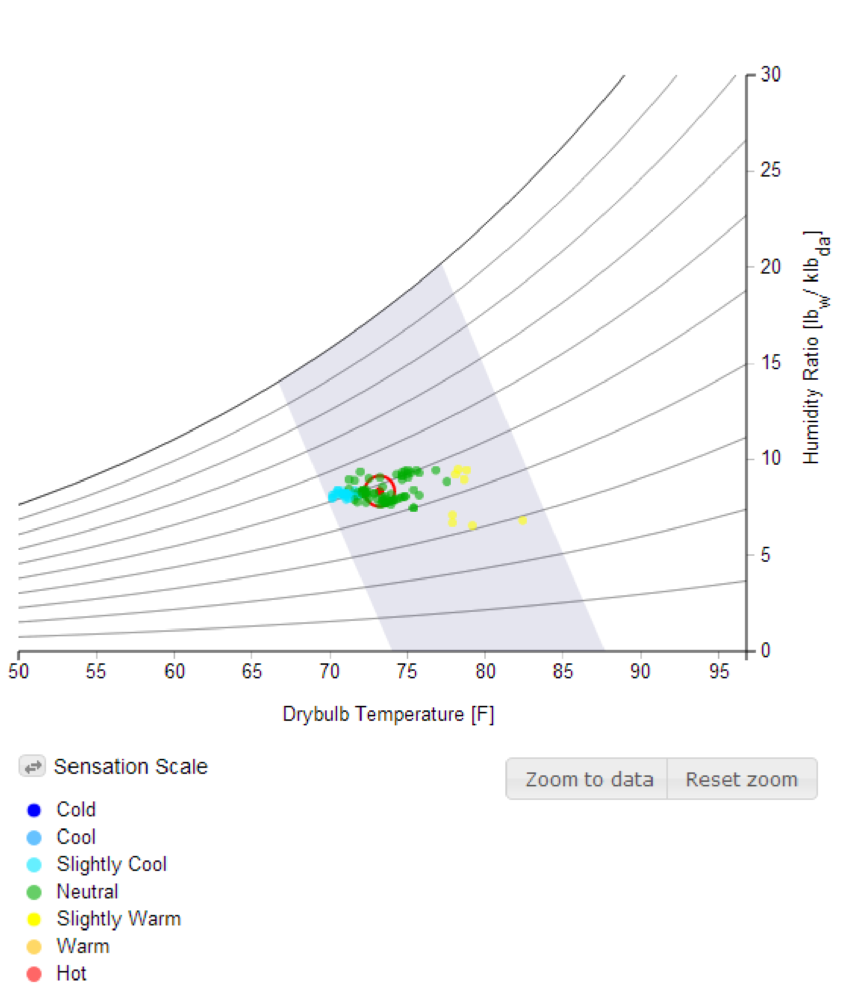


Figure 56: Average Day Thermal Comfort Results for Study Period

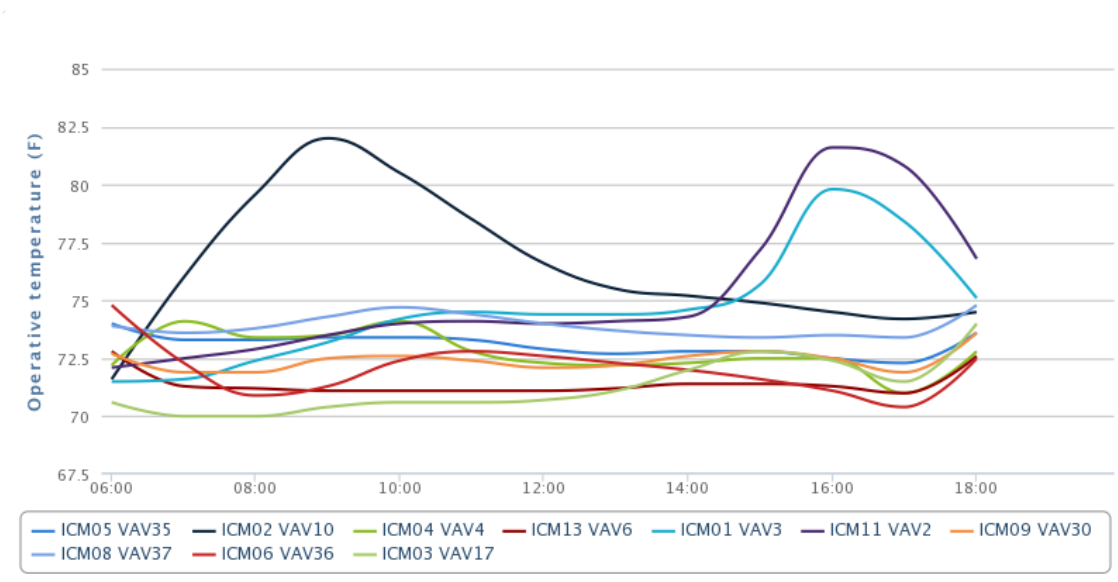


Figure 57: Average Day Operative Temperature Results for Study Period

The measured thermal comfort results indicate that while there is room for improvement, the building is largely under thermal control in a range that is acceptable according to ASHRAE Standard 55. Another way of analyzing the thermal comfort performance of the building is to determine how well the building is meeting the building/occupant controllable temperature setpoints. The occupants are able to change the thermostats in their spaces