Commercial Building Indoor Environmental Quality Evaluation: Methods and Tools

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By

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List of Acronyms and Symbols

HVAC – Heating ventilation and air conditioning

POE – Post occupancy evaluation

OPR – Owner’s project requirements

CFR – Current facility requirements

PMP – Performance measurement protocols for commercial buildings

UFAD – Underfloor air distribution

DV – Displacement ventilation

ICM – Indoor climate monitor

PUCC – Portable UFAD commissioning cart

BMS – Building management system

BUS – Building use survey

CBE – Center for the Built Environment

IEQ – Indoor environmental quality

WSPFK – WSP Flack and Kurtz

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1 Background

1.1 Introduction

It is well established that Americans spend the majority of their time indoors and a large portion of that time in commercial buildings. In their role as our second homes, commercial buildings consume a large share of total energy (19%), water (3.3%), and material resources and consequently produce a large share of CO_2 (18%) (“Buildings Energy Data Book,” n.d.; EPA, 2009). Commercial buildings are thus worthy of our intense scrutiny. Buildings are complex systems—attempts at harmonizing comfortable shelter, aesthetics, and usability in an economical and resource-efficient manner. Given the complexity of the system, there are a number of tradeoffs that make optimal design and operation difficult.

Commercial buildings are nearly universally one-off designs, meaning there is a unique set of design challenges that lead to a unique design solution that is built only once. Commercial buildings therefore do not benefit from the improvements gained in the prototype phase of other engineering designs like cars and airplanes. Additionally, most designers and builders are disconnected from the project after construction, preventing the appropriate feedback loop to improve design and construction practices. This one-off nature of building design and construction leads to repeated poor designs and buildings that do not perform as intended. Buildings are often far from being well-tuned, tested, and reliable. Thus, buildings provide ample opportunity for performance improvement—efficiency tuning, retrofits, and feedback on design and construction solutions.

Building performance is a broad category that could include items such as structural performance and life-cycle assessment, though is typically synonymous with energy performance. This study, however, reviews and contributes to the methods and tools used to evaluate only the indoor environmental quality (IEQ) components of building performance: acoustics, indoor air quality, lighting, and thermal comfort.

There are many motivations for focusing on the IEQ performance of buildings, including health, productivity, lifecycle costs, and energy implications of IEQ-related design decisions. Multiple studies have linked poor indoor air quality (IAQ) with sick-building-syndrome (SBS) (W. J. 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 (W. J. 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 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).

With these motivations in mind, this study focuses on the evaluation of building IEQ performance as a step in the process of building IEQ performance improvement. Performance evaluation is tied to a number of different goals:

- **Commissioning**: Evaluate building performance to ensure proper construction and operation of building systems. The intricacies of commissioning types (e.g. retro, continuous) are discussed in section 1.2.

- **Post occupancy evaluation**: Evaluate building performance to compare design intent to actual performance with a focus on occupant feedback.
- **Rating systems**: Evaluate building performance, comparing to appropriate benchmarks, to obtain a scorecard type summary of performance (e.g. LEED, EnergyStar).

While each of these goals addresses a slightly different set of motives and procedures, each seeks to improve building performance through an evaluation of the current state of the building. These goals are described in further detail in this section, with particular attention given to overlapping goals and how the aims of this study align with the aims of these broader categories of building performance improvement.

In addition to understanding how building performance evaluation fits into the greater scheme of commissioning and post-occupancy-evaluation, this introduction section discusses the existing literature on performance evaluation guides, tools, and applications.

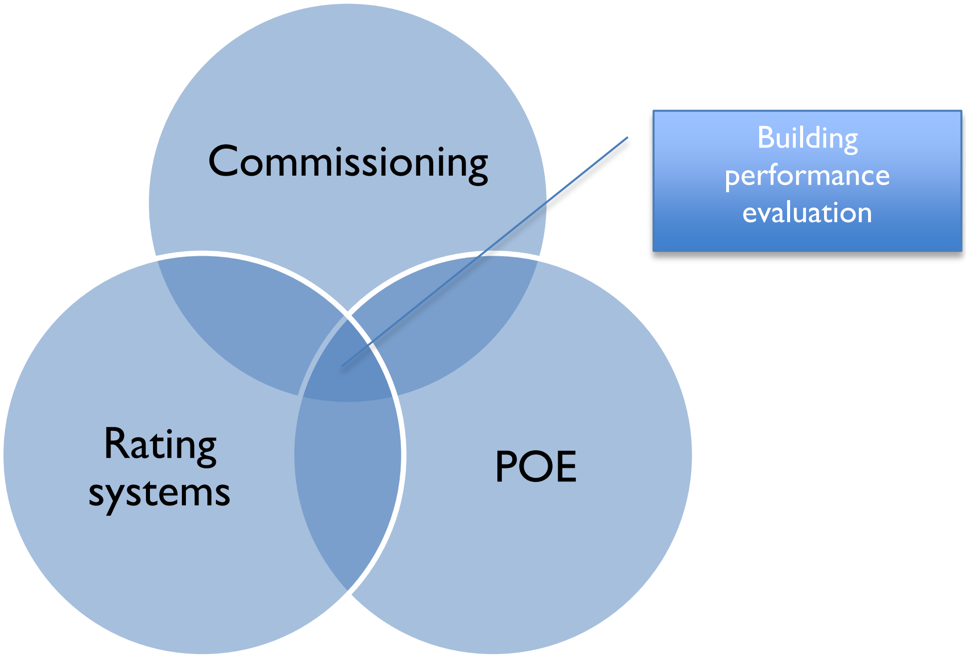


Figure 1: Relationship of building performance evaluation to commissioning, rating systems, and POE

1.2 Commissioning

Commissioning is the set of steps that are taken after construction to ensure the building is performing to the design intent. Design intent is specified by the Owner's Project Requirements (OPR) in the case of a new building or the Current Facility Requirements (CFR) in the case of an existing building (ASHRAE, 2012). ASHRAE Guideline 0 (ASHRAE, 2005) details the commissioning process but focuses on the documentation and high-level actions necessary at each phase of a building project, rather than specific testing instructions.

In the building sector, performance evaluation is typically thought of as being part of the commissioning process, though commissioning is broader in scope. While the IEQ performance evaluation focus of this study is a small (and rarely performed) subset of the commissioning process, grounding the scope of this study within the larger scope of commissioning helps place this study within the larger HVAC world. Commissioning is increasingly becoming part of standard practice and there is often confusion regarding the different types. The following outline summarizes the different types of commissioning and their intended applications:

1. **Commissioning (Cx)**: Sometimes referred to as *initial commissioning*, this type of commissioning is done immediately after the construction of a new building.
2. **Existing building commissioning (EBCx)**
    a. **Retro-commissioning:** If a building did not undergo initial commissioning after construction, it is often *retro-commissioned.*
    b. **Re-commissioning**: If a building underwent retrofitting or remodeling, it is typically *re-commissioned*, though sometimes this process is also referred to as *retro-commissioning*.
3. **On-going commissioning**: After a building has been commissioned, continuous tuning of systems occurs in response to detected problems and measurement/evaluation procedures like those detailed in this study.
    a. **Monitoring-based commissioning (MBCx):** This type of commissioning places focus on measurements and monitoring of building management system (BMS) trend logs to discover problems and improve performance of systems.
    b. **Continuous commissioning® (CC®):** This system of commissioning was developed in the Energy Systems Laboratory at Texas A&M University and focuses on system optimization rather than adherence to OPR/CFR (M. Liu, Claridge, & Turner, 2003).

IEQ measurement and evaluation is not typically covered in commissioning and existing building commissioning, though is sometimes covered in ongoing-commissioning procedures. IEQ evaluation is considered a subset of procedures that are not required in the commissioning process and are typically only performed for "high-performance" buildings. The term *high-performance building* typically refers to a subset of commercial buildings that express a design intent to perform significantly better than local codes require (ASHRAE/CIBSE/USGBC, 2010). As building owners become increasingly concerned about building performance beyond energy efficiency and high-performance building becomes the standard, IEQ performance will transition more into the standard commissioning process. As of this writing, the two recent guides (ASHRAE/CIBSE/USGBC, 2010; ASHRAE, 2012) serve to fill the IEQ evaluation gap in current commissioning practices. The details of these guides as they relate to this study are presented in section 1.4.

1.3 Post Occupancy Evaluations

Post occupancy evaluations (POE) are human-centered building evaluations with a focus on occupant satisfaction and feedback loops (Zimmerman & Martin, 2001; Zimring & Reizenstein, 1980). While the primary tools of commissioning tend to be functional testing checklists and building management system (BMS) control point trend review, the primary tools of POEs tend to be handheld sensors and occupant surveys. POEs are largely case studies that focus on occupant satisfaction and fulfillment of design and program intentions.

The Post-occupancy Review Of Buildings and their Engineering (PROBE) process (Cohen, Gilbert, Bordass, & Associates, 1995) was an early pioneer in applying POE procedures to a large set of buildings. The PROBE studies alerted the building industry to the importance of closing the design-construction-occupancy feedback loop and to the importance of occupant surveys. The PROBE process used the Building Use Studies Ltd. (BUS) survey along with energy analysis to provide feedback on building performance. The Vital Signs project out of the University of California Berkeley was another early pioneer in developing POE procedures for application to a large set of buildings (Benton, n.d.). The context of the Vital Signs project was educational, though helped inspire a similar program called the Tool Lending Library at the Pacific Energy Center, a publicly funded energy efficiency resource center in San Francisco (Benton & Chace, 1996).

There are many survey tools available for studying IEQ satisfaction among occupants. Schiavon and Peretti's review of IEQ surveys (2011) provides a historical account of IEQ surveys. The focus of this thesis is primarily on *objective* IEQ evaluation methods, though subjective surveys do play a role in the case study presented in Chapter 3. In this case study, the Center for the Built Environment (CBE) survey is used and details of that survey are presented in that section.

Beyond surveys, there have been few standardized methods for POE in buildings. In addition to the PROBE process mentioned above, the Center for Building Performance and Diagnostics (CBPD) have a standardized process for POE that includes both survey methods and objective measurements (Choi, Loftness, & Aziz, 2012). The CBPD National Environmental Assessment Toolkit (NEAT) uses the Cost Effective Open-Plan Environment (COPE) project as its survey methodology (G. Newsham, J. Veitch, 2009). In addition to the survey, the NEAT system largely mirrors the type of system that will be discussed as the primary work of this thesis. Further details of the NEAT system are discussed in section 1.6.1.

In Taiwan, Chiang et al. (2001) developed a procedure for assessing IEQ in senior health care facilities which included both survey and measurement techniques based on earlier work done on assessing indoor air quality in residences. The authors relied heavily on statistics to determine anomalies in IEQ with the aim of determining a relationship between objective measurements and comments from occupants. This study and others by the Architecture department at Cheng-Kung University were early pioneers of IEQ scoring systems which are discussed in further detail in section 1.5.

One goal of POE is often to benchmark buildings against a large database. Multiple efforts to create large databases of building IEQ performance have been undertaken, though most have focused on thermal comfort. These efforts are summarized by Gossauer and Wagner (2007) and in Table 1.

Table 1: Summary of long-term POE studies adapted from Gossauer and Wagner (2007)

Project	Study Years	Objectives
ASHRAE RP-1161(De Dear, 1998)	1980-1995	Influence of personal control on thermal comfort, self-controlled acquisition of physical and subjective data
BASE (EPA, 2003)	1994-1998	Provide a database of IAQ-related parameters in office spaces
SCATs (Nicol, J. F. and McCartney, 2000)	1997-2000	Correlation between comfort temperature and indoor/outdoor temperatures, behavioral analyses
PROBE (Cohen et al., 1995)	1995-2002	Energy and environmental performance, thermal comfort, occupant satisfaction, feedback
ProKlima (Bischof, Bullinger-	1995-2003	Contribution of the indoor climate, energy concept and

Project	Study Years	Objectives
Naber, Kruppa, Müller, & Schwab, 2003)		psychological factors to the illness symptoms and thermal comfort
HOPE ("HOPE," 2006)	2002-2005	Benchmarking of 'healthy' and energy efficient buildings, input into CEN standards
CBE (CBE, 2008)	1996 onward	Diagnosis of problems, evaluation of new building technologies, quality benchmarking
CCC ("Construction Clients' Charter," n.d.)	2001 onward	Feedback on the performance of industry products for buildings

A review of POE benefits and barriers (Zimmerman & Martin, 2001) discussed a number of items lacking in the then-current world of POE. This paper acts as an illuminating source of goals to tackle, which includes:

- Not standardized practice: the industry does not recognize or understand the concept of continuous improvement and designers are not expected or paid to return to their designs after construction.
- Split incentives: the building industry is hugely fragmented, resulting in potentially competing incentives for designers, contractors, and clients.
- Indicators and benchmarks: what defines a "good building" is not standardized.
- Liability: more information could lead to unknown liability issues for poor performance.

Such barriers are still largely unresolved, though recent performance measurement guides have begun to tackle the problem of unstandardized procedures and metrics. Discussed in the next section, these guides are largely built upon previous POE efforts.

1.4 IEQ performance measurement guides

Concerns about maintaining adequate indoor environmental quality have increasingly accompanied the stricter building energy codes such as ASHRAE 90.1 (ANSI/ASHRAE/IESNA, 2010). Recently, documents to standardize and eventually codify IEQ measurement and performance have been written. In the United States, the ASHRAE/CIBSE/USGBC Performance Measurement Protocols for Commercial Buildings (ASHRAE/CIBSE/USGBC, 2010) adds to the scope of a similar earlier European standard (CEN, 2007), discussed below.

1.4.1 EN15251 and REHVA Indoor Climate Quality Assessment

The European standard EN15251 (2007) provides guidance on IEQ measurement, standards, and input values to use in energy simulation software. This standard was created largely as guidance for architects and engineers tasked to follow European Council and Parliament directive on the energy performance of buildings (EPDB), which mandated energy performance certificates, among other items (European Parliament and Council, 2003). The focus of EN15251 is largely on defining and subsequently ensuring good IEQ while making design decisions to lower building energy use. Because EN15251 is a standard and is primarily used for energy simulation, there are few included practical guidelines on how to accurately and efficiently measure IEQ performance. A number of papers have been written to help fill this gap (Marino, Nucara, & Pietrafesa, 2012; Ncube & Riffat, 2012; Olesen, 2007), though recently the publication of the REHVA Indoor Climate Quality Assessment guidebook (ICQ) has addressed the need for guidelines for thermal comfort and indoor air quality (REHVA, 2011). However, a single source guidebook for all IEQ parameters, like the Performance Measurement Protocols, does not have a European equivalent at this time.

The REHVA Indoor Climate Quality Assessment guidebook provides theory, procedures, and metrics to use when evaluating thermal comfort and indoor air quality, though focuses primarily on technical fundamentals rather than methods and procedures. Much like the Performance Measurement Protocols discussed in the next section, the REHVA ICQ guidebook represents a good first attempt at outlining the issues of IEQ evaluation, though the depth of explanation is potentially impractical for digestion by practitioners (commissioning agents, designers, and operators).

An important feature of EN15251 and the REHVA ICQ is the breakdown of IEQ categories as shown in Table 2. There is some debate about the interpretation of these categories as aligned with levels of quality (Arens, Humphreys, De Dear, & Zhang, 2010; Michael A. Humphreys, 2005; Nicol & Wilson, 2011). The categories are intended to express a bandwidth of acceptable IEQ (category I being the narrowest band), though the narrowest bandwidth is not necessarily the highest quality IEQ and is associated with negative energy consequences. Although there is some criticism surrounding these categories, they provide a method for categorizing buildings according to IEQ performance. This type of categorization is absent in ASHRAE's Performance Measurement Protocols discussed in the next section. Such categorization was proposed for ASHRAE Standard 55 though was not accepted. The categories presented in Table 2 provide the foundation for the IEQ index models discussed in section 1.5 of this document.

Table 2: Categories for IEQ (EN 15251, 2007)

Category	Explanation
I	High level of expectation only used for spaces occupied by very sensitive and fragile persons
II	Normal expectation for new buildings and renovations
III	A moderate expectation (used for existing buildings)
IV	Values outside the criteria for the above categories (only acceptable for limited periods)

1.4.2 Performance Measurement Protocols for Commercial Buildings

The Performance Measurement Protocols (PMP) provides a set of protocols that facilitate the appropriate and accurate comparison of measured energy, water, and indoor environmental quality performance of commercial buildings (ASHRAE/CIBSE/USGBC, 2010). The primary motivations include: lower energy and water consumption without adversely affecting occupant comfort, verification of "high-performance" or "green" design goals, and feedback for designers and engineers. The protocols are provided in three different levels that represent a range of accuracy and cost: Basic, Intermediate, and Advanced. Additionally, the protocols provide guidance on issues of temporal and spatial resolution.

At the Basic level of the PMP, low-cost procedures are defined to capture potential problem areas and provide an overview of whole building energy and water annual usage. For the IEQ sections of the PMP, an occupant survey such as the Center for the Built Environment (CBE) survey (CBE, 2008) is the first step in determining potential performance issues, along with a walk-through inspection. In the walkthrough, simple low-cost measurements may be taken to support survey results.

At the Intermediate level of the PMP, problem areas that were discovered during the Basic level procedures are further explored using hand-held instrumentation. The protocols outlined at this level require a higher level of expertise and cost to perform. The Advanced level of the PMP builds upon the Intermediate level in accuracy as well as greater temporal/spatial resolution. The measurements suggested at this level are of increased complexity and cost and are typically thought of as research-level procedures.

Table 3 and Table 4 provide summaries of the PMP requirements for only the IEQ parameters. Table 3 is a subset of Table 4 and is intended to provide a quicker overview of the objective measurement requirements for each IEQ category and level of the PMP because this project focuses primarily on objective measures. Table 4 is broader in scope and provides a summary of all the requirements for the IEQ parameters of each level of the PMP, including subjective measures, instrumented measures, and cost. A detailed discussion of the strengths and weaknesses of the PMP is provided in section 4.1.