within a tight temperature range (we were told 70-74 by the building engineer). This tight range turned out to be broader than expected according to the BMS data that was obtained during the testing period. Figure 58 shows how the setpoints varied during one week of testing. There are multiple VAV zones overlapping in each line color, but we can see that only one zone (VAV34) changes setpoint at all during the week and one zone (VAV35) has an unreasonably high setpoint (85 degrees F) that is likely a control point error.

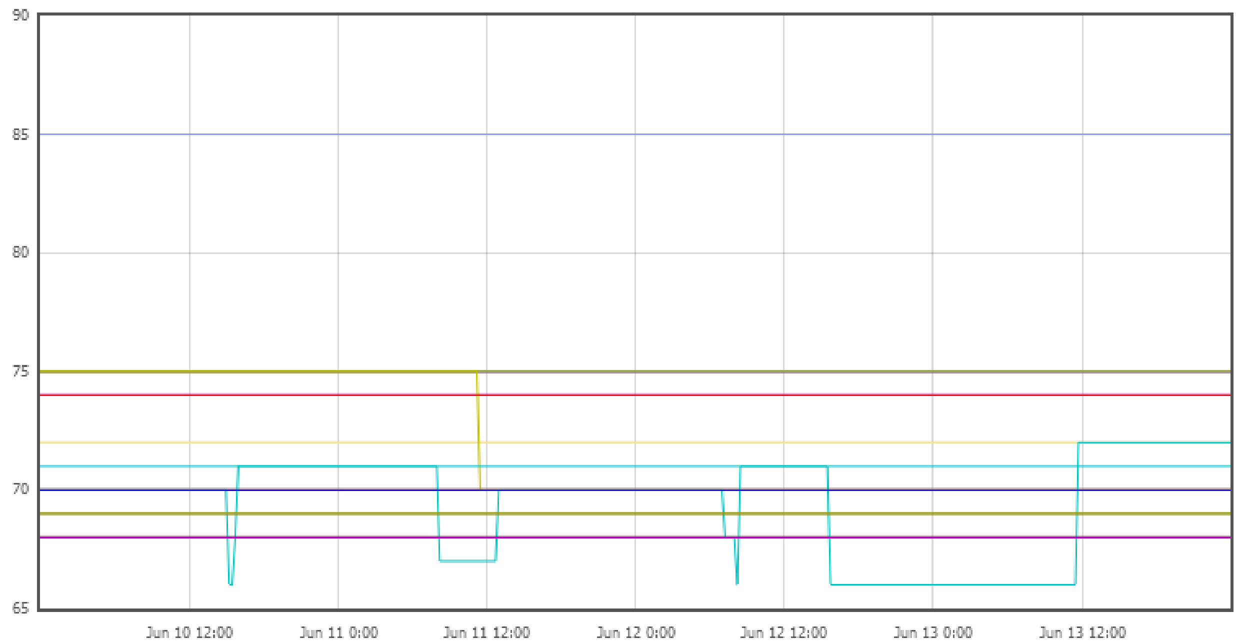


Figure 58: BMS Temperature Setpoints for One Week of all VAV Zones of the floor Studied

Figure 59 shows a histogram of deviation from setpoint for all VAV zones on the floor studied during the two week study period. The bar to the very left (7 percent at -10 deviation) represents zone VAV35 which had the unreasonably high setpoint discussed previously. The histogram is otherwise a fairly symmetric distribution centered around zero deviation from setpoint, indicating that ~75 percent of the time the building is within a few degrees of setpoint, and the rest of the time the building is either too far above or below setpoint. As discussed before, the setpoints vary from 68-75 degrees F (removing the outlier of zone VAV35) which represents a broad spectrum on the comfort scale depending on the clo and met values of the occupants. The actual heating and cooling setpoints are +/- 1 degrees F from these trended setpoints (68 degrees F setpoint would mean 67 degrees F heating setpoint and 69 degrees F cooling setpoint). The stability of the setpoints over time indicates that the occupants are not actively changing setpoints. Only 13 percent of the surveyed occupants indicated that they had control over the thermostat. This may indicate a company policy to not adjust thermostats or may indicate a lack of awareness of thermostat controls in the building. Assuming a clo value of 0.8 and a met rate 1.1, 71 degrees F is the lowest operative temperature allowed by ASHRAE Standard 55, suggesting that a cooling setpoint of 69 degrees F (the lowest observed during the study period) is likely to result in occupants being too cold. Additionally, a 2 degrees F deadband between heating and cooling setpoints can often result in VAV zones fighting each other and frequent switching between heating and cooling mode, resulting in high energy consumption.