Table 3: Summary of PMP objective measurement requirements for the IEQ parameters

Level	Thermal Comfort	Indoor Air Quality	Lighting	Acoustics
Basic	Spot measurements of temperature, relative humidity, mean radiant temperature, air speed	Outside air flow rates at each outside air intake Spot measurements of temperature and humidity to characterize occupant perceptions of IAQ	Spot measurements of illuminance in selected spaces	Spot measurements of A-weighted sound pressure level (dBA) in occupied spaces
Intermediate	Temperature, relative humidity, incident solar radiation, air speed over intervals of 1-15 minutes	If strong local ambient pollutant source is suspected, determine OA quality at site OA flow rates at each OA intake At least one week continuous CO_2 monitoring in representative spaces	Full grid measurements of illuminance and luminance Determination of discomfort glare	Detailed measurement of background noise in octave bands for comparison with single-number ratings such as NC, RC, and NCB Spot measurement of reverberation time (T_{60}) for general assessment of speech communication issues
Advanced	Detailed and continuous measurement of temperature gradients and transients and radiation asymmetry for detailed spatial resolution	Measure moisture content beneath surfaces where moisture is observed Continuous measurement of CO_2, $PM_{2.5}$, and TVOCs CoC only if suspected to be present	High resolution measurement of illuminance, luminance, and discomfort glare with HDR photography	Measurement of speech privacy and speech communication (AI, PI, SII, or SIL) for special-purpose room uses Measurement of sound and vibration isolation (NIC, IIC, $D_{nt,w}$ and $L'_{nT,w}$) from outside sources and between interior rooms

Table 4: PMP requirements according to performance level - Adapted from Table 2-1 in PMP (ASHRAE, 2010a)

Basic Level	Descriptive Information	Subjective Measures	Instrumented Measures	Cost
Thermal Comfort	Basic thermal-comfort related building/system characteristics, including complaint log	Occupant survey of thermal comfort and job satisfaction during one-week window or for sample of occupants Operator survey of building characteristics	Spot measurements of thermal-comfort-related parameters for problem diagnosis (temperature, relative humidity, mean radiant temperature, air speed)	\$1000-\$2000 for annual survey; \$1500-\$3000 for optional diagnostic visit (100,000 ft^2 building)
Indoor Air Quality	Obtain EPA data to determine outdoor air quality at site Site assessment to determine basic IAQ-related building/HVAC system characteristics, including complaint log, to spot potential IAQ problems	Occupant survey of IAQ satisfaction; informal interview during the IAQ evaluation Interview building manager to gather facility data	Outside air flow rates at each outside air intake Spot measurements of temperature and humidity to characterize occupant perceptions of IAQ	\$1500 initial; \$1500-\$3000 recurring per year (1-3 visits 100,000 ft^2 building)
Lighting/Daylighting	Basic lighting-related space characteristics to determine potential lighting problems	Occupant survey of lighting satisfaction	Spot measurements of illuminance in selected spaces	\$600-\$1850 initial; \$400-\$1500 for followup investigations
Acoustics	Room finishes of open office plan, private offices and meeting rooms Location of mechanical equipment, plumbing and outdoor noise sources	Occupant survey of acoustics satisfaction	Spot measurements of A-weighted sound pressure level (dBA) in occupied spaces	\$2000-\$3000

Intermediate Level	Descriptive Information	Subjective Measures	Instrumented Measures	Cost
Thermal Comfort	Specific thermal-comfort related building/system characteristics, including occupancy data	Occupant right-now survey of thermal sensation, comfort, and acceptability plus description of thermal environment during right-now survey	Measurements of thermal-comfort-related parameters for problem diagnosis (temperature, relative humidity, incident solar radiation, air speed) with intervals of 1-15 minutes	\$6000-\$10,000 for field testing; \$25,000-\$40,000 first cost 1 year's testing
Indoor Air Quality	Evaluate interior source locations and determine exhaust/ventilation system characteristics. Ensure adequate pressure differential for source control	-	If strong local ambient pollutant source is suspected, determine OA quality at site OA flow rates at each OA intake At least one week continuous CO_2 monitoring in representative spaces	\$350-\$2500 per CO_2 sensor; \$5000-\$8500 per zone tested

Intermediate Level	Descriptive Information	Subjective Measures	Instrumented Measures	Cost
Lighting/Daylighting	Specific lighting-related space and occupancy characteristics	Diagnostic survey of occupant lighting satisfaction	Full grid measurements of illuminance and luminance Determination of discomfort glare	$2150-$6800; $1300-$3400 for followup testing
Acoustics	Specific acoustic-related space and occupancy characteristics for assessment of acoustic annoyance	-	Detailed measurement of background noise in octave bands for comparison with single-number ratings such as NC, RC, and NCB Spot measurement of reverberation time (T_{60}) for general assessment of speech communication issues	$9000-$12,000

Advanced Level	Descriptive Information	Subjective Measures	Instrumented Measures	Cost
Thermal Comfort	Detailed thermal-comfort related building/system/occupant characteristics	Specialized survey measuring thermal perception of specific body parts subjected to asymmetrical or transient thermal environments	Detailed and continuous measurement of temperature gradients and transients and radiation asymmetry for detailed spatial resolution	$5-$50,000 for instruments; $10,000-$20,000 recurring
Indoor Air Quality	Detailed IAQ-related building/system and occupant characteristics	-	Measure moisture content beneath surfaces where moisture is observed Continuous measurement of CO_2, $PM_{2.5}$, and TVOCs Measure contaminants of concern (CoC) only if suspected to be present	$20,000-$30,000 initial; $17,500 recurring
Lighting/Daylighting	Detailed lighting-related building/system/occupant characteristics	-	High resolution measurement of illuminance, luminance, and discomfort glare with HDR photography	$800-$5200 initial; $400-$1200+ for followup
Acoustics	Detailed acoustics-related building/system/occupant characteristics	-	Measurement of speech privacy and speech communication (AI, PI, SII, or SIL) for special-purpose room uses Measurement of sound and vibration isolation (NIC, IIC, $D_{nt,w}$ and $L'_{nT,w}$) from outside sources and between interior rooms	$15,000-$20,000 initial

1.4.3 Measurement guide critiques

IEQ measurement procedures and metrics are a recent development and thus such guides need improvement. Highlighting issues specifically within the PMP is one of the primary objectives of this thesis; however, there is already a small body of literature that has begun to tackle this job for both the PMP and EN15251.

For the PMP, a number of critiques of the Basic level protocols were reported by Kim et al. (2012). In this study, a field test of the protocols in an office building was conducted and the authors commented on weaknesses in the protocols. The study's primary critique suggested that there was too little guidance and consistency regarding spot measurements at the basic level. Additionally, the authors suggested that spot measurement would not be sufficient to capture dynamic problems and thus requested more guidance for continuous measurement. This study also looked at linking subjective survey results to objective spot measurements. The study's spot measurements did not correlate to user satisfaction and the spot measurements did not reveal the source of dissatisfaction.

The results of the Kim et al. study highlight the complexity of the relationship between subjective and objective building performance measures. Section 1.5 reviews multiple studies that attempt to formulate models that define the relationship between subjective and objective IEQ measurements.

For EN15251, a task group named CommonCense was formed to evaluate and critique the standard. This group has produced many documents that offer guidance with EN15251 as well as suggestions for improvement ("CommonCense downloads," n.d.). An overall critique produced by the CommonCense group focused primarily on thermal comfort and lighting issues with the Standard (Nicol & Wilson, 2011). The primary concerns of the authors were compliance standards and the IEQ categories mentioned before in Table 2. For mechanically controlled buildings, EN15251 requires that the Predicted Mean Vote (PMV) for IEQ category I be 0 ± 0.2. The authors note that because PMV is computed from air temperature, radiant temperature, air speed, clothing insulation and metabolic rate, the error over each parameter is additive, requiring impossible accuracy requirements (especially when considering clothing and metabolic rate) for each parameter sensor. Additionally, the standard does not allow for the cooling effect of air movement.

The authors were additionally concerned that there is a bias toward mechanical controlled buildings over naturally ventilated buildings. This concern also relates to the concern that IEQ categories will be treated as quality categories. Because naturally ventilated buildings necessarily have a wider range of IEQ conditions, they are less likely to fall into category I, which some practitioners may interpret as being of lower quality. A further discussion of IEQ categories and their critiques is presented in section 1.5.

1.4.4 Diagnostics vs. evaluation

The PMP aspires to be a guidebook for measurement, diagnostics, and evaluation. As a first edition, the PMP goes a long way toward providing guidance in each of these topics, though there is uneven treatment of each realm in each different IEQ section of the PMP. While the IEQ survey provides a basic way of evaluating occupant satisfaction by benchmarking against either the CBE (CBE, 2008) or Building Use Studies Ltd. (BUS) survey databases, there are few guidelines regarding IEQ objective measurement benchmarking—largely because such benchmarks do not yet exist. Therefore, the IEQ objective measurement sections of the PMP are diagnostic rather than evaluation driven. This section proposes an important distinction between diagnostics and evaluation, including motivational and procedural differences.

A diagnostics approach to building measurement involves a reactive process: an occupant expresses dissatisfaction with an IEQ parameter in his/her work area and measurements are taken to diagnose the problem. Diagnostics are thus targeted evaluations and thus typically smaller in scope and cost.

Evaluations in contrast are undertaken to provide a broader picture of overall space or building performance. There does not necessarily need to be a problem or complaint to evaluate the IEQ performance of a building. Thus, evaluation is typically larger in scope and cost. Evaluations can be based on benchmarks of similar buildings or a set of standard metrics, as in the case of certain rating systems. The PMP provides little guidance on this evaluative type approach, leaving researchers without a standard set of procedures that could be used to generate benchmarks for IEQ measurement. While IEQ building-level evaluation is rare, the work presented in this thesis along with recent literature discussed in the following section 1.5 has begun to tackle these procedural issues.

1.5 IEQ rating systems

Numerical rating systems such as EnergyStar and LEED are attractive to clients and designers because they condense whole building performance into a single number. There is an extensive body of literature that discusses the merits of the various rating systems, which is not the intent of this section, though a summary of the relevant IEQ monitoring LEED Existing Buildings Operations and Maintenance (EBOM) credits is available in Table 5. This section aims to introduce recent developments in IEQ rating systems outside of LEED. These studies are distinct from benchmarking studies that use large-scale databases such as the CBE Survey, PROBE, SCATs, and ASHRAE RP-1161 discussed in section 1.3.

Table 5: LEED EBOM IEQ monitoring credits ("LEED credit library," n.d.)

	LEED EBOM 2009	LEED EBOM v4 Draft changes
Occupant survey	EQc2.1: Occupant comfort-occupant survey	EQc10: develop a corrective action plan if more than 20% of occupants are dissatisfied. New survey every 2 years
IAQ	EQc1.2: Outdoor air delivery monitoring	EQc2: Enhanced indoor air quality strategies. Combined some elements from 2009 EQc1.2 and 1.4
Lighting	EQc2.4: Daylight and views	EQc5: Daylight and quality views. Many changes, including a requirement for 300 lux illuminance level in all occupied spaces EQc4: Interior lighting. Added this credit, partially taken from 2009 EQc2.2. Added quality requirements for hardware, surface reflectance, and luminance.
Thermal comfort	EQc2.3: Thermal comfort monitoring	EQc3: Thermal comfort. No changes.

While many of the systems discussed in this section build from the evaluation criteria that are presented in EN15251, the PMP does not include similarly straightforward criteria. The criteria presented in the PMP are aimed more toward the goal of providing recommended values of IEQ parameters rather than providing criteria for assessment categories that could be used to build an overall IEQ rating model.

1.5.1 Subjective (survey) vs. objective (measurements) IEQ evaluation

Historically, IEQ measurement has been seen as being complex, expensive, and unstandardized, resulting in surveys being used as the primary tool for gauging IEQ performance (Zimmerman & Martin, 2001). As discussed in section 1.3, there are many different surveys available for use; the case study presented in Chapter 3 uses the CBE survey (CBE, 2008). The CBE survey report includes a building scorecard, though its overall rating is based on a question about general satisfaction with the building as opposed to a combination of categories.

Surveying is often the simplest and least-expensive method for evaluating IEQ concerns in a building. Occupant satisfaction is ultimately the primary interest of the building owner/operator regardless of physical IEQ conditions. However, the subjective nature of surveys and range of opinions for similar IEQ physical conditions complicate the use of surveys as the only tool for evaluating building IEQ performance. Additionally, surveys do not always capture IEQ issues that may have energy implications (e.g. over-lighting) and have limited diagnostic capability. Nicol and Wilson (2011) discuss other issues associated with surveys, including:

- Difficulty finding representative period for survey: this critique is addressed by doing "right-now" surveys at different times of the day/week/month/year.
- Interpreting the results: there are not clear guidelines for the practitioner on how to transform subjective measures into standardized limits (except perhaps Percent-Persons-Dissatisfied (PPD) in thermal comfort).
- Which questions should be asked?

Many of the issues identified with surveys also apply to objective measurements, including the issues of spatial/temporal resolution and interpretation of results. Other issues include:

- Sensor accuracy/calibration: there are complex and often expensive methods for keeping instruments calibrated.
- Cost: the sensors themselves are often expensive, but the labor associated with deploying sensors across a large building and then analyzing the vast amount of data can quickly become impractical.

While a mathematical relationship between objective measurements and subjective satisfaction is often not well-defined (see studies in Table 6), and both subjective and objective measurement methods have issues, their combined use typically provides a clear understanding of the indoor environmental quality of a space through straightforward analysis and interpretation. Time-consuming analysis and interpretation are costly and thus there are many recent efforts, including this thesis, which aim to reduce the amount of analysis and interpretation that is needed.

1.5.2 Categorization of indoor environmental quality

As discussed previously, there is some contention regarding the categories defined for EN15251 (Table 2). There are many reasons these categories are contentious, though the criticisms generally fall under two main reasons: (1) what the categories mean and how to appropriately interpret the categories, (2) the limits that are assigned to the categories. As noted by Nicol and Wilson (2011), the descriptions of the categories in EN15251 are not designed to imply levels of quality, but rather focus on expectations of the occupants as opposed to tightness of control. While there is a subtle difference in presentation, both have the same underlying principle of tightness of control, in which the default interpretation is tighter control is equivalent to higher quality. The conditional limits assigned to the categories are the other major point of contention. Such critiques are discussed in detail in section 4.2, though one of the primary concerns is a lack of measurable occupant satisfaction levels between categories. Indoor environmental quality is difficult to quantify as a set of measureable parameters, and quality is often in the eye of the beholder.

Despite the challenges of the categorizing indoor environmental quality and the dangers associated with linking tightness of control to quality, such categories provide a starting point for the development of many of the IEQ models discussed in the next section. Some studies choose to define their own quality categories while others use existing standards. To avoid confusion of whether such categories should be interpreted as "quality categories," this study uses the term "assessment classes," where it is left up to the specific model of what is being assessed (e.g. quality or tightness of control). Further discussion of how to improve categorization of IEQ and IEQ rating systems is in section 4.2.2.

1.5.3 IEQ models

Indoor environmental quality models combine multiple IEQ parameters into a single number and attempt to relate occupant satisfaction with objective measurements. An IEQ index is the result of an IEQ model—a numerical rating. This combination is often used for rating or ranking a building according to its IEQ. Multiple studies have presented models for combining IEQ parameters. Table 6 summarizes the major literature surrounding IEQ models and which aspects of IEQ models were included (ordered by year published):

- Objective measures: which IEQ parameters were measured with instruments?
- Subjective measures: were occupants or professionals surveyed?
- Subjective/Objective relationship: what sort of relationship was reported between the two measures (e.g. linear, nonlinear)?
- Assessment classes: does the study include a breakdown into "assessment classes", if so, how are they defined? The details of the assessment classes are provided in Table 7.
- IEQ category weights: does the study attempt to apply weights to different IEQ categories, if so, what are the weights?

The IEQ models summarized in Table 6 fall into two basic categories:

1. Studies that attempt to correlate subjective and objective measures, providing equations that predict occupant satisfaction for each IEQ category based on objective measurements and overall IEQ quality as a combination of each sub-index (Studies 3-5). This overall IEQ quality index is then compared to a fixed set of ranges that define the quality of IEQ in the space or building.
2. Studies in which objective measurements are made and compared against a fixed set of criteria that determine what assessment class the measurement falls into. This discretization of measurements creates a breakdown of time-spent in each assessment class, which can then be used to determine single value indexes for each IEQ category and overall IEQ (Studies 1, 2, 6). These studies may or may not include subjective measurements, but they are not included as part of the overall IEQ index.

Most IEQ model studies weight the IEQ categories when determining overall IEQ quality in order to apply a factor of relative importance. This weighting of IEQ categories is based on occupant survey results or determined through regression coefficients. Frontczak and Wargocki (2011) summarized much of the literature available on IEQ category weighting, most of which is included in Table 6. Building on the work of Frontczak, Wargocki and others, Kim and de Dear (2012) looked at relationships between IEQ categories and overall workspace satisfaction. Rather than apply a simple weighting scheme to IEQ categories to obtain overall IEQ quality, Kim and de Dear used Kano's model of customer satisfaction to break down IEQ category performance into more detailed relationships with satisfaction (Basic Factors, Bonus Factors, and Proportional Factors). Frontczak et al. (2012) provide another detailed analysis of the relative importance of IEQ categories to workplace satisfaction, though do not provide a specific weighting scheme. These three studies offer clear guidance on the relationship between satisfaction with IEQ categories and building features and overall occupant satisfaction though the details are beyond the scope of this project, which focuses on evaluating IEQ performance primarily through objective measurements.

The application of IEQ models in this project is discussed in sections 2.2.6 and 3.7.2. Section 4.2 provides a detailed discussion of the strengths and weaknesses of IEQ models.

Table 6: Summary of IEQ models in literature

Study	Objective Measures	Subjective Measures	Subjective/ Objective Relationship	Assessment Categories	IEQ Category Weights
1. (Chiang et al., 2001)	Acoustics: sound level pressure (dBA) IAQ: CO, CO_2, PM_{tot} Lighting: illuminance TC: air speed, air temperature, relative humidity	Simultaneous right-now survey	Linear regression	Healthy range (HR) Uncertain range (UR) Non-healthy range (NR)	-
2. (Chiang & Lai, 2002)	Acoustics: sound level pressure (dBA) IAQ: CO, CO_2, PM_{tot}, HCHO, VOCs Lighting: illuminance, illuminance uniformity at face, daylight-use ratio TC: air speed, air temperature, relative humidity, PMV	Expert survey to determine category weightings	-	20, 40, 60, 80, 100 <60 means "sanitary risk"	Acoustics: 0.203 IAQ: 0.209 Lighting: 0.164 TC: 0.208 EMF*: 0.135 *Electro-magnetic field
3. (Lai, Mui, Wong, & Law, 2009; Wong, Mui, & Hui, 2008)	Acoustics: sound level pressure (dBA) IAQ: CO_2 Lighting: illuminance TC: operative temperature	One-time survey of 293 occupants	Single-variable regression (per category) Multivariate regression (overall IEQ)	-	Regression constants; higher = greater importance: Acoustics: 4.74 IAQ: 4.88 Lighting: 3.7 TC: 6.09
4. (Cao et al., 2012)	Acoustics: sound level pressure (dBA) IAQ: CO_2 Lighting: illuminance TC: operative temperature	Simultaneous right-now survey	Single-variable regression (per category) Multivariate regression (overall IEQ)	-	Regression constants; higher = greater importance: Acoustics: 0.224 IAQ: 0.118 Lighting: 0.171 TC: 0.316
5. (Ncube & Riffat, 2012)	Acoustics: sound level pressure (dBA) IAQ: CO_2 Lighting: illuminance TC: PPD	Simultaneous right-now survey	Multivariate regression (overall IEQ)	I: $80 < IEQ \leq 100$; Very high quality IEQ II: $60 < IEQ \leq 80$; High quality IEQ III: $40 < IEQ \leq 60$; Medium quality IEQ IV: $20 < IEQ \leq 40$; Low quality IEQ V: $0 \leq IEQ \leq 20$; Very low quality IEQ	Acoustics: 0.18 IAQ: 0.36 Lighting: 0.16 TC: 0.30
6. (Marino et al., 2012)	Acoustics: sound level pressure (dBA) IAQ: CO_2 Lighting: illuminance TC: operative temperature	-	-	EN15251: I, II, II, IV	Acoustics: 0.16 IAQ: 0.15 Lighting: 0.146 Summer TC: 0.189 Winter TC: 0.173

Table 7: Summary of assessment class conditions for IEQ models in literature

Study	Assessment Class	Acoustics	IAQ	Lighting	Thermal Comfort
1. (Chiang et al., 2001)	Healthy	dBA < 44	CO < 8 ppm $CO_2 < 550$ ppm $PM_{10} < 0.09$ mg/m^3	lx > 110	$18.5 \leq$ air temp ≤ 24.5 °C $43 \leq RH \leq 67$ % air speed < 0.45 m/s
	Uncertain	$44 \leq dBA \leq 46$	$8 \leq CO \leq 10$ ppm $550 \leq CO_2 \leq 650$ ppm $0.09 \leq PM_{10} \leq 0.11$ mg/m^3	$90 \leq lx \leq 100$	$17.5 \leq$ air temp ≤ 18.5 °C $24.5 \leq$ air temp ≤ 25.5 °C $37 \leq RH \leq 43$ % $67 \leq RH \leq 73$ % $0.45 \leq$ air speed ≤ 0.55 m/s
	Non-healthy	dBA > 46	CO > 10 ppm $CO_2 > 650$ ppm $PM_{10} > 0.11$ mg/m^3	lx < 90	air temp < 17.5 °C air temp > 25.5 °C RH < 37 % RH > 73 % air speed > 0.55 m/s
2. (Chiang & Lai, 2002)	100	$dBA \leq 50$	CO < 2 ppm $CO_2 < 600$ ppm $PM_{10} < 0.025$ mg/m^3 VOCs < 0.05 mg/m^3 HCHO < 8 ppb	lx > 500	$\lvert PMV \rvert > 0.5$
	80	$50 < dBA \leq 53$	$2 \leq CO \leq 4.5$ ppm $600 \leq CO_2 \leq 800$ ppm $0.025 \leq PM_{10} \leq 0.05$ mg/m^3 $0.05 \leq VOCs \leq 0.1$ mg/m^3 $8 \leq HCHO \leq 16$ ppb	$300 \leq lx \leq 500$	$0.5 \leq \lvert PMV \rvert \leq 1$
	60	$53 < dBA \leq 56$	$4.5 \leq CO \leq 9$ ppm $800 \leq CO_2 \leq 1000$ ppm $0.05 \leq PM_{10} \leq 0.15$ mg/m^3 $0.1 \leq VOCs \leq 0.3$ mg/m^3 $16 \leq HCHO \leq 100$ ppb	$150 \leq lx \leq 350$	$1 \leq \lvert PMV \rvert \leq 1.5$
	40	$56 < dBA \leq 59$	$9 \leq CO \leq 15$ ppm $1000 \leq CO_2 \leq 2500$ ppm $0.15 \leq PM_{10} \leq 0.35$ mg/m^3 $0.3 \leq VOCs \leq 3$ mg/m^3 $100 \leq HCHO \leq 1000$ ppb	$70 \leq lx \leq 150$	$1.5 \leq \lvert PMV \rvert \leq 2$
	20	dBA > 59	CO > 15 ppm $CO_2 > 2500$ ppm $PM_{10} > 0.35$ mg/m^3 VOCs > 3 mg/m^3	lx < 70	$\lvert PMV \rvert < 2$

Study	Assessment Class	Acoustics	IAQ	Lighting	Thermal Comfort
			HCHO > 1000 ppb		
3. (Lai et al., 2009; Wong et al., 2008)	Level of acceptance (0-1); regression model for each IEQ category and overall IEQ	$1 - \left(\frac{1}{1+e^{(9.54-0.134*dBA)}}\right)$ where $45 \leq$ dBA ≤ 72	$1 - \frac{1}{2}\left(\frac{1}{1+e^{(3.118-0.00215*CO_2)}} - \frac{1}{1+e^{3.23-0.00117*CO_2}}\right)$ where $500 \leq CO_2 \leq 1800$	$1 - \left(\frac{1}{1+e^{(-1.017+0.00558*lx)}}\right)$ where $200 \leq$ lx ≤ 1600	$1 - \left(\frac{PPD}{100}\right)$
4. (Cao et al., 2012)	Occupant satisfaction (0-1); regression model for each IEQ category and overall IEQ	$-0.0230 * \text{dBA} + 1.382$ where $39 \leq$ dBA ≤ 56	$-0.0002 * CO_2 + 0.244$ where $275 \leq CO_2 \leq 2360$	$-5 \times 10^{-7}\text{lx}^2 - 0.106$ where $140 \leq$ lx ≤ 2150	$-0.0063t_o^2 + 0.287t_o - 2.934$ where $16.6 \leq t_o \leq 30.3$ °C; $15 \leq$ RH ≤ 75 %; $0.01 \leq$ air speed ≤ 0.44 m/s
5. (Ncube & Riffat, 2012)	Sub-index for each IEQ category (0-100); apply sub-index to overall IEQ index; apply overall IEQ index to quality categories listed in Table 6	$100 - 2\left(\text{Actual dBA} - \text{Design dBA}\right)$	**Choice 1**: $100 - \{395 \times \exp(-1.83q^{0.25})\}$ where q is ventilation rate (l/s) **Choice 2**: $100 - \{395 \times \exp(-15.15\text{CO}_2^{-0.25})\}$ **Choice 3**: $100 - \left\{\exp\left[5.98 + \left(\frac{C_i}{-112}\right)^4\right]\right\}$ where C_i is perceived air quality measured in decipol	$-176.16X^2 + 738.4X - 690.29$ where $X = \{\ln(\ln(\text{lux}))\}$	100 - PPD
6. (Marino et al., 2012)	I	dBA < 40	CO_2 above outdoor concentration $CO_2 < 350$ ppm	lx > 750	(Operative temperature) Winter: $21 \leq t_o \leq 25$ °C Summer: $23.5 \leq t_o \leq 25.5$ °C air speed < 0.15 m/s
	II	$40 \leq$ dBA ≤ 45	$350 \leq CO_2 < 500$ ppm	$500 \leq$ lx ≤ 750	Winter: $20 \leq t_o \leq 21$ °C $25 \leq t_o \leq 26$ °C Summer: $23 \leq t_o \leq 23.5$ °C $25.5 \leq t_o \leq 26$ °C $0.15 \leq$ air speed ≤ 0.18 m/s
	III	$45 \leq$ dBA ≤ 50	$500 \leq CO_2 < 800$ ppm	$300 \leq$ lx ≤ 500	Winter: $18 \leq t_o \leq 20$ °C $26 \leq t_o \leq 28$ °C Summer: $22 \leq t_o \leq 23$ °C $26 \leq t_o \leq 27$ °C

Study	Assessment Class	Acoustics	IAQ	Lighting	Thermal Comfort
					$0.18 \le$ air speed ≤ 0.21 m/s
	IV	dBA > 50	CO_2 > 800 ppm	lx < 300	Winter: t_o <18 °C t_o >28 °C Summer: t_o <22 °C t_o >27 °C air speed >0.21 m/s

1.6 Performance measurement methods and tools

Finding accurate, easy-to-use, and inexpensive measurement equipment is one of the major hurdles in IEQ performance evaluation. With the explosion of wireless monitoring equipment in recent years, measuring various building parameters has become a much less labor-intensive process. However, there are still a number of operational hurdles that still make measurement a cumbersome process. The following sections describe devices and procedures that represent recent attempts at developing tools to measure building performance.

1.6.1 Devices

While sensor and logging device manufacturers have made products that are increasingly accurate and easy-to-use (wireless), the work of creating devices with multiple sensors is still largely in the hands of the users. IEQ measurement requires a combination of devices and individual sensors to capture the state of IEQ in a space. Section 2.1.2 details the devices used in the toolkit developed for this project. This section provides a brief review of similar devices that have been discussed in the literature.

Figure 2 - Figure 4 show pictures of IEQ measurement carts, and Figure 5 - Figure 7 show pictures of thermal comfort measurement carts. The sensors associated with each cart are provided in Table 8.

Figure 2: EnviroBot (Choi, Loftness, & Aziz, 2012)

Figure 3: Comprehensive IEQ monitoring cart (Kim & Haberl 2012)

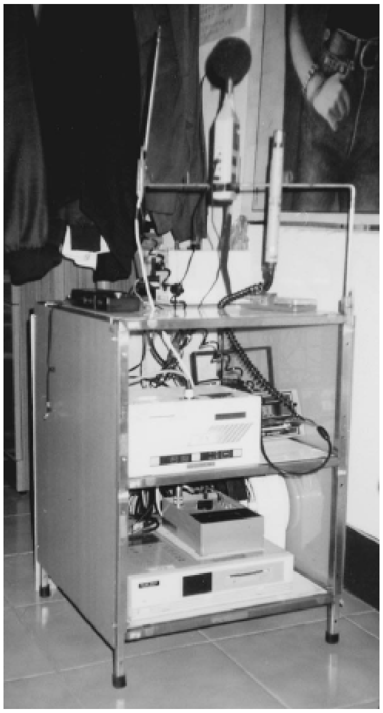


Figure 4: IEQ cart (C.M. Chiang et al., 2001)

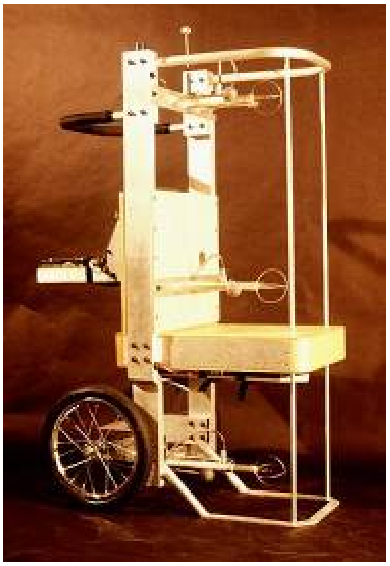


Figure 5: Instrumented chair-like cart (Benton, Bauman, & Fountain, 1990)

Figure 6: SCATs instrumented cart (Nicol, J. F. and McCartney, 2000)

Figure 7: UFAD commissioning cart (Webster, Bauman, & Anwar, 2007)

Table 8: Summary of IEQ cart instrumentation

Cart	Acoustics	IAQ	Lighting	Thermal Comfort
EnviroBot (Choi, Loftness, & Aziz, 2012)	-	CO_2, CO, PM_{tot}, TVOCs	Illuminance, camera for HDR luminance	Air temperature at 0.1, 0.6, 1.1m; RH; hand-held air speed and radiant temperature
Comprehensive IEQ monitoring cart (Kim & Haberl 2012)	Sound level meter	CO_2, CO, PM_{tot}, TVOCs	Horizontal and vertical illuminance, camera for HDR luminance	Air temperature and globe temperature at 0.1, 0.6, 1.1, 1.7m; air speed; RH
IEQ cart (C.M. Chiang et al., 2001)	Sound level meter	CO_2, CO, PM_{tot}	Illuminance	Air temperature; air speed; RH
Instrumented chair-like cart (Benton et al., 1990)	-	-	Illuminance	Air temperature, air speed, and globe temperature at 0.1, 0.6, 1.1m; dewpoint temperature and chair surface temperature at 0.6m, radiant asymmetry at 1.1m
SCATs instrumented cart (Nicol, J. F. and McCartney, 2000)	-	-	-	Air temperature; globe temperature; air speed; RH. Instruments tethered to cart and placed on occupant desktops when in use.
UFAD commissioning cart (Webster et al., 2007)	-	-	-	Air temperature at 0.1, 0.23, 0.49, 0.73, 0.98, 1.2, 1.5, 1.7, 2.1, 2.5, 2.8, 3.3m, underfloor temperature and pressure, floor and ceiling surface temperature (IRT)

These carts represent a wide range of abilities and size. Carts are primarily useful for their ability to move multiple sensors around a space and to have multiple wired sensors log to one location. With the advent of wireless sensors, this restriction of keeping sensors together is lifted. While there are still some practical advantages to having multiple sensors on one cart, the bulkiness of carts makes them difficult to move around spaces, travel with, and get measurements directly in the workspace while the occupant is present.

1.6.2 Objective measurement procedures and handling metadata

Measurement procedures describe the details of how a sensor is used to collect data. These details include temporal and spatial resolution as well as special instructions on the placement of the sensor and the presence of occupants. Table 9 provides a summary of the spatial and temporal procedural variables for the POE studies previously reviewed and for the PMP. The PMP also includes detailed instructions for proper sensor usage and some sections include information as to the presence of occupants (Acoustics, IAQ). The REHVA ICQ guidebook does not include information on measurement procedures.

Table 9: Objective measurement procedural variables summary

Protocol		Acoustics	IAQ	Lighting	Thermal Comfort
PMP (Intermediate level)	Temporal	Background noise: 30 seconds minimum per measurement	Continuous for at least 1 week	Unknown	Continuous for unknown length of time
	Spatial	Background noise: at any valid measurement point where occupants are—at least 4 locations per room	Spaces with unusual or atypical activities; omit sparsely occupied and unoccupied areas	Illuminance: 2.5ft above floor at regular grid spacing = ¼ space between luminaires Luminance: 11 specific locations (see PMP pgs 145-146)	At typical workstations; Close to locations where occupants identified issues; In relevant areas of control system (diffusers, radiators, windows)
EPA BASE	Temporal	Background noise: continuous measurement for 3 days	CO, CO2: continuous for 3 days and 5-minute averages on mobile cart (20 locations) VOCs, PM, HCHO: one 9-hour integrated sample	Continuous measurement for 3 days	Continuous measurement for 3 days and 5-minute averages on mobile cart (20 locations)
	Spatial	3 fixed locations	3 fixed locations and 20 mobile cart locations	3 fixed locations	3 fixed locations and 20 mobile cart locations
(Choi, Loftness, & Aziz, 2012)	Temporal	Spot measurements and 24 hour continuous measurements during summer, winter, and swing seasons over 5 year period (unknown how long per building); Cart measurements made for 15 minutes with 15 second interval data and averaged			
	Spatial	10-15% of workstations per floor; Cart placed in the position of the occupant's chair			

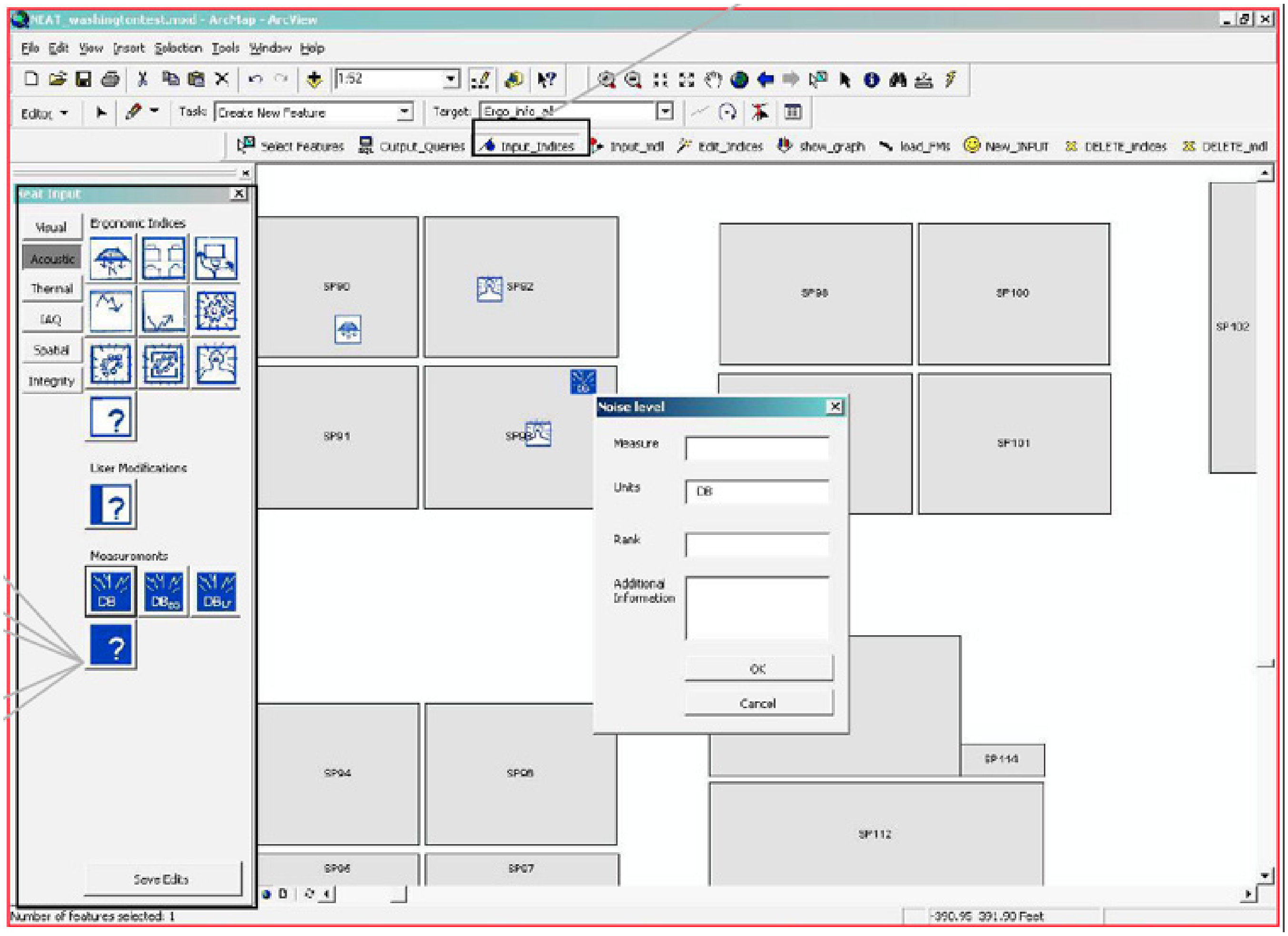
Protocol		**Acoustics**	**IAQ**	**Lighting**	**Thermal Comfort**
(Kim & Haberl 2012)	Temporal	One week of measurements per building; Continuous measurement at 1, 5, 15 minute logging intervals			
	Spatial	Unknown			
(C.M. Chiang et al., 2001)	Temporal	24 hours of continuous measurement			
	Spatial	Sensors installed in breathing zone but in a fixed location that minimizes influence on living behavior of elders in study. Unknown density of measurement locations.			
(Cao et al., 2012)	Temporal	Warmup of 3 minutes before measurement; 20 minutes for measurement period; 1 minute intervals; mean of 20 minute interval used for analysis			
	Spatial	Workstations of the occupants that were surveyed while occupant was present			

There is a wide range of temporal and spatial resolution used in these IEQ studies, though each study represents only a temporal and spatial snapshot of a building. There is little guidance from the literature on how many hours of data needs to be collected in order to provide a representative sample. The studies in Table 9 ranged from 1-day to 5 years in length. Further discussion of measurement procedures is provided in section 4.3.

With improved technology and cheap storage, continuous measurement is more common practice today. With continuous measurement comes the need for analysis tools to break down the data into meaningful summaries of performance. The literature contains little discussion of custom analysis tools and procedures, which this project aims to provide (section 2.2).

Metadata is "data about data," which in the context of building performance evaluation field studies is the data describing location, time, and sensors of measurements taken. Handling metadata is one of the most time consuming aspects of field studies. Much of this time spent is unavoidable; the time it takes to familiarize oneself with the building being studied (layout, systems, control sequences). However, some of the time dedicated to metadata is avoidable through efficient procedures. Section 4.3 provides a discussion of this project's attempts to minimize time associated with metadata collection and handling. Existing literature on this issue is sparse, though this section reviews the effort at the Center for Building Performance and Diagnostics (CBPD) to develop and document efficient metadata collection and handling procedures.

CBPD has had a long history of IEQ evaluation and created a system in the early 2000s to collect IEQ measurements and link the sensor data to occupant feedback data and location data (Azizan, Kim, & Viraj, 2005; Choi et al., 2012). The system uses a relational database backend (Oracle) with a web frontend (Java), coupled with a GIS-based metadata collection system. More than any other system in the literature, the CBPD National Environmental Assessment Toolkit provides the best example of the type of integrated IEQ evaluation toolkit that this project proposes. The GIS-based metadata system allows for both input and output of data. For example, on a map of a building floor plan, a user could designate both that a measurement was taken and the metadata associated with that measurement (type, sensor, time, location)—see Figure 8. Later, the user could retrieve the reading associated with that measurement through the GIS interface.


Task: Create New Feature

Target: Ergo_info_all

Units: DB

Figure 8: NEAT screenshot of inputting a sound level measurement spatially in GIS (Loftness & Aziz, n.d.)

1.7 Statement of the problem

As standards and high performance building rating systems like LEED continue to push for better performing buildings, the need for evaluating performance beyond energy and water consumption has become increasingly relevant and pressing. IEQ parameters have strong influence over energy consumption, both through design related decisions and in the operation of the building. Setting energy benchmarks without corresponding IEQ benchmarks is shortsighted. With a focus on low-energy buildings, the comfort of the occupants and their satisfaction with the IEQ should not be overlooked.

While there is recent guidance regarding indoor environmental quality measurements from the Performance Measurement Protocols (PMP) (ASHRAE/CIBSE/USGBC, 2010), there is limited guidance on how to perform all of these measurements to a satisfactory level within a constrained timeframe and budget. The barriers to post-occupancy evaluations documented by Zimmerman and Martin (2001)—standard practice, split incentives, indicators and benchmarks, and liability—are largely still valid today.

Additionally, there is currently a lack of guidance on how to summarize these IEQ evaluations for the purposes of 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. How should survey results be combined with measured results in such a roll-up? Should one be weighted more than the other? Given that it is impractical to measure IEQ parameters in both temporal and spatial totality, how is this snapshot type of measurement accounted for in such a roll-up? Is there a minimum or standard spatial/temporal frequency that can provide an accurate picture of overall IEQ performance?

This study presents the results of a two-year effort to develop better methods and tools in order to address the above questions and the barriers that face making evaluating building performance standard practice.

1.8 Objectives

In order to address the previously identified need for better methods and tools for evaluating building performance, this project seeks to:

1. Develop a hardware and software toolkit for facilitating the evaluation of IEQ performance in commercial buildings based on the ASHRAE/CIBSE/USGBC Performance Measurement Protocols.
2. Evaluate the success of the toolkit through a case study
3. Explore IEQ models as a method for rating IEQ performance
4. Provide an example implementation of the PMP and suggestions for improvement

The toolkit aims to simplify the process of building performance evaluation, tying together the multiple pieces needed to appropriately evaluate performance. In doing so, the toolkit hopes to be a prototype for future cost-effective, commercially available toolkits.

The toolkit's success will be evaluated through a case study that provides feedback on toolkit procedures and features from practitioners. In addition to feedback on the toolkit, the case study will provide a source of data to explore three of the IEQ rating systems discussed in section 1.5. Specifically, issues of spatial and temporal resolution are explored as they relate both to IEQ ratings and procedural feasibility.

Finally, this project aims to provide critical feedback on the PMP in an effort to widen the appeal of IEQ evaluation to current practitioners and other potential interested parties such as LEED.

1.9 Significance

IEQ evaluation through objective measurement is often identified as too expensive to be cost-effective for clients. Indeed, to this author's knowledge, the procedures outlined in the PMP and this thesis have thus far only been done by researchers and academics. The creation of a toolkit that makes IEQ performance evaluation cost-effective for clients and practitioners has the ability to create a larger market for IEQ evaluation through multiple avenues, including the addition of IEQ evaluation procedures to:

- Standard commissioning (re-, retro-, monitoring based) procedures,
- Existing building performance rating systems like LEED,
- Design team in-house evaluation procedures (architect, mechanical/electrical/plumbing, lighting, and acoustics designers)

A larger market for IEQ evaluation has the potential to improve the IEQ of both existing and new buildings, resulting in a more comfortable and energy-efficient building stock.

1.10 Thesis Overview

Chapter 2 of this thesis details the development of a Building Performance Evaluation Toolkit that aims to simplify the process of measuring building performance. This chapter serves as the primary documentation for the toolkit, which was designed to be easily replicated and improved upon by other researchers and potential commercial interests.

Chapter 3 details the analysis of a case study that used the toolkit. This chapter investigates the complexities involved in summarizing IEQ performance, providing a set of recommendations as feedback on current guidelines.

Chapter 4 provides detailed discussion of the strengths and weaknesses of the toolkit components, IEQ models, and the PMP guidebook.