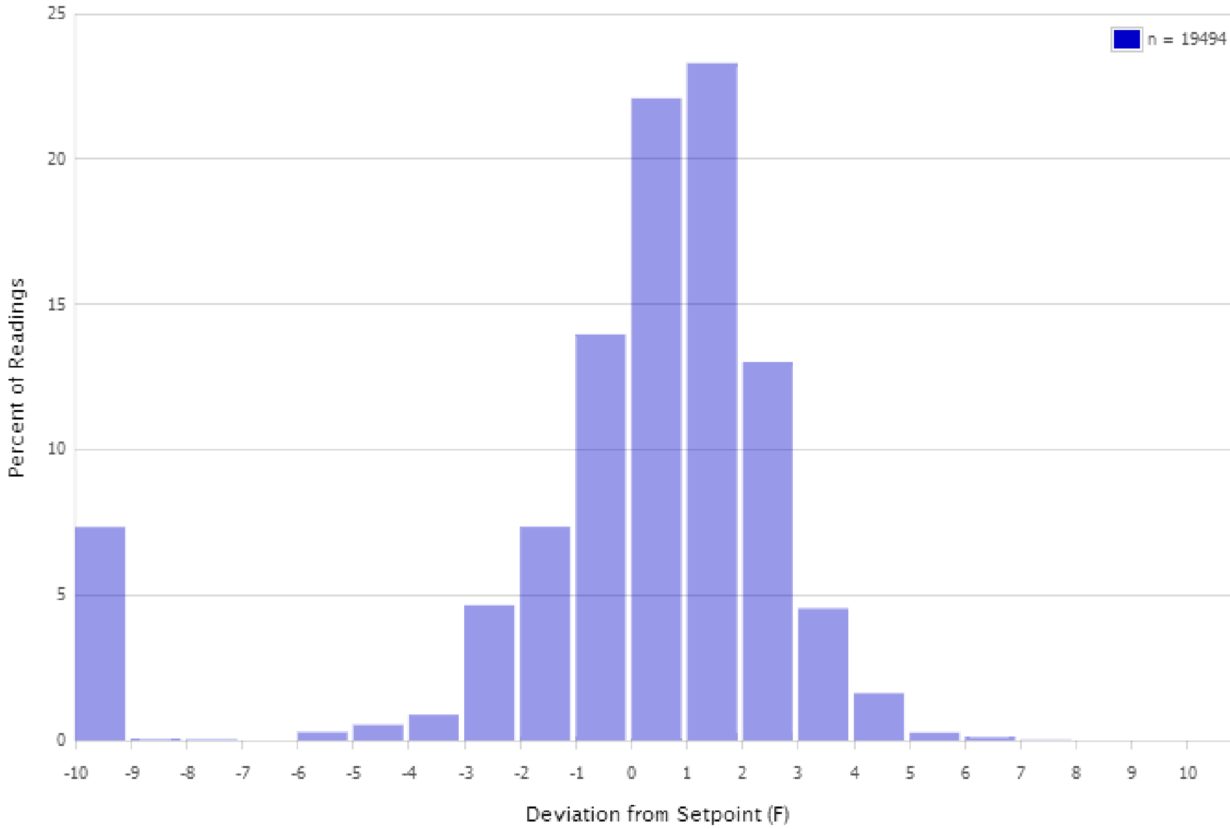


Figure 59: Setpoint Analysis Histogram for BMS Temperature Data During Study Period

Chapter 5: Discussion

Indoor environmental quality is by nature somewhat subjective—though satisfaction surveys do not always uncover potential problems or energy impacts (e.g. energy wasted by overlighting or improper economizer operation). The addition of objective measurements can help 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 (Heinzerling et al., 2013) 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. (Goins, 2011) 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 a few 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 sMAP-based time series data). The steps of aggregating, charting, and analyzing the data are 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 (Heinzerling, 2012). Kim provides a more extensive critique of the PMP, highlighting many of the same issues we discovered (Kim & Haberl, 2012; Kim, 2012). 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 (Salter & Lawrence, 2012). 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. 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 studies described here only collected illuminance data, though future case studies plan to employ high dynamic range (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 the 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 (clo and met). Future Toolkit implementations will include the adaptive comfort model from ASHRAE Standard 55 (2010) (ANSI/ASHRAE, 2010c) and a method for evaluating SET. The PMV/PPD method is quite sensitive to clo and met, 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 met, 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 (Hoyt et al., 2012) 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 pitot static methods. Subjective assessment of IAQ can be unreliable and is often conflated with thermal comfort (e.g. occupants tend to associate cooler temperatures with higher IAQ) (Fang, Clausen, & Fanger, 1998). However, extensive IAQ objective measurement is high-cost with limited accuracy. Therefore, the PMP, we believe 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 (Dickerhoff, 2013). Until measurements beyond CO_2 are included in the Toolkit, interpretation of IAQ performance will remain very limited.

5.3 Feedback From Practitioners

Part of the intention of the field studies was to solicit feedback from the practitioners who conducted some of field studies work. Generally, we either sent or brought the Toolkit to them with instructions for setting up and conducted a hands-on training session with them. However, in each case we participated in the deployment of the equipment and ensured it was operating before leaving. We asked them to conduct ancillary tests such as the PUCC and acoustics testing which seemed to go well. We encouraged them to use the software to study the results and exercise the many options. Unfortunately, they all (some more than others) did not follow up with this task and therefore provided very little feedback. It appeared that they all had serious time limitations that interfered with this type of engagement, since it was on a voluntary basis. They also did not seem especially engaged with the importance of IEQ, probably because engagement at this depth was new to them. Likewise, there was general lack of interest from occupants to complete the occupant satisfaction survey so the response rates were low. From these experiences we conclude the following:

- Most users found the concept and setup of the Toolkit to be relatively easy
- Most were lukewarm about its overall merits, most likely due to reluctance to spend time to understand it
- The users likewise did not appear to see much potential in a service based on the Toolkit in a way that would benefit their business or clients; we believe this is partly due to a general lack of interest and knowledge about IEQ, and limited engagement with the Toolkit.