2 Building Performance Evaluation Toolkit

The Building Performance Evaluation Toolkit (hereon referred to as the Toolkit) represents the major body of work that was completed for this thesis. While the Toolkit represents a process of collaboration between Tom Webster, George Anwar, Darryl Dickerhoff, and Tyler Hoyt, the design and implementation was primarily the work of this author (apart from hardware development of sensor motes). The Toolkit represents the culmination of ideas behind enabling a system to achieve time-efficient IEQ diagnostics and evaluation. The Toolkit also includes devices to measure energy and water, but these aspects of the Toolkit and PMP are not discussed in this thesis. The Toolkit is designed around the PMP, though does not strictly adhere to all recommended procedures and tools. Table 10 provides a summary of how the Toolkit addresses the objective measurement requirements of the PMP (continuation of Table 3). Deviation from the PMP is discussed where relevant in the subsequent sections.

Table 10: Toolkit alignment with PMP

Level	Thermal Comfort	Indoor Air Quality	Lighting	Acoustics
Basic	Spot measurements of temperature, relative humidity, mean radiant temperature, air speed	Outside air flow rates at each outside air intake Spot measurements of temperature and humidity to characterize occupant perceptions of IAQ	Spot measurements of illuminance in selected spaces	Sound level meter Spot measurements of A-weighted sound pressure level (dBA) in occupied spaces
Intermediate	Temperature, relative humidity, incident solar radiation, air speed over intervals of 1-15 minutes	If strong local ambient pollutant source is suspected, determine OA quality at site OA flow rates at each OA intake At least one week continuous CO_2 monitoring in representative spaces	Full grid measurements of illuminance and luminance Determination of discomfort glare	Sound level meter Detailed measurement of background noise in octave bands for comparison with single-number ratings such as NC, RC, and NCB Spot measurement of reverberation time (T_{60}) for general assessment of speech communication issues
Advanced	Detailed and continuous measurement of temperature gradients and transients and radiation asymmetry for detailed spatial resolution	Measure moisture content beneath surfaces where moisture is observed Continuous measurement of CO_2, PM2.5, and TVOCs CoC only if suspected to be present	High resolution measurement of illuminance, luminance, and discomfort glare with HDR photography	Measurement of speech privacy and speech communication (AI, PI, SII, or SIL) for special-purpose room uses Measurement of sound and vibration isolation (NIC, IIC, $D_{nt,w}$ and $L'_{nT,w}$) from outside sources and between interior rooms
Toolkit	Continuous measurements of air and globe temperature, air speed, relative humidity at 30 second	Continuous measurement of CO_2 in representative spaces.	Continuous measurement of horizontal illuminance in representative spaces on workstation plane.	Spot measurements of A-weighted sound pressure level (dBA) in occupied spaces. Support for continuous measurement of sound pressure level.

Level	Thermal Comfort	Indoor Air Quality	Lighting	Acoustics
	intervals. Support for stratified systems measurement			

The goals of the Toolkit include:

- Develop a hardware platform that minimizes setup time and post-study data management time.
- Develop a centralized data management and analysis system that stores all project-related data from sensors, building management systems, location metadata, and surveys.
- Develop data analysis and visualization capabilities, including:
  - Presentation of results in "near real time" to toolkit operators on-site and off-site.
  - Data reduction capabilities for benchmarking and rating.

2.1 Toolkit hardware

The hardware components of the Toolkit include a wireless mesh networking system, sensors, and custom devices designed to house multiple sensors.

Usability and accuracy were the major objectives behind the Toolkit hardware design. Cost also played an important role, though costs were assumed to be high for a prototype design. The word "usability" masks a broad set of design parameters that together achieve an intuitive and usable system. The following sections will highlight where decisions were made to achieve greater usability within the target group of commissioning agents, mechanical/electrical/plumbing (MEP) consultants, and building operators. Table 11 provides an overview of the Toolkit instrumentation and cost based on off-the-shelf pricing in low volumes (unless otherwise noted).

Table 11: Toolkit instrumentation summary

Basic Level	Sensor/Instrument	Accuracy (±)	Quantity	Cost (per sensor)
Thermal Comfort	Infrared temperature (surface temperature)	2 ˚C or 1.5% of reading	4	$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
Indoor Air Quality	CO_2	30ppm + 3% measured value	20	$65
Lighting/Daylighting	Illuminance	5%	20	$440
Acoustics	Sound level meter	-	1	$1495

Basic Level	Sensor/Instrument	Accuracy (±)	Quantity	Cost (per sensor)
Wireless System	Mote + IO Board	-	25	$650[1]
	Embedded computer	-	1	$1000
	Tablet w/ 4G cellnet	-	1	$700
	Wireless router	-	1	$200

2.1.1 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.

Recently, 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 9 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 (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) (Dawson-Haggerty, Jiang, Tolle, Ortiz, & Culler, 2010) that is detailed in section 2.2.1. Drivers for Johnson Controls Metasys, Siemens Apogee, and Automated Logic Controls have been used successfully to import BMS data in real-time.

---

[1] Research level pricing at low volume

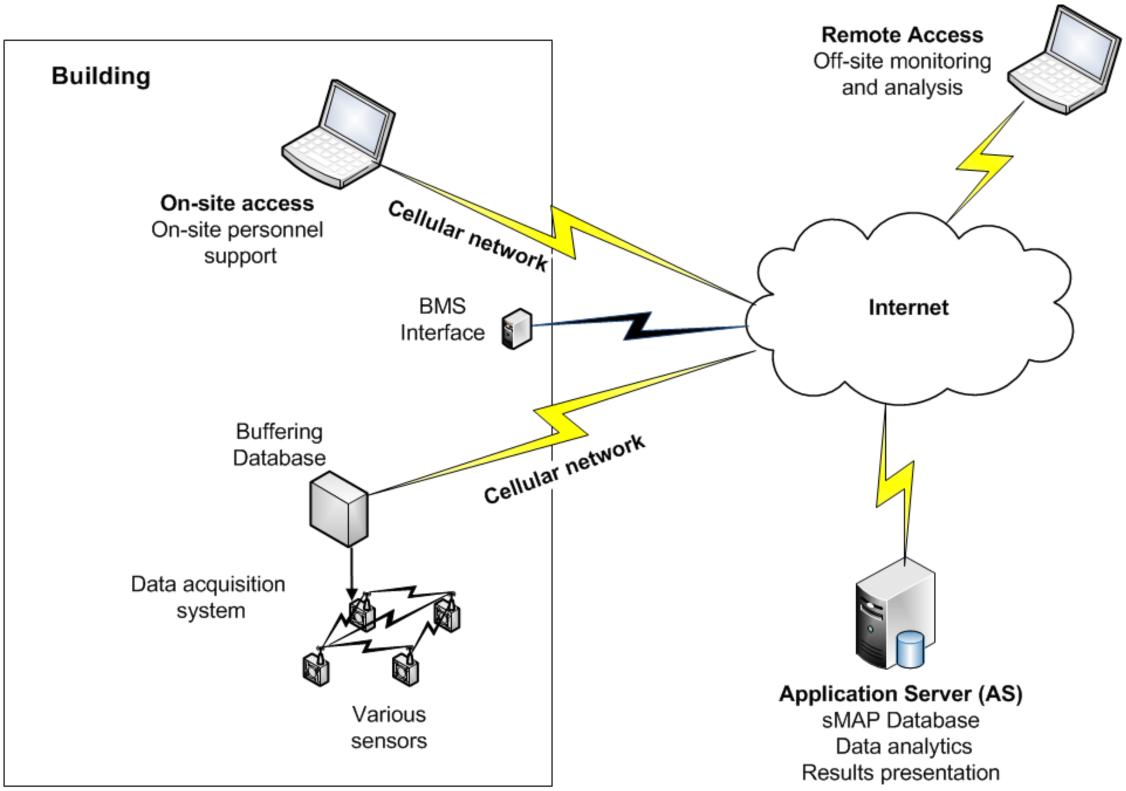


Figure 9: System architecture

2.1.1.1 Wireless mesh networking

Wireless mesh networking involves a set of wireless motes that form a web of connections with each other. This technology enables two important features for wireless sensing in buildings:

1. The ability to create a robust network of redundant connections,
2. The ability to create a spatially large network of sensors

In a traditional point-to-point wireless network system, each mote needs to be within range of the wireless access point (base station). With a wireless mesh network, motes only need to be within range of one other mote in order to pass data packets back to the base station. Buildings can be challenging environments for wireless signals (concrete and metal walls and floors), making robust mesh networking an appropriate fit.

For the Toolkit, Dust Networks (now Linear Technologies) wireless technology was used. An earlier evaluation of multiple wireless mesh networking products concluded that Dust Networks technology was the most robust, low power, and fastest to establish an effective network typology.

2.1.2 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.

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

The Indoor Climate Monitor (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), and a wireless enabled input-output board, an illuminance sensor and a CO_2 sensor were added to the device. 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. Figure 10 and Figure 11 show the outside and inside of the ICM device respectively. The details of the sensors used, including part numbers and manufacturers are available in Appendix A - ICM .

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 10: ICM device with CO_2, illuminance, globe, air velocity, dry bulb temperature, and relative humidity

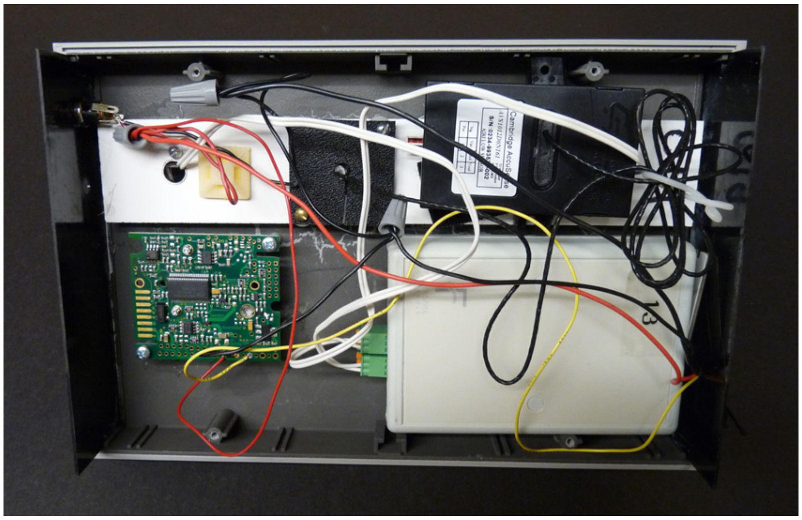


Figure 11: The inside of the ICM device

2.1.2.1.1 Thermal comfort sensors

Thermal comfort is characterized by two personal variables (clothing insulation and metabolic activity) and four physical variables: air temperature, relative humidity, air speed, and mean radiant temperature. From these parameters, operative temperature can also be computed, which represents the combination of the convective and radiant components of heat transfer resulting in a close approximation of the temperature humans feel in an environment. Operative temperature is used in ASHRAE Standard 55 (ANSI/ASHRAE, 2010a) for determining comfort.

The ICM measures dry-bulb temperature using a radiation-shielded thermistor. Both the globe temperature sensor and the dry-bulb temperature sensor use thermistors that are accurate to 0.1°C with 1% interchangeability. Each thermistor was calibrated using a dry-well temperature calibration unit while connected to the wireless input-output board that computes temperature based on a 10,000-ohm reference resistor. The details of the radiation shielding and ICM globe temperature sensor are available in Paliaga (2004). Additional theory behind the globe temperature sensors are available in Benton et al. (1990), Humphreys (1977), and Fountain (1987). While the ping pong ball globe thermometer is not a standard black globe thermometer, it provides a faster response time with good accuracy (Benton et al., 1990). Globe temperature, air speed, and dry-bulb temperature can be used to compute mean-radiant temperature corrected for sphere diameter according to Equation 1 (where *Tr* is mean radiant temperature, T_g is the globe temperature, T_a is the air temperature, *D* is the diameter of the ping-pong ball, *V* is the air velocity, σ is the Stephan-Boltzman constant, and $\in$ is the emissivity of the globe.

Equation 1: Calculation of mean-radiant temperature

$$T_r = \left[\frac{6.32D^{-0.4}V^{0.5}}{\sigma\epsilon}\left(T_g - T_a\right) + T_g^4\right]^{0.25}$$

For the purposes of the Toolkit, operative temperature is computed as the average of mean-radiant temperature and dry-bulb temperatures. Future work will add the ability to compute other thermal comfort parameters including Standard Effective Temperature (SET).

Details of the air-speed sensor are available in Paliaga (2004). The details of the relative humidity sensor are available in Appendix A - ICM .

2.1.2.1.2 Lighting sensor

The basic level of the PMP suggests measurements of horizontal illuminance in areas that were deemed problematic in an occupant survey. At the intermediate level, the PMP suggests full grid measurement of horizontal illuminance and luminance 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. Due to the difficulty of proceduralizing luminance measurement and analysis, the Toolkit deviates from the PMP suggested procedures for lighting evaluation. HDR photography coupled with the lighting simulation program Radiance can provide evaluation of luminance information, but methods for automated collection and analysis are challenging. Future implementations of the Toolkit hope to include luminance measurements along with analysis methods similar to those provided by Konis (2012).

Horizontal illuminance is measured using a Licor Photometric sensor which has cosine correction and is accurate to ±5%. 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 which is accurate to ±2% to obtain calibration coefficients of reasonable relative accuracy.

2.1.2.1.3 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 (PM_{10}, $PM_{2.5}$, ozone, or air-toxics non-attainment problems), the primary concern for IAQ is to achieve an adequate level of ventilation while preventing water/moisture situations that lead to biological growth. 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, 2010b). The Toolkit deviates from the PMP and does not include a tool for the measurement and analysis of outdoor air flow rates, though such a tool could be added in the future. Methods for accurately measuring outdoor air flow rates can be complex and require access to multiple mechanical spaces in a building (see section 4.1.3 for further discussion). CO_2 measurement was chosen as the parameter to indicate indoor air quality because of its prevalent use in buildings for demand-controlled ventilation. Ozone, volatile organic compounds (VOCs), and particulate matter ($PM_{2.5}$ and PM_{10}) were also considered, though reasonably priced sensors were deemed to be too inaccurate to provide valuable IAQ performance evaluation.

CO_2 measurement is one method of estimating ventilation level within a space. The PMP suggests that CO_2 measurement is a highly inaccurate, but nevertheless potentially useful tool for diagnosing ventilation issues. 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.

Fundamentally, there are numerous problems associated with using CO_2 as an indicator of IAQ, though its wide application in demand-controlled ventilation (DCV) has made it an important tool to understand and measure. ASHRAE Standard 62.1 (ANSI/ASHRAE, 2010b) allows CO_2 demand-controlled ventilation to be used as a dynamic reset strategy for outdoor air intake flow rates and the PMP provides basic guidance on how to measure and interpret CO_2. Fisk et al. (2010) suggest that commercially available CO_2 sensors for buildings are not highly accurate and largely prevent the energy savings from DCV from being realized. Nevertheless, Fisk et al. see value in CO_2 measurement and DCV, urging improved sensor accuracy. Additionally, Fisk et al. notes that the difference between outdoor CO_2 and indoor CO_2 levels is a better indicator of ventilation rate than indoor alone, suggesting that the repeatability of the sensor, rather than its accuracy is more important.

With all of the cautionary literature regarding CO_2 measurement in mind, a CO_2 sensor was deemed useful enough to include on the ICM. Because the ICM devices are placed on the user's desk, the response time for CO_2 indicating occupancy is smaller than those suggested in the aforementioned studies. 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 K-30 CO_2 module with 1% repeatability and 3% accuracy was selected for ICM as a balance of 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 ppm (baseline outdoor level). The sensors were spot checked against an EGM-4 CO_2 sensor by PP Systems that has an accuracy of <1% and found to be within 50 ppm.

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

The Portable UFAD Commissioning Cart (PUCC) was designed to be a portable and wireless alternative to a previously CBE designed UFAD commissioning cart (Webster et al., 2007). Underfloor air distribution (UFAD) is a type of air distribution system in which air is delivered in the occupied space from an underfloor plenum. The PUCC measures temperature at 4", 10", 24", 48", 67", and 4" 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 12 is a photograph of the PUCC and Figure 13 shows the PUCC disassembled and ready for transport in a golf-bag carrier. The details of the included sensors are available in Appendix B – PUCC .

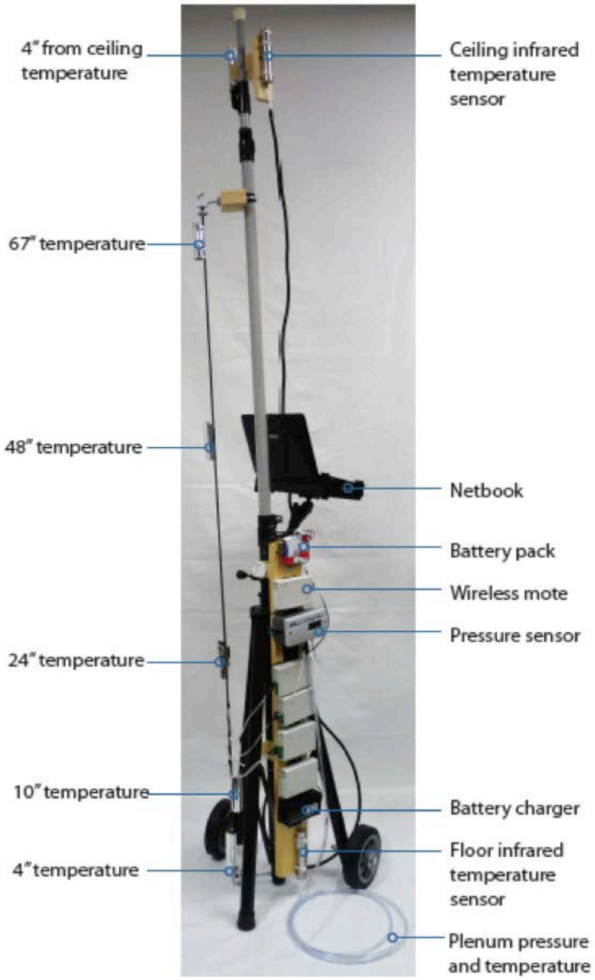


Figure 12: Portable UFAD commissioning cart

Figure 13: PUCC disassembled and ready for transport in golf bag carrier

2.1.2.3 Acoustics measurement

The Toolkit includes a Larson Davis LxT sound level pressure meter connected to a wireless mote. At the basic level, the PMP requires A-weighted sound pressure level measurements in representative spaces. At the intermediate level, the PMP requires octave band analysis to be performed by an acoustics consultant. The Toolkit deviates from the PMP in this regard and does not include a tool or analysis method for completing octave band analysis, though the LxT meter has the add-on capability if such analysis were deemed appropriate in the future.

2.2 Toolkit software

The Toolkit software consists of the data management backend and the analysis and visualization web frontend. The frontend is accessible at http://smap.cbe.berkeley.edu. The open-source code for this frontend is hosted at http://code.google.com/p/cbesmap. The design goals of the Toolkit software included:

- Web-based

- Customized analysis and visualization of PMP metrics
- Open-source
- Easily customizable
- Simple to use

Section 2.2.1 details the backend technology that enabled the fulfillment of many of the above goals, while sections 2.2.4 through 2.2.6 detail the analysis and rating capabilities related to each IEQ category.

2.2.1 Backend details

There are two backends that support the web frontend of the Toolkit: the Simple Mapping and Actuation Profile (sMAP) system and Django (MySQL). 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.

sMAP is a set of tools to enable simple and efficient exchange of time-series data through web-enabled applications (Dawson-Haggerty et al., 2010). sMAP has three major components which are shown in Figure 14.

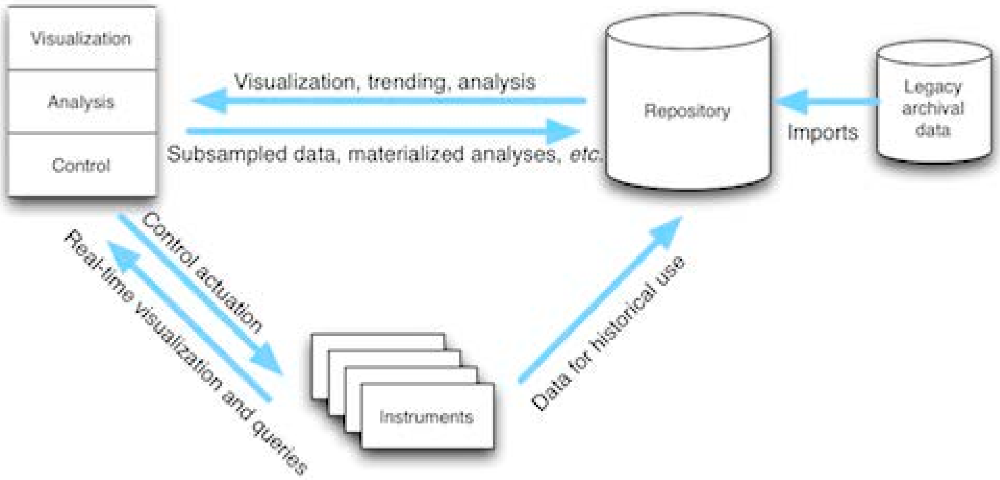


Figure 14: sMAP components and data exchange paths (Dawson-Haggerty, 2012)

1. Instrument drivers:
   A library of instrument drivers is available to enable the connection of devices to sMAP through HTTP. There are drivers for wireless devices, for BMS systems (Johnson Controls, Siemens, and Automated Logic Controls), weather services, power meters, and others. Additionally, new drivers are easily written in Python based on the existing example drivers.
2. Repository:
   The sMAP repository (Archiver) is a database system optimized for time series data (fast-retrieval, efficient compressible storage). 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).

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 MySQL database, to allow for simple python-based interaction with sMAP. Figure 15 displays the major database tables that make up the Toolkit relational backend.

While sMAP includes methods for associating metadata with time-series data, the methods assume static sensors. The Toolkit uses sensors that change location over time, but are associated with the same project. For example, the acoustics meter will be used in multiple locations during a project, but there is little reason to generate a new stream of data each time the sensor is moved. Thus, a traditional relational database (MySQL) is used to identify chunks of time-series data with the corresponding set of locational metadata. An example of how these data relationships are implemented is provided in the next section.

The Django backend also controls user/group/project management components. Each project is associated with a group. This group can contain multiple users. A user can be part of multiple groups allowing that user to see multiple projects. This flexibility in user/group management allows for a multiuser system in which projects can remain private and independent.

The Django backend comes with an administrative web frontend that provides manual access to database tables: http://smap.cbe.berkeley.edu/admin. The administrative frontend allows new users and groups to be added as well as less frequently accessed Toolkit items, which include:

- IEQ model definition
- IEQ space definition

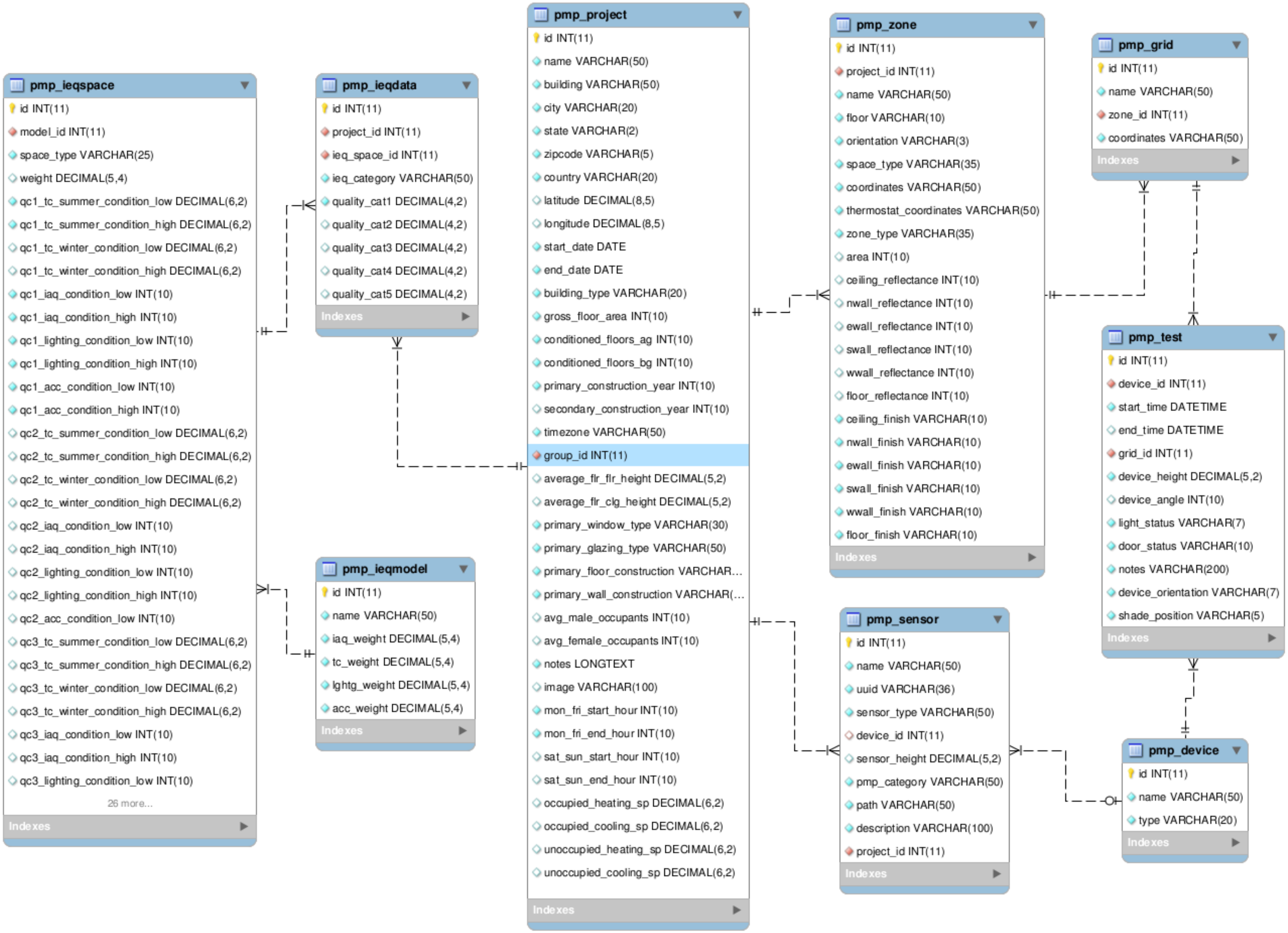
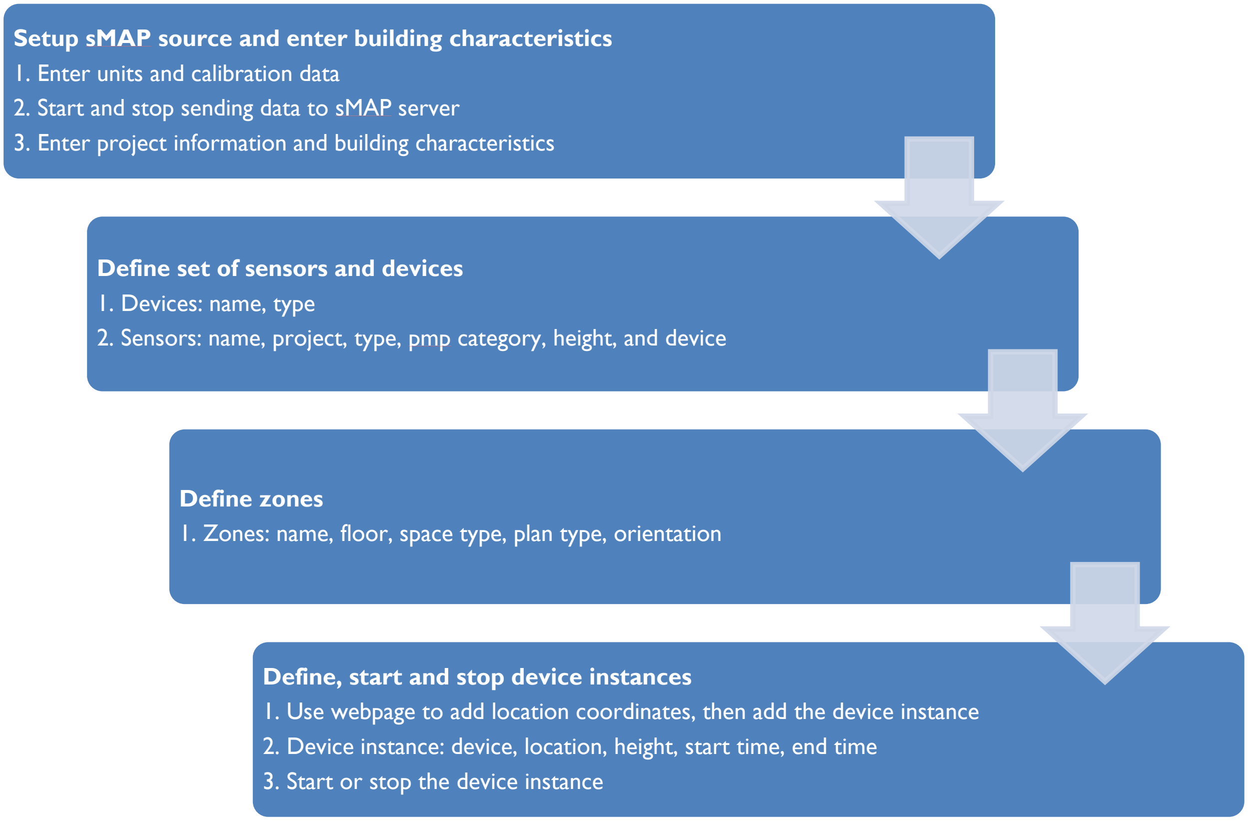


Figure 15: Django/MySQL table relationships

2.2.2 Setting up a project and collecting data

An overview of the process of setting up a Toolkit project and collecting data is shown in Figure 16.



Setup sMAP source and enter building characteristics

1. Enter units and calibration data
2. Start and stop sending data to sMAP server
3. Enter project information and building characteristics

Define set of sensors and devices

1. Devices: name, type
2. Sensors: name, project, type, pmp category, height, and device

Define zones

1. Zones: name, floor, space type, plan type, orientation

Define, start and stop device instances

1. Use webpage to add location coordinates, then add the device instance
2. Device instance: device, location, height, start time, end time
3. Start or stop the device instance

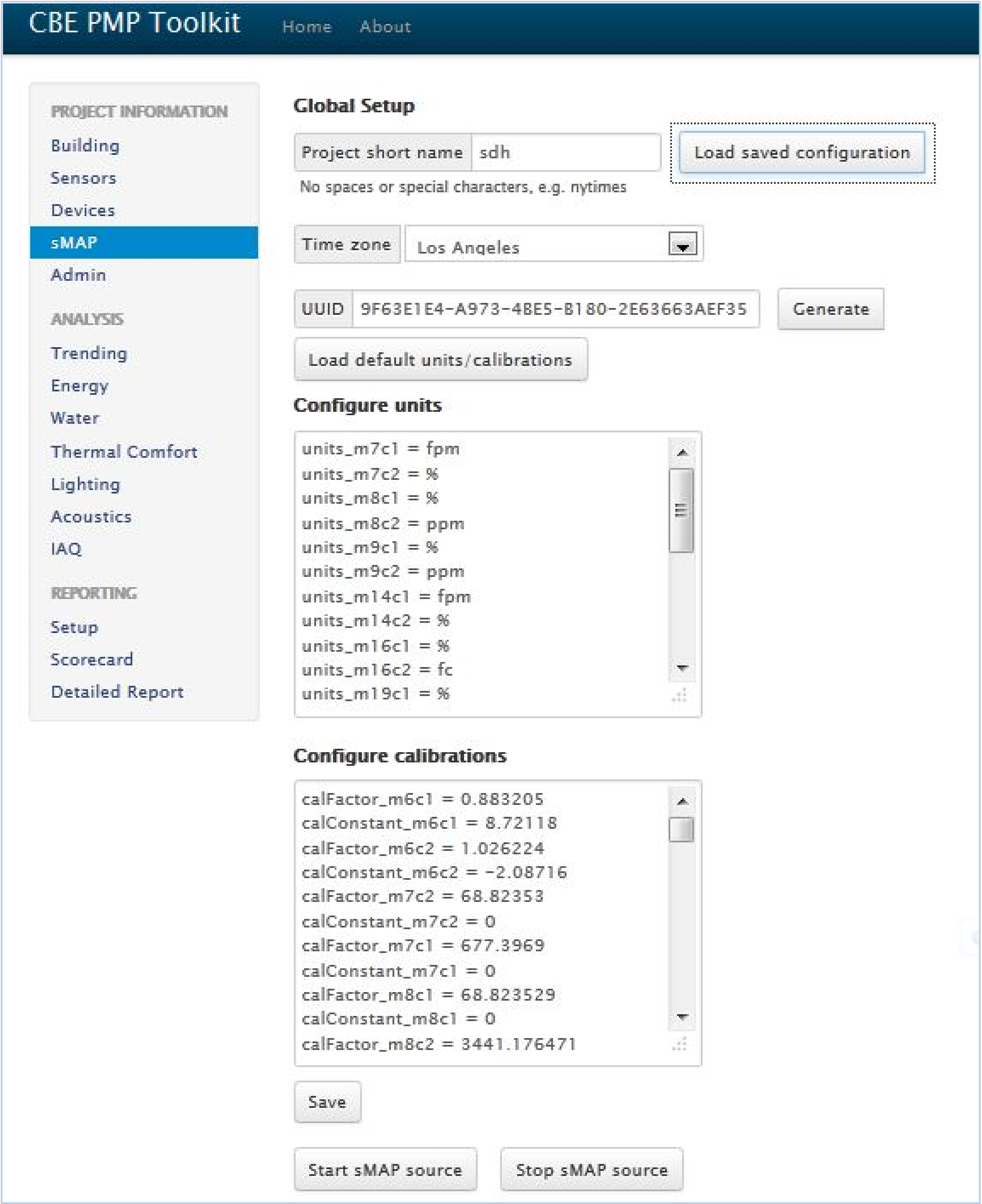
Figure 16: Overview of project setup

This section will provide an example of how to setup a Toolkit project for the Sutardja Dai Hall (SDH) building on the UC Berkeley campus.

2.2.2.1 Setup sMAP source and enter building characteristics

The first step in starting a Toolkit project is to setup the data source to send data to the sMAP repository. The Toolkit is designed to make this as much or as little configurable as the user desires. A standard set of Toolkit sensors can be easily started to send data with the click of a button, but that set of sensors can also be configured. There is a web frontend that exposes this configuration and the starting and stopping of the sMAP data source. While any set of sensors could be used to send data to the repository, this document will only provide an example based on the wireless sensor system that was designed for the Toolkit.

Figure 17 shows the web frontend that enables the configuration of a sMAP data source.



Project short name: sdh

No spaces or special characters, e.g. nytimes

Time zone: Los Angeles

UUID: 9F63E1E4-A973-4BE5-B180-2E63663AEF35

```
units_m7c1 = fpm
units_m7c2 = %
units_m8c1 = %
units_m8c2 = ppm
units_m9c1 = %
units_m9c2 = ppm
units_m14c1 = fpm
units_m14c2 = %
units_m16c1 = %
units_m16c2 = fc
units_m19c1 = %
```

```
calFactor_m6c1 = 0.883205
calConstant_m6c1 = 8.72118
calFactor_m6c2 = 1.026224
calConstant_m6c2 = -2.08716
calFactor_m7c2 = 68.82353
calConstant_m7c2 = 0
calFactor_m7c1 = 677.3969
calConstant_m7c1 = 0
calFactor_m8c1 = 68.823529
calConstant_m8c1 = 0
calFactor_m8c2 = 3441.176471
```

Figure 17: sMAP source setup

- **Project short name**: a short name (no spaces) for the project to identify this set of data within the sMAP respository. Example: sdh
- **Load saved configuration**: if you have previously defined a project short name and saved that configuration file, type in the project short name and then click *Load saved configuration* to retrieve that configuration file.
- **Time zone**: select the appropriate time zone for this project

- **UUID**: click *Generate* to create a new universally unique identifier (UUID) for your project.
- **Load default units/calibrations**: pressing this button will load the default units and calibration coefficients for the Toolkit.
- **Unique units**: the default unit is °F. Any other units must be defined here. The syntax is:

  ```
  units_m<mote_number>c<channel_number> = unit
  ```

  Example: to set the units for mote 2 channel 2 to feet per minute, add the line:

  ```
  units_m2c2 = fpm
  ```

- **Unique calibrations**: the default calibration is no calibration (slope = 1 and constant = 0). To set the linear calibration coefficients of a sensor, the syntax is:

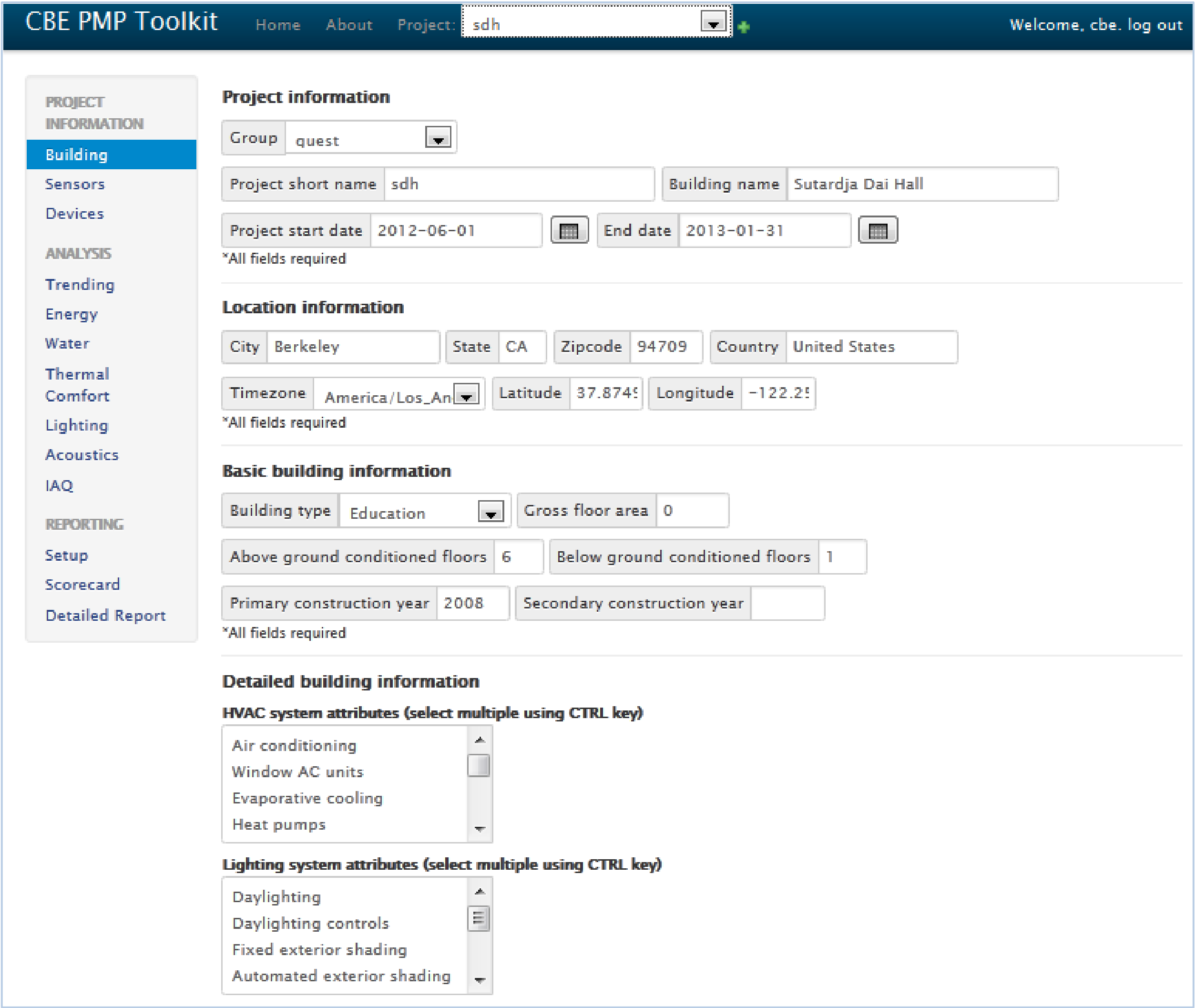
  ```
  calFactor_m<mote_number>c<channel_number> = slope
  calConstant_m<mote_number>c<channel_number> = constant
  ```

  Example: to set the calibration coefficients for the ICM anemometer, add the lines:

  ```
  calFactor_m7c1 = 677.3969
  calConstant_m7c1 = 0
  ```

- **Save**: click *Save* to save the configuration using the project short name
- **Start/Stop sMAP source**: use these buttons to start and stop the exchange of data from the wireless system to sMAP. Restarting a sMAP source with different configuration parameters will change those parameters for new and existing data.

The second step in setting up a Toolkit project is to define the project and building characteristics. Figure 18 shows a partial screenshot of the *Building* page of the frontend. This page is used to collect information about the building being studied. The fields chosen for this page are derived from the PMP and provide the necessary information for EnergyStar, CBECS, and the CBE Survey.



Project information

Group: guest

Project short name: sdh

Building name: Sutardja Dai Hall

Project start date: 2012-06-01

End date: 2013-01-31

*All fields required

Location information

City: Berkeley

State: CA

Zipcode: 94709

Country: United States

Timezone: America/Los_An

Latitude: 37.874!

Longitude: -122.2!