All of these issues point to potential difficulties with commercialization, the need for robust promotion, and methods to smooth the learning curve associated with the software. However, near the end of the project two CBE partners have expressed interest in starting new services based on the Toolkit. These partners represent different segments of the building industry (manufacturer and architecture) than the practitioners who participated in this study (all mechanical consulting engineers). This level of IEQ evaluation is beyond typical mechanical firm consulting services and may be more suited to other segments of the building industry that are particularly interested in IEQ and occupant satisfaction.

5.4 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 to 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 acceptance. 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 via LEED and national and state building performance standards. 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 CBE and potentially others, the third step requires interest from a hardware manufacturer. We believe that ICM and PUCC wireless devices could be made at quantity for a reasonable cost. Consulting firms interested in the Toolkit as an added service opportunity suggest 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 Electric's tool lending library (Pacific Energy Center, n.d.) could be a feasible route for getting this type of system into the marketplace.

Chapter 6: Conclusions

A toolkit with both hardware and software elements was designed for practitioners around the requirements of the PMP. This toolkit was evaluated through three case studies, which were reported on here.

- 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 to the building owner.
- 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.

GLOSSARY

Acronym	Definition
ABC	Automated baseline calibration
ADC	Analog to digital converters
AHU	Air handling unit
ANSI	American National Standards Institute
ASA	Acoustical Society of America
ASHRAE	American Society of Heating, Refrigerating and Air Conditioning Engineers
BMS	Building Management System
BPG	Best practices guide
C	Celsius
CBE	Center for the Built Environment
CEN	European Committee for Standardization
CIBSE	Chartered Institution of Building Services
clo	Clothing insulation value
CO_2	Carbon Dioxide
DAC	Digital to analog converters
dBA	Background noise level decibel A-weighted
DV	Displacement ventilation
EB	Existing Building
EQI	Environmental Quality Index
F	Fahrenheit
fc	Foot-candles
fpm	Feet per minute
ft	feet
ft^2	Square feet
GIS	Geographic Information System

Acronym	Definition
HDR	High dynamic range
HTML	Hypertext Markup Language
HTTP	Hypertext Transfer Protocol
HVAC	Heating, ventilating, and air-conditioning
I^2C	Inter-integrated circuit
IAQ	Indoor Air Quality
ICM	Indoor climate monitor
IEQ	Indoor Environmental Quality
IESNA	Illuminating Engineering Society of North America
IO	Input/output
IRTs	Infrared temperature sensors
LEED	Leadership in Energy and Environmental Design
lx	Lux
M&V	Measurement and Verification
m^2	Square meters
MEP	Mechanical/electrical/plumbing
met	Metabolic rate
MRT	Mean-radiant temperature
MySQL	Open source structured query language (SQL) database
PGA	Programmable gain amplifier
PM	Particulate matter
PMP	Performance Measurement Protocol
PMV	Predicted Mean Vote
PostgreSQL	Django web application software
PPD	Predicted Percentage Dissatisfied
ppm	Parts per million

Acronym	Definition
PUCC	Portable Underfloor Air Distribution Commissioning Cart
PSOC	Programmable system–on-a-chip
RAS	Room-air-stratification
REHVA	European Heating and Ventilating Association
SET	Standard Effective Temperature
SBS	Sick building syndrome
sf	Square feet
sMAP	Simple Mapping and Actuation Profile
SPI	Serial peripheral interface
Toolkit	Prototype toolkit
UFAD	Underfloor Air Distribution
UFT	Underfloor fan terminal
USGBC	United States Green Building Council
V	Volts
VAV	Variable air volume
VOCs	Volatile organic compounds
WSPFK	WSP Flack and Kurtz

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APPENDIX A: Accessing the Toolkit

The Toolkit is available at http://smap.cbe.berkeley.edu. A guest user account (username "guest" and password "guest") is available for browsing projects without private data. Documentation for the toolkit is available at the above website, including training videos for using the Toolkit. The opensource code and bug reporting for the project is available at http://code.google.com/p/cbesmap.