*All fields required

Basic building information

Building type: Education

Gross floor area: 0

Above ground conditioned floors: 6

Below ground conditioned floors: 1

Primary construction year: 2008

Secondary construction year:

*All fields required

Detailed building information

HVAC system attributes (select multiple using CTRL key)

Air conditioning
Window AC units
Evaporative cooling
Heat pumps

Lighting system attributes (select multiple using CTRL key)

Daylighting
Daylighting controls
Fixed exterior shading
Automated exterior shading

Figure 18: Building page of toolkit frontend

2.2.2.2 Define set of sensors and devices

The data that is sent to sMAP is coded with unique "stream" identifiers called UUIDs and path names that are coded as follows:

```
/<short_project_name>/m<mote_number>/c<channel_number>
```

Example: the path to mote 2 channel 2 for the SDH project would be:

```
/sdh/m2/c2
```

Each data stream has a UUID and a path, though the path is not necessarily unique (though in practice it is). The UUID is the piece of information used to connect the Django metadata backend with the sMAP repository backend. sMAP streams are equivalent to Toolkit sensors.

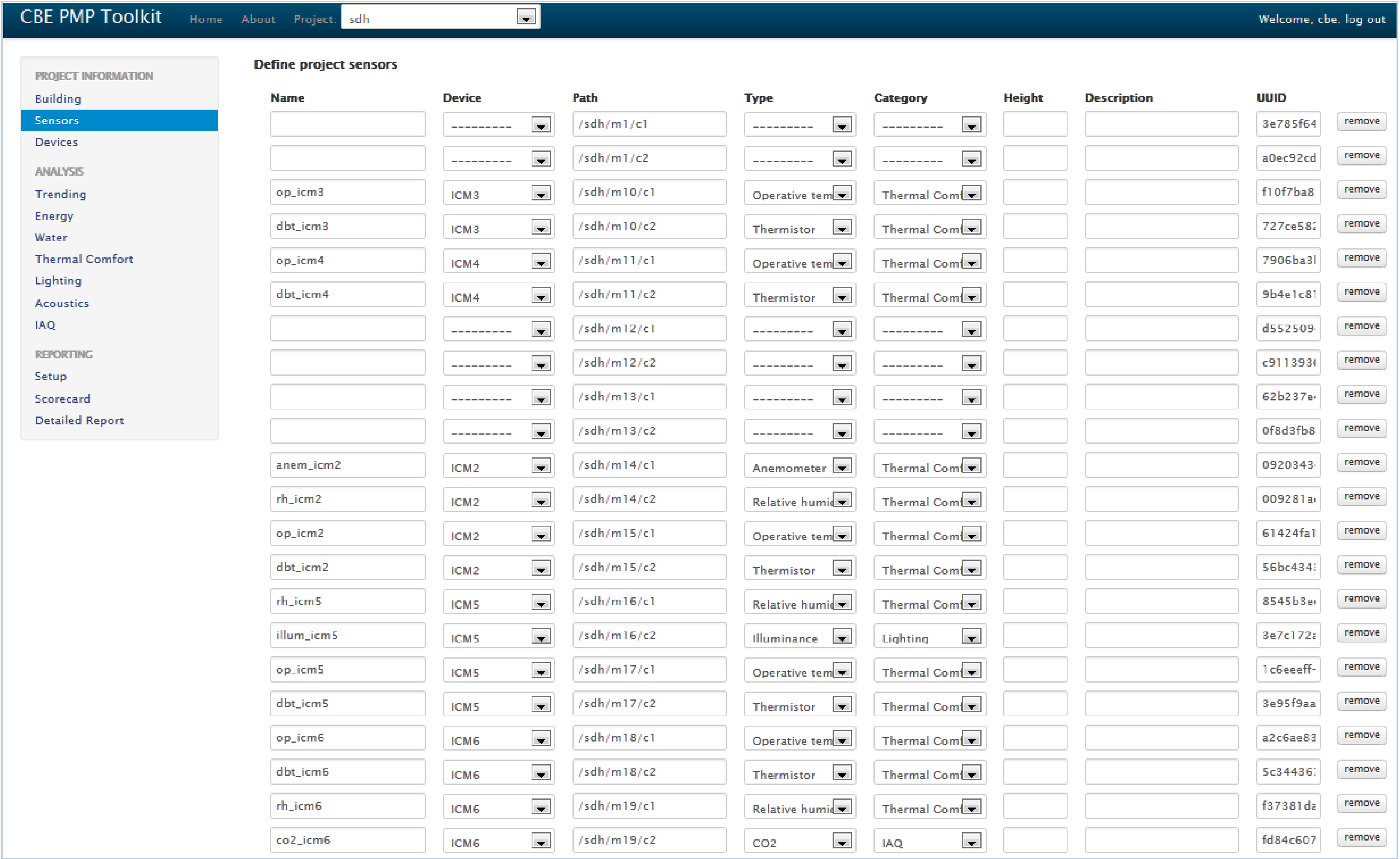
In order to have meaningful information about the sensors, sensor information must be entered and connected to the appropriate sMAP stream. This process can be skipped if the default set of Toolkit sensors is used. However, all sensors are fully customizable on a project-by-project basis. Figure 19 shows a partial screenshot of the sensor configuration page for the SDH project. A sensor entry has the following fields that help identify and categorize the sensor:

- Project – connection to *Project* table
- Name – user defined name
- Device – connection to *Device* table
- Path – sMAP path
- Type – select from list
- Category – PMP category
- Height – height of sensor within device
- Description
- UUID – sMAP UUID

Devices represent a combination of sensors or a single sensor. A device is the instrument that is used in the field. Each sensor must be associated with a device. There is an existing list of devices available by default in the Toolkit, which includes:

- Cart (PUCC)
- ICM1 – 20
- Fixed poles (for each orientation and zone type [interior or perimeter])
- Plenum mote
- FPB inlet (fan-powered-box inlet temperature mote)
- FPB outlet (fan-powered-box outlet temperature mote)
- FPB power
- Chilled water temperature
- Plug load power
- Air highway temperature
- Surface temperature
- Sound level meter

Devices are not project specific and new ones can be added through the device instance page discussed in section 2.2.2.4.



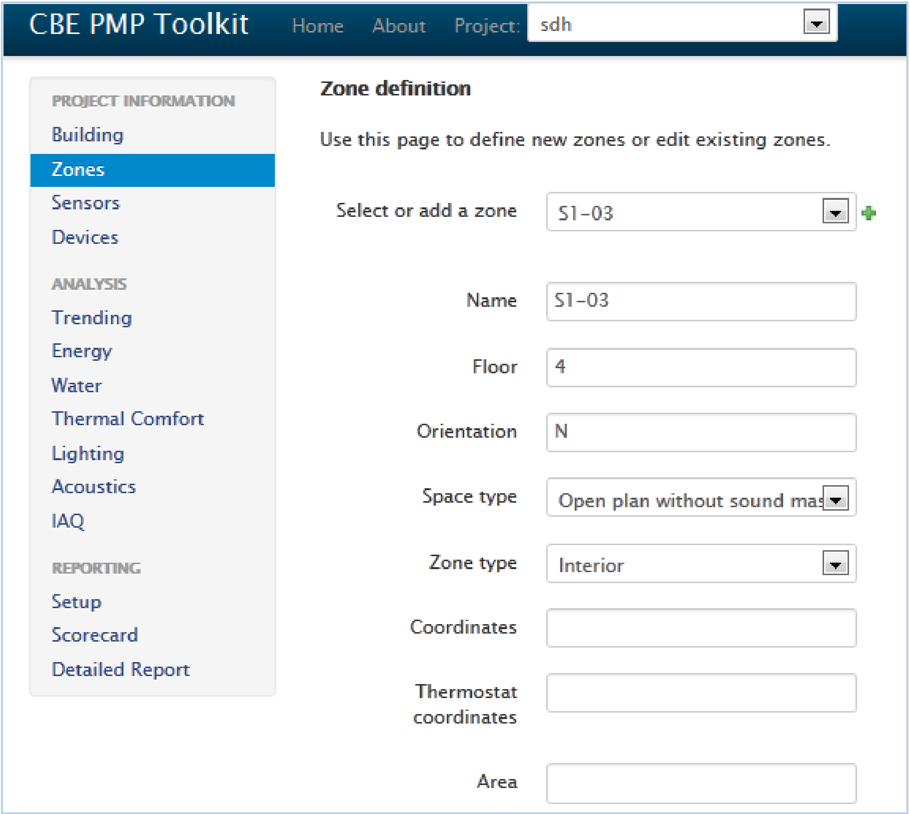
Define project sensors

Name	Device	Path	Type	Category	Height	Description	UUID	
	---------	/sdh/m1/c1	---------	---------			3e785f64	remove
	---------	/sdh/m1/c2	---------	---------			a0ec92cd	remove
op_icm3	ICM3	/sdh/m10/c1	Operative tem	Thermal Com			f10f7ba8	remove
dbt_icm3	ICM3	/sdh/m10/c2	Thermistor	Thermal Com			727ce58	remove
op_icm4	ICM4	/sdh/m11/c1	Operative tem	Thermal Com			7906ba3	remove
dbt_icm4	ICM4	/sdh/m11/c2	Thermistor	Thermal Com			9b4e1c8	remove
	---------	/sdh/m12/c1	---------	---------			d552509	remove
	---------	/sdh/m12/c2	---------	---------			c91139	remove
	---------	/sdh/m13/c1	---------	---------			62b237e	remove
	---------	/sdh/m13/c2	---------	---------			0f8d3fb8	remove
anem_icm2	ICM2	/sdh/m14/c1	Anemometer	Thermal Com			0920343	remove
rh_icm2	ICM2	/sdh/m14/c2	Relative humi	Thermal Com			009281a	remove
op_icm2	ICM2	/sdh/m15/c1	Operative tem	Thermal Com			61424fa1	remove
dbt_icm2	ICM2	/sdh/m15/c2	Thermistor	Thermal Com			56bc434	remove
rh_icm5	ICM5	/sdh/m16/c1	Relative humi	Thermal Com			8545b3e	remove
illum_icm5	ICM5	/sdh/m16/c2	Illuminance	Lighting			3e7c172	remove
op_icm5	ICM5	/sdh/m17/c1	Operative tem	Thermal Com			1c6eeeff-	remove
dbt_icm5	ICM5	/sdh/m17/c2	Thermistor	Thermal Com			3e95f9aa	remove
op_icm6	ICM6	/sdh/m18/c1	Operative tem	Thermal Com			a2c6ae83	remove
dbt_icm6	ICM6	/sdh/m18/c2	Thermistor	Thermal Com			5c34436	remove
rh_icm6	ICM6	/sdh/m19/c1	Relative humi	Thermal Com			f37381d	remove
co2_icm6	ICM6	/sdh/m19/c2	CO2	IAQ			fd84c607	remove

Figure 19: Toolkit sensor configuration

2.2.2.3 Define zones

The third step in setting up a Toolkit project is to define building zones. Zones break the building into sections of similar characteristics. Depending on the type of testing being done, a zone could be thermal, lighting, or acoustics. In practice, thermal zones are typically defined by thermostats, and lighting and acoustics zones are defined by rooms. Zones play an important role in analysis filtering. For example, a researcher may be interested in comparing measurements taken in the eastern orientation of the building and the western orientation of the building. Having well-defined zones makes this type of filtered analysis simple. Figure 20 shows a partial screenshot of the zone definition webpage.



Project: sdh

Zone definition

Use this page to define new zones or edit existing zones.

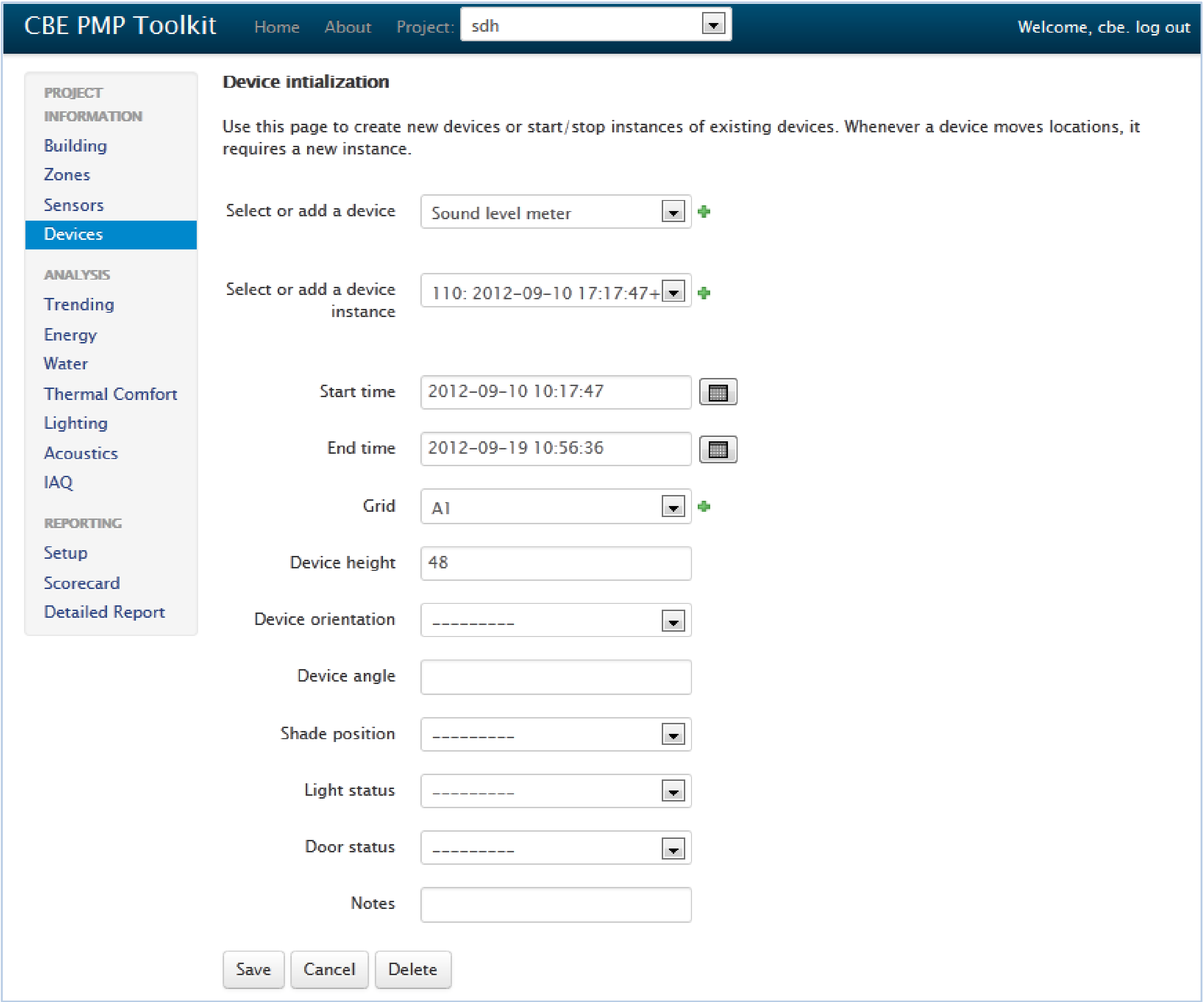
Select or add a zone	S1-03
Name	S1-03
Floor	4
Orientation	N
Space type	Open plan without sound mas
Zone type	Interior
Coordinates	
Thermostat coordinates	
Area	

Figure 20: Zone definition webpage

2.2.2.4 Define, start, and stop device instances

The final step in setting up a Toolkit project is to define, start, and stop device instances. A device instance is simply a time slice of a device's data stream. These instances mark locations in a data stream when a particular "test" was conducted. For example, a researcher may take the acoustics meter into one room, record a device instance for 5 minutes, then move on to another room and record another 5-minute device instance. The device may be continuously monitoring between these device instances, the data of which would be available on the trending page, but the researcher is only interested in these 5-minute slices of data for analysis.

Device instances are required for analyses. A device instance associates a data stream with spatial and temporal metadata, allowing analysis filtering. Device instances may be long-term continuous monitoring as in the case of the ICM device or short-term slices as in the case of the sound level meter. The *End time* of the device instance may be left initially blank, to be filled in when the device instance is complete. Figure 21 shows a screenshot of the device instance initialization webpage.



Device intialization

Use this page to create new devices or start/stop instances of existing devices. Whenever a device moves locations, it requires a new instance.

Select or add a device: Sound level meter
Select or add a device instance: 110: 2012-09-10 17:17:47+
Start time: 2012-09-10 10:17:47
End time: 2012-09-19 10:56:36
Grid: A1
Device height: 48
Device orientation: ---------
Device angle:
Shade position: ---------
Light status: ---------
Door status: ---------
Notes:

Figure 21: Device instance initialization webpage

2.2.3 Trend analysis

Trend analysis is a key part of the commissioning process to ensure building system components and schedules are working as designed. In field studies, trend analysis has the added benefit of allowing field technicians to ensure proper sensor operation. Trending tools are typically part of building management systems (BMS), though often these included tools have limited capabilities and cumbersome methods.

Fast retrieval of real-time data through the Internet is a major benefit of the sMAP system that provides the backbone of the Toolkit trending application. Typical BMS systems rely on non-optimized databases that can make trend review a slow, laborious process. Figure 23 shows a screenshot of the Toolkit trending application. The Toolkit trending application borrows heavily from the trending application included with sMAP, which is a Javascript graphing application with a tree structure that allows browsing and choosing of data sources to be plotted. Significant work was done to add features to this base functionality as well as provide a connection to the Django metadata backend that is separate from sMAP.

The Toolkit trending application includes buttons to help define an analysis period (custom, hour, day, month) as well as buttons that allow the user to step through a period at a time. These backward/forward buttons will move a period that is defined by the end time minus the start time as defined by the user. For example, if the user clicks the "day" button, the end time will change to be one day ahead of the start time and the backward/forward buttons will move the time range a day at a time.

Multiple data streams can be selected by using the "Alt" key. The "Chart options" button provides a dialog box (Figure 22) that allows the user to switch between rectangular zooming and hovering over points to get exact values. Other chart options include the ability to highlight weekends and/or operational hours, as well as device instances. For example, while the sound-level meter may be recording continuously, a user may want to highlight the sections of the trend where device instances were recorded (section 2.2.2.4).

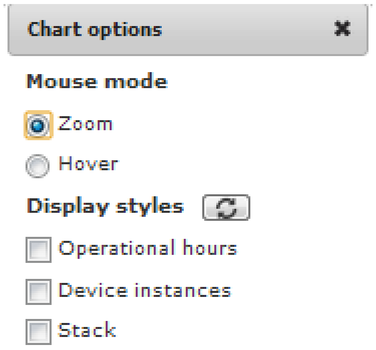


Chart options ✖

Mouse mode

● Zoom

○ Hover

Display styles

☐ Operational hours

☐ Device instances

☐ Stack

Figure 22: Trending chart options dialog

An interactive legend is available underneath the plot that allows users to show/hide or remove trends, as well as change axes assignments and obtain more information about the plotted stream (metadata). Figure 23 shows a plot of ICM data (CO_2, operative temperature, dry-bulb temperature, and relative humidity), where relative humidity and CO_2 are shown on the secondary y-axis and temperature is shown on the primary y-axis; metadata for the relative humidity sensor is also shown.

LoadTime	870ms, 11669 points
Metadata/Extra/Project	sdh
Metadata/SourceName	CBE Vigilent Motes
Metadata/Toolkit/name	rh_icm3
Metadata/Toolkit/pmp_category	IAQ
Metadata/Toolkit/sensor_height	null
Metadata/Toolkit/sensor_type	Relative humidity
Path	/sdh/m9/c1
Properties/ReadingType	double
Properties/Timezone	America/Los_Angeles
Properties/UnitofMeasure	%
uuid	3c10d6b1-dc2b-59ca-b611-0dbcc72c2092

Figure 23: Toolkit trending application

2.2.4 Thermal comfort analysis

The Toolkit thermal comfort analysis webpage includes multiple ways of assessing thermal comfort performance in both diagnostics and evaluation capacities. The webpage is divided into five main sections:

1. Analysis type: Different devices are suitable for different analysis types. The details of each analysis type are provided the subsections that follow.
2. Temporal filtering: Much like the temporal filtering available on the trending webpage, this section is where a user would enter the dates/times of the period to be analyzed.
3. Spatial filtering: A tree of zone spatial filters that allow a user to drill-down or aggregate data according to a particular spatial feature such as orientation. Additionally in this section, a user can choose to aggregate the results by either zone or orientation. For example, aggregating by orientation will average all of the results for each orientation, showing only as many results as there are orientations with valid data.
4. Resample/Average: Most analyses require multiple streams of data. These streams need to be timestamp aligned and the user has the ability to choose the resampling rate. In addition to resampling, the Toolkit averages readings over the resampling period. Timestamps are aligned starting at midnight of the first day of the period chosen. The period that is averaged is directly following the aligned timestamp. For example, data with a resample/average rate of 3600 seconds would align the data to hourly timestamps that fall on the hour (7am, 8am, 9am, etc.) that represent the average of the hour immediately following the timestamp (7am is the average of data from 7am to 8am).
5. Chart: The final section is the chart, which displays when the user clicks the "Plot" button. Like the trending webpage, a user can step through sequential analysis periods by using the forward/backward buttons.

These sections are collapsible/expandable to ease visual clutter on the webpage. Screenshots of the thermal comfort analysis sections occur in the next few subsections.

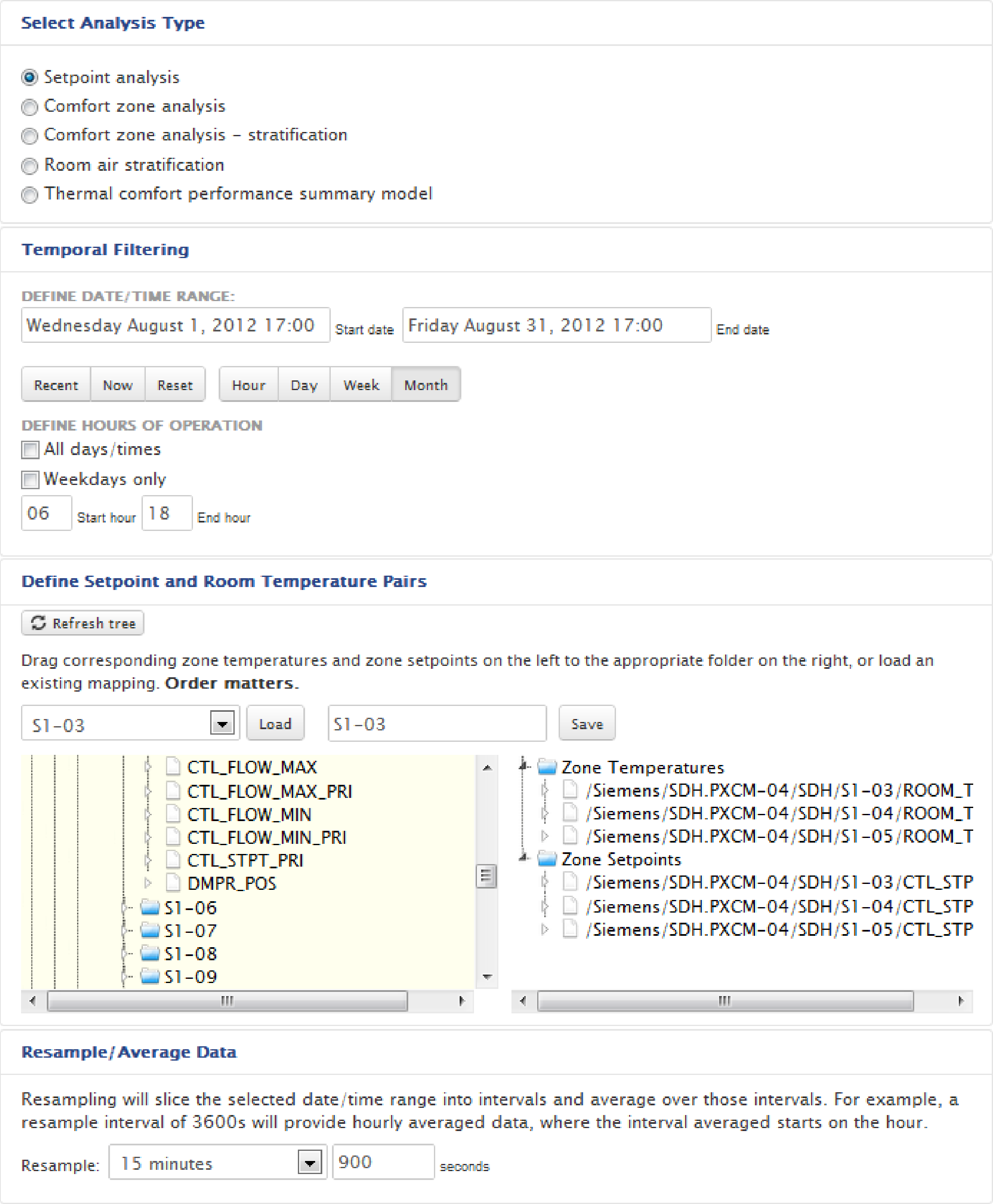
2.2.4.1 Setpoint analysis

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 is 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. In this situation, the Toolkit device would be set as the "setpoint" data stream.

For example (Figure 24), in order to determine how well zones on the 4th floor of Sutardja Dai Hall are controlling to temperature setpoint, a user needs to:

1. Select the "Setpoint analysis" analysis type.
2. Select the time period of interest: the month of August is selected and the hours of operation have been specified as 6am to 6pm.
3. Select the streams of data for comparison: by dragging and dropping streams of data from the left tree structure to the folders in the right tree structure, the user has selected zone temperature and zone setpoint of a few VAV boxes on the 4th floor of Sutardja Dai Hall.

4. Select the resample/average rate: a rate of 15 minutes has been selected.
5. Plot.



Select Analysis Type

● Setpoint analysis
○ Comfort zone analysis
○ Comfort zone analysis – stratification
○ Room air stratification
○ Thermal comfort performance summary model

Temporal Filtering

DEFINE DATE/TIME RANGE:
Wednesday August 1, 2012 17:00 Start date
Friday August 31, 2012 17:00 End date

DEFINE HOURS OF OPERATION
☐ All days/times
☐ Weekdays only
06 Start hour
18 End hour

Define Setpoint and Room Temperature Pairs

Drag corresponding zone temperatures and zone setpoints on the left to the appropriate folder on the right, or load an existing mapping. **Order matters.**

S1-03 Load
S1-03 Save

CTL_FLOW_MAX
CTL_FLOW_MAX_PRI
CTL_FLOW_MIN
CTL_FLOW_MIN_PRI
CTL_STPT_PRI
DMPR_POS
S1-06
S1-07
S1-08
S1-09

Zone Temperatures
/Siemens/SDH.PXCM-04/SDH/S1-03/ROOM_T
/Siemens/SDH.PXCM-04/SDH/S1-04/ROOM_T
/Siemens/SDH.PXCM-04/SDH/S1-05/ROOM_T
Zone Setpoints
/Siemens/SDH.PXCM-04/SDH/S1-03/CTL_STP
/Siemens/SDH.PXCM-04/SDH/S1-04/CTL_STP
/Siemens/SDH.PXCM-04/SDH/S1-05/CTL_STP

Resample/Average Data

Resampling will slice the selected date/time range into intervals and average over those intervals. For example, a resample interval of 3600s will provide hourly averaged data, where the interval averaged starts on the hour.

Resample: 15 minutes 900 seconds

Figure 24: Setup for setpoint analysis

Figure 25 shows the resulting histogram plot. The y-axis represents the percent of readings that fall into a particular bin of deviation from setpoint. The bins are defined as *lower bound* ≤ *x* < *upper bound*. In this example, at least one zone is not being controlled well, with over 30% of readings falling above five degrees below setpoint temperature.

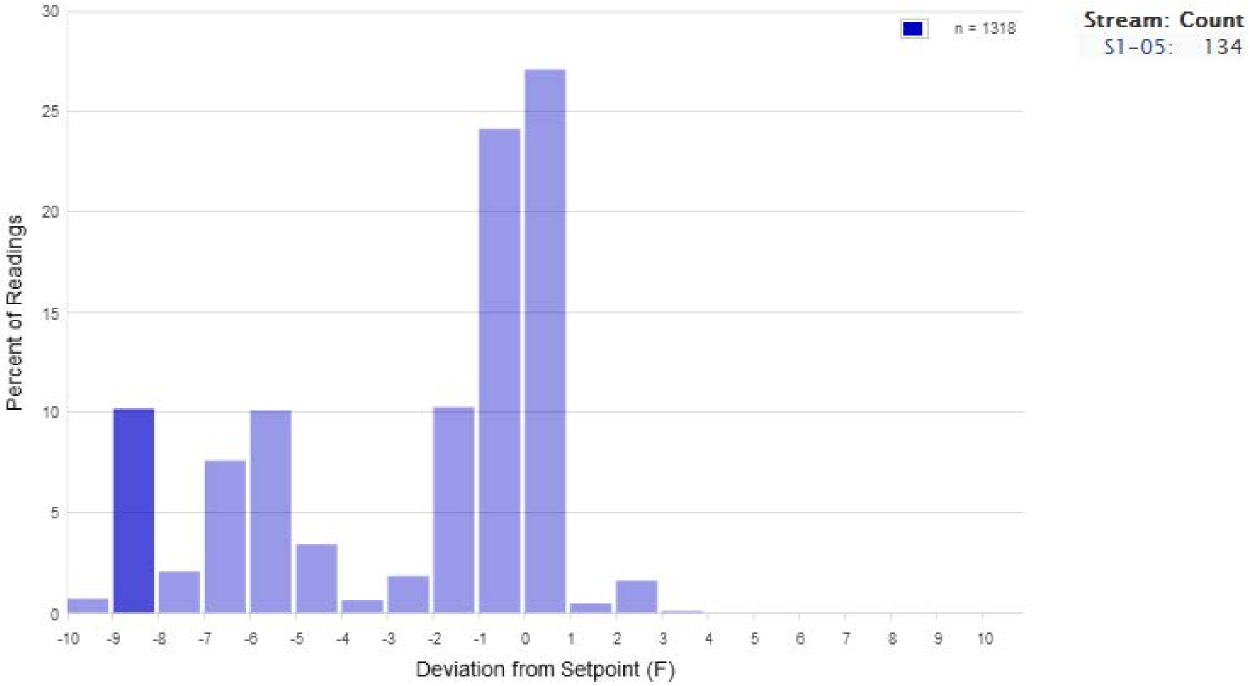


Figure 25: Setpoint analysis histogram

To get more information about the potential problematic VAV box, the user can click on a column of the histogram to find out which VAV boxes were included in that bin and how many readings were in the bin. In Figure 25 the user has clicked the -8 to -9 bin and the legend on the right of the plot shows that only VAV 5 (S1-05) is included in this bin with 134 readings falling 8-9 degrees below setpoint. The VAV name is a link that allows the user to look at the trends associated with this VAV box, which are shown in Figure 26 (green is zone setpoint, blue is zone temperature). Clearly this zone is being kept quite cold which likely represents a thermal comfort issue in the space. The next section discusses how such a potential thermal comfort issue could be diagnosed further with the use of the Toolkit ICM devices and the "Comfort zone analysis" tool.

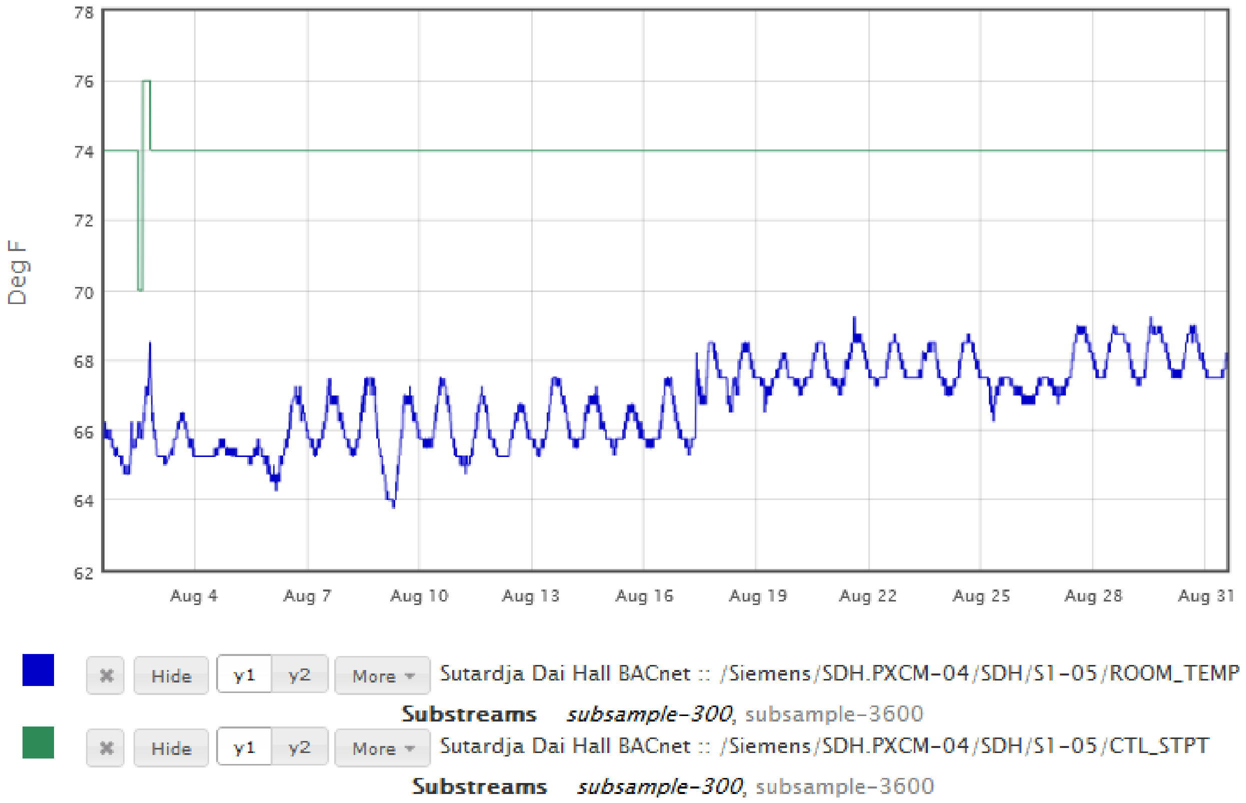


Figure 26: Zone temperature and setpoint trends of VAV S1-05

2.2.4.2 Comfort zone analysis

The Toolkit comfort zone analysis webpage allows users to analyze the comfort data from the Toolkit Indoor Climate Monitors (ICMs). The setup for the comfort zone chart is similar to the setpoint analysis chart except instead of defining setpoint pairs, the user can choose to filter according to spatial parameters, such as orientation or zone type. The steps for setting up a comfort chart analysis are:

1. Choose the "Comfort analysis" chart type and enter clothing insulation (clo) and metabolic activity rate (met) values. To get more information on appropriate clothing and metabolic rate values a user can click the "Comfort tool" button which links to the CBE Comfort Tool web application which provides an in-depth tool for assessing comfort according to ASHRAE Standard 55.
2. Choose a valid temporal range and whether or not to use custom hours of operation. For the comfort zone analysis, a one-day range is typically an appropriate length of time for analysis.
3. Choose which spatial elements to filter the data by. In the case of the comfort chart analysis, spatial filtering will limit the data according to ICM location. Figure 27 shows an example of data that will be filtered to only include the "E" orientation. More than one filter can be applied by holding down the "Alt" key. A user can also choose to aggregate the results by orientation or by zone.
4. Choose an appropriate resample/average rate.
5. Plot. Figure 28 shows the chart created of the two ICMs that are located in the "E"

orientation. To the right of the chart, the average Predicted Mean Vote (PMV) and Percent-Persons-Dissatisfied (PPD) is shown as well as the percent of data that falls within the comfort zone boundaries that are shown in orange. The comfort zone boundaries are defined according to the clo and met values defined in step 1. By clicking on a data point, the specific PMV and PPD for that point are shown. Additionally, hovering over a data point will show the exact values and the time at which the data point was taken.

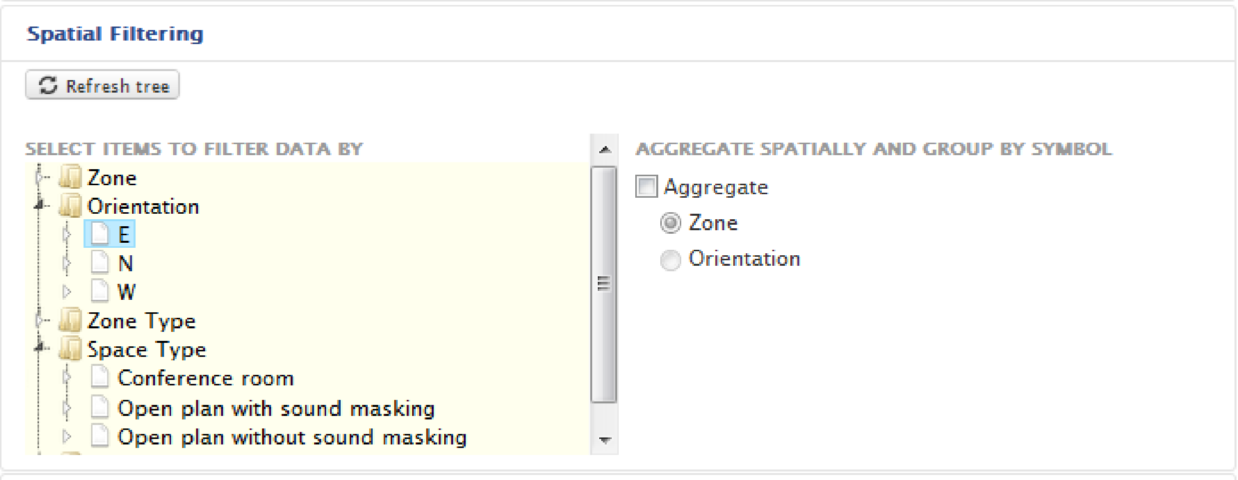


Figure 27: Comfort zone analysis spatial filtering

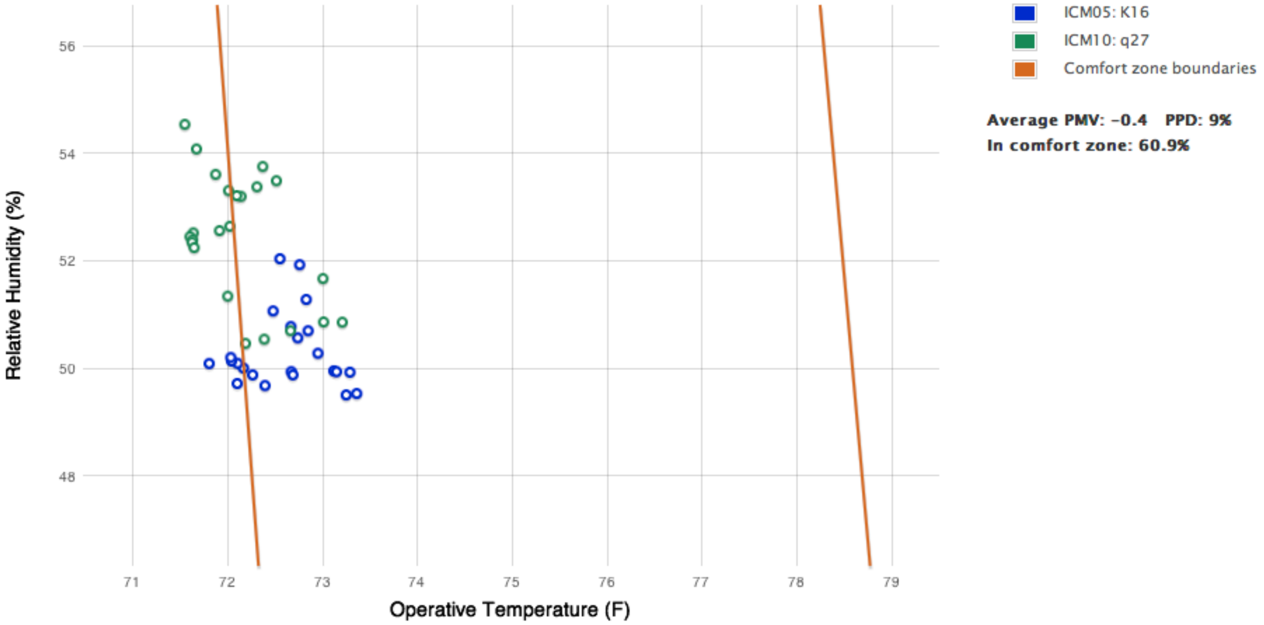
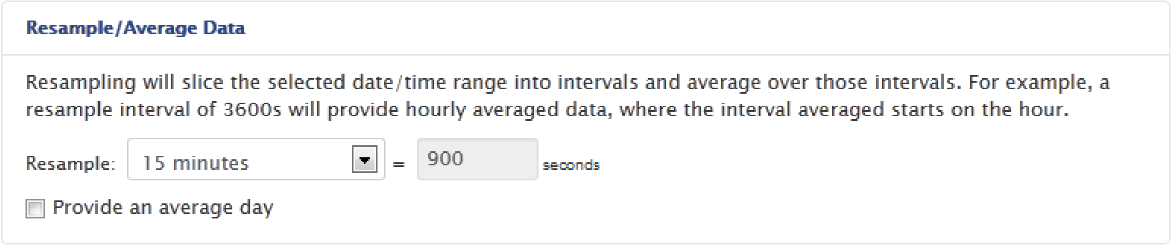


Figure 28: Comfort zone analysis chart

There is one additional option the user may select which provides another method of reducing a large amount of ICM thermal comfort data: "Provide an average day." For the comfort analysis chart, this option will show up under the "Resample/Average Data" section of the webpage (Figure 29). When this option is selected, the data is split into hourly data and averaged across the days selected in the temporal filtering section. This method allows the user to reduce a large number of days of data into one "representative" or average day broken up into hourly values. The output is the same as the examples above, except that a maximum of 24 points is shown.



Resample/Average Data

Resampling will slice the selected date/time range into intervals and average over those intervals. For example, a resample interval of 3600s will provide hourly averaged data, where the interval averaged starts on the hour.

Resample: 15 minutes = 900 seconds

☐ Provide an average day

Figure 29: Average day checkbox as part of the Resample/Average Data section

2.2.4.3 Stratified systems analysis

Stratification refers to the increasing temperature gradient of the air in a space that is conditioned by a stratified system: an underfloor air distribution system (UFAD) or displacement ventilation system (DV). The Toolkit includes two analysis types for analyzing stratification data: room-air stratification and comfort zone analysis – stratification. As part of the Toolkit, stratification data is collected by the portable UFAD commissioning cart (PUCC). Figure 30 shows an example chart of room-air-stratification analysis. The chart provides a visual display the temperature gradient of the air in the space; a steeper slope indicates lower stratification. The steps for using both stratification analysis types are identical to the steps used for the comfort zone analysis with one exception. The user must select whether to use the “Cart” or “Fixed poles” or both as the stratification devices. Fixed poles are an optional Toolkit device which can be used for studying stratified systems. Like the PUCC, fixed poles measure temperature at multiple heights in a space. Rather than the short-term measurements that the PUCC takes, fixed poles take continuous readings in one location for the duration of the study, allowing a deeper analysis of how stratification varies over the course of the study period. If both the “Cart” and “Fixed poles” options are selected, the PUCC instances that match the filtering are plotted and fixed pole measurements that fall in zones where PUCC measurements were taken are plotted for the time closest to the time of the PUCC measurement in that zone.

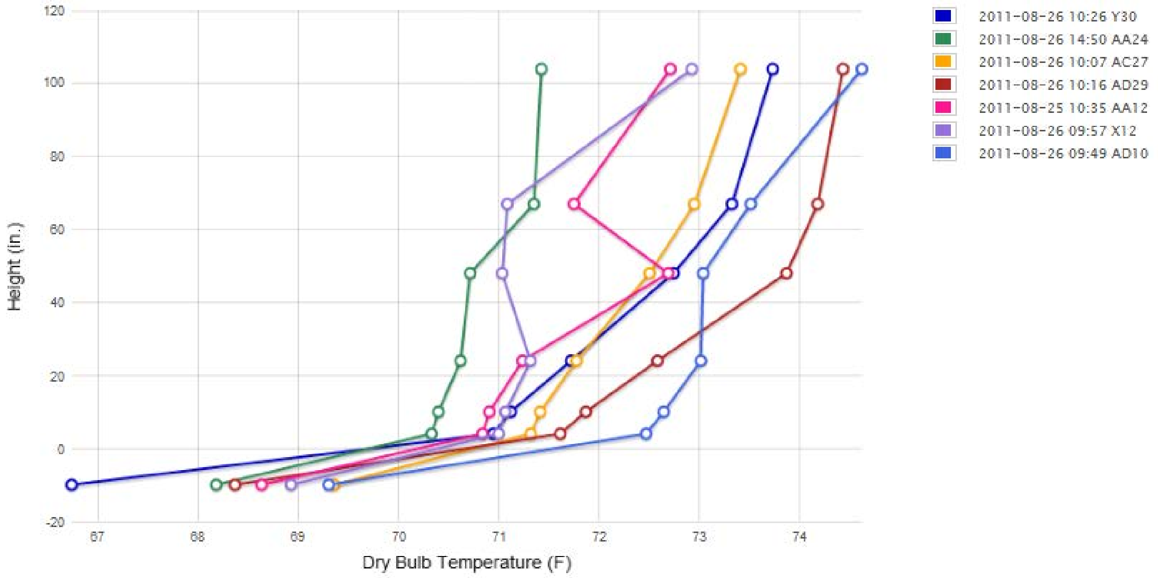


Figure 30: Room air stratification chart

The comfort zone analysis – stratification chart (Figure 31) provides another summary of stratification performance. The chart displays average occupied zone air temperature on the x-axis and occupied zone stratification on the y-axis. The occupied zone is defined as the area a person would occupy if standing, which is typically defined as ankle height - 0.1m (4”) to head height - 1.7m (67”). The average occupied zone temperature is thus the weighted average of the temperatures in this zone. Equation 2 shows how the average occupied zone temperature is computed for the PUCC.

Equation 2

$$T_{oz,avg} = \left(\frac{1}{67-4}\right)\left[(10-4)\left(\frac{T_4+T_{10}}{2}\right)+(24-10)\left(\frac{T_{10}+T_{24}}{2}\right)+(48-24)\left(\frac{T_{24}+T_{48}}{2}\right)+(67-48)\left(\frac{T_{48}+T_{67}}{2}\right)\right]$$

The occupied zone stratification refers to the difference in the temperature at head height and ankle height. This chart provides a quick summary of how stratification and zone temperature varies across the study area (when using the PUCC). Figure 31 shows an example of the comfort zone stratification chart. The beige colored area represents the boundaries of the comfort zone as defined by the clo and met values and a fixed stratification boundary of 3°C (5.4°F).

Plotting PUCC measurements by zone or orientation on the comfort analysis-stratification chart provides an easy way to assess whether a zone/orientation tends to be comfortable and within stratification limits. Increased stratification within the ASHRAE Standard 55 (2010) upper limit of 3°C (5.4°F) corresponds to better performance (Bauman, 2003). Too little stratification indicates a well-mixed environment while too much stratification can potentially cause thermal comfort problems.

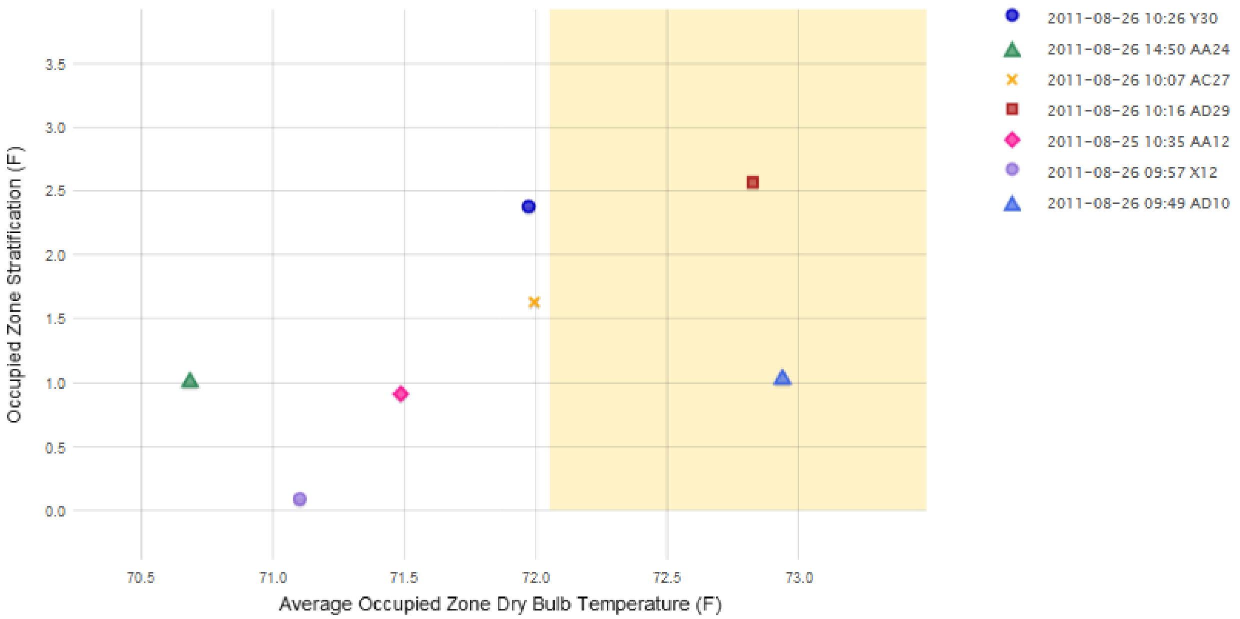


Figure 31: Comfort zone stratification analysis chart

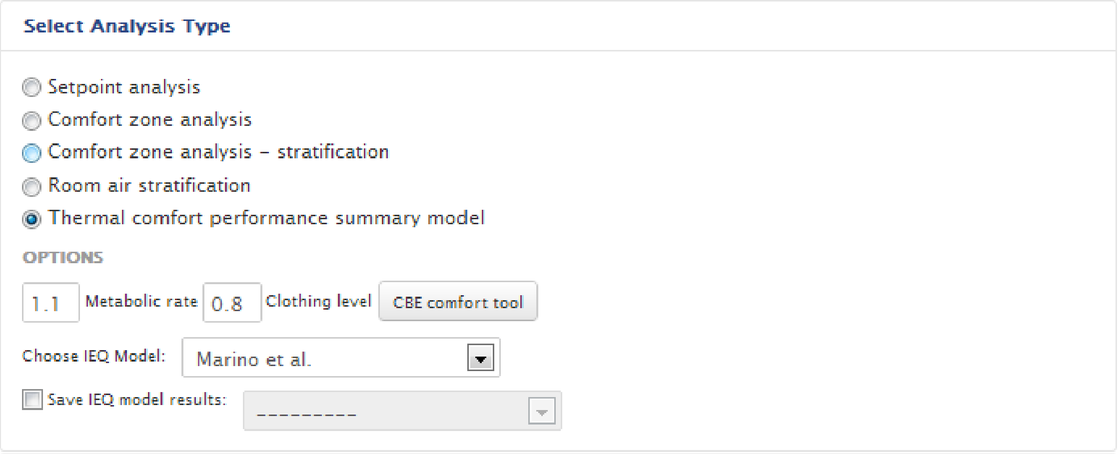
2.2.4.4 Thermal comfort performance summary model

The last type of thermal comfort analysis tool is the performance summary model. This type of analysis is available for each IEQ category and behaves the same way for each. An explanation of how the performance summary model works is provided in section 2.2.6. There are currently two pre-defined models that a user can select: the Ncube et al. and Marino et al. models. The specifics of each model are available in Table 6 and Table 7.

To run a performance summary model, a user needs to:

1. Define metabolic rate and clothing values
2. Choose the IEQ model
3. Choose whether or not to save the model results: If the user decides to save the model results, those results will show up on the "Scorecard" page of the Toolkit. Multiple results can be saved, though typically a user should only save multiple results if there are different space-types that need to be captured separately.
4. Select appropriate temporal and spatial filters
5. Select a resample/average rate
6. Plot

Steps 1-3 are shown in Figure 32 and an example summary performance model chart is shown in Figure 33. The results are binned according the space type because the model can be defined to have different assessment conditions for different space types. For example, a corridor typically has different lighting requirements than a private office. If there are multiple space types in the selected data set that align with model-defined space types, the data is split out accordingly. Any data that does not align with a specific model-defined space type is assigned to the "Default" space type and compared to the default conditions defined in the model. The example shown in Figure 33 shows that all of the data for this example falls into the default space type. The chart displays the percentage of the defined data set that falls within the conditions of the different assessment categories defined by the chosen model.



Select Analysis Type

○ Setpoint analysis
○ Comfort zone analysis
○ Comfort zone analysis – stratification
○ Room air stratification
● Thermal comfort performance summary model

OPTIONS

1.1 Metabolic rate 0.8 Clothing level

Choose IEQ Model: Marino et al.

☐ Save IEQ model results: ---------

Figure 32: Thermal comfort performance summary model initial setup

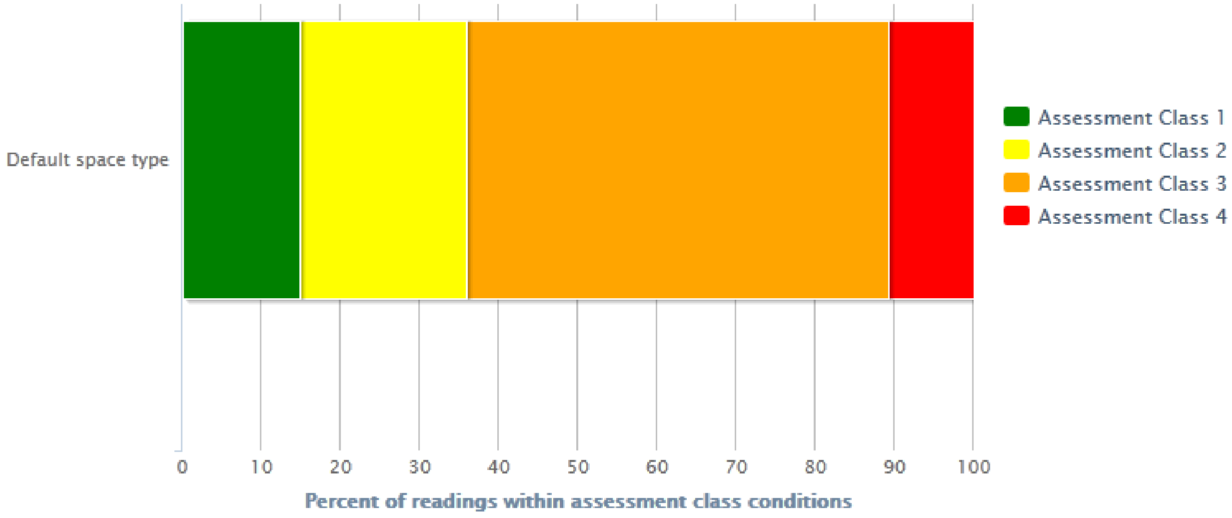


Figure 33: Example chart from thermal comfort performance summary model

A user can get more information about the breakdown of data according to assessment class by clicking on the bars, which will pop-up a boxplot chart showing the distribution of the data that fall into each assessment class (minimum, lower quartile, median, upper quartile, maximum). All boxplots in the Toolkit compute outliers using the 1.5 times the interquartile range method. Figure 34 shows the boxplots for the classes defined for the example in Figure 33. The diverging pattern of data is a consequence of how the classes are defined. In this example, class 1 is defined as having an operative temperature between 74.3˚F and 77.9˚F. If the data do not fall into that range they are compared against the larger range (73.4 - 78.8˚F) for class 2. The ranges grow as the classes increase. For this example, the boxplots show that when the data do not fall within an assessment class, it is usually because they are too cold (the data for the larger ranges collect at below the bottom of the previous range).

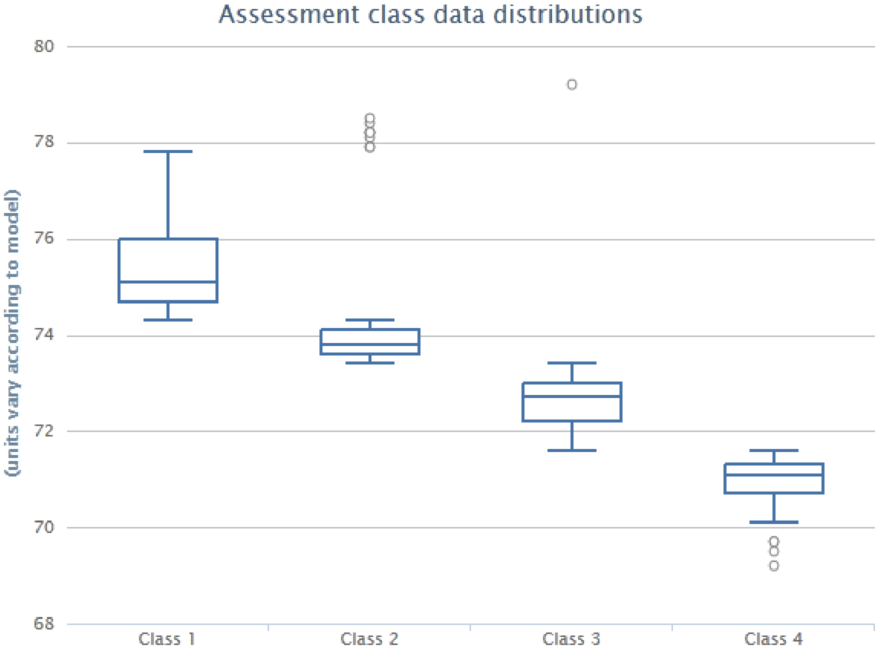


Figure 34: Assessment class data distributions for the example in Figure 33

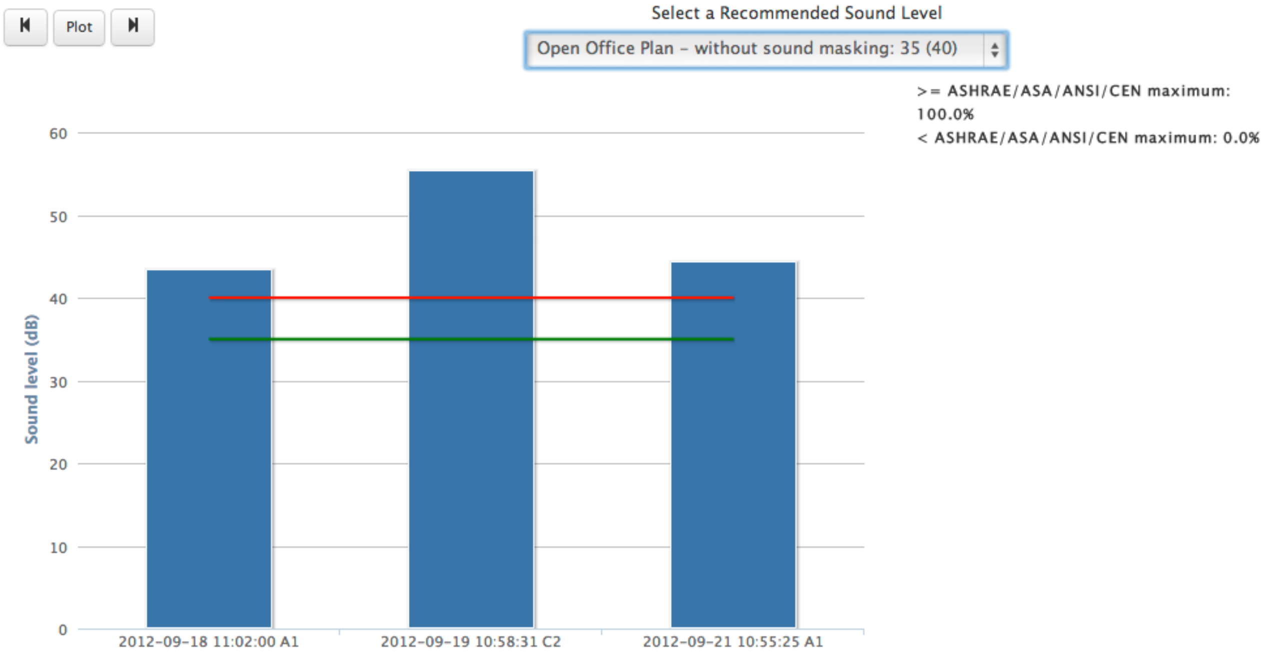
2.2.5 Lighting, acoustics, and indoor air quality analyses

The analysis options for lighting, acoustics, and indoor air quality are identical and explained in the next three sections. Each type of analysis requires that the user select appropriate temporal and spatial filters in the same manner as explained for the thermal comfort sections. The examples below come from acoustics and lighting tests, though the chart type, functions, and procedures are identical for lighting, acoustics, and indoor air quality.

2.2.5.1 Whole test period analysis

The “whole test period analysis” is used for short-term tests. There are two chart types to choose from: column and boxplot. The column chart shows the average over the whole test period for each test that matches the filtering. The boxplot tends to be helpful for short-term tests of highly variable parameters, such as sound and sometimes light levels. The boxplot chart will take the length of the test and split it into 1-minute chunks which are then summarized as a boxplot. The example given in Figure 35 is a column chart series of five-minute acoustics tests. Figure 36 is a boxplot chart series of the same five-minute tests, resampled to one-minute averages and summarized as boxplots.

The recommended and maximum acoustics levels for different space types are given in a drop-down menu above the chart. To compare the results of a data set to recommended/maximum levels for a given space type, a user can select the space type from the menu and it will draw a lines corresponding to the recommended (green) and maximum (red) levels. The information to the right of the graph shows what percentage of the tests fall above or below the maximum level. For lighting analyses, rather than recommended sound levels, the user can select from a drop-down menu of IESNA recommended illuminance values. There is no equivalent function for the indoor air quality analysis because there are no associated recommended levels for CO_2. However, the PMP suggests that levels above 700 ppm above outdoor concentration indicate poor ventilation.



Open Office Plan – without sound masking: 35 (40)

>= ASHRAE/ASA/ANSI/CEN maximum: 100.0%
< ASHRAE/ASA/ANSI/CEN maximum: 0.0%

Figure 35: Acoustics example of whole-period analysis column chart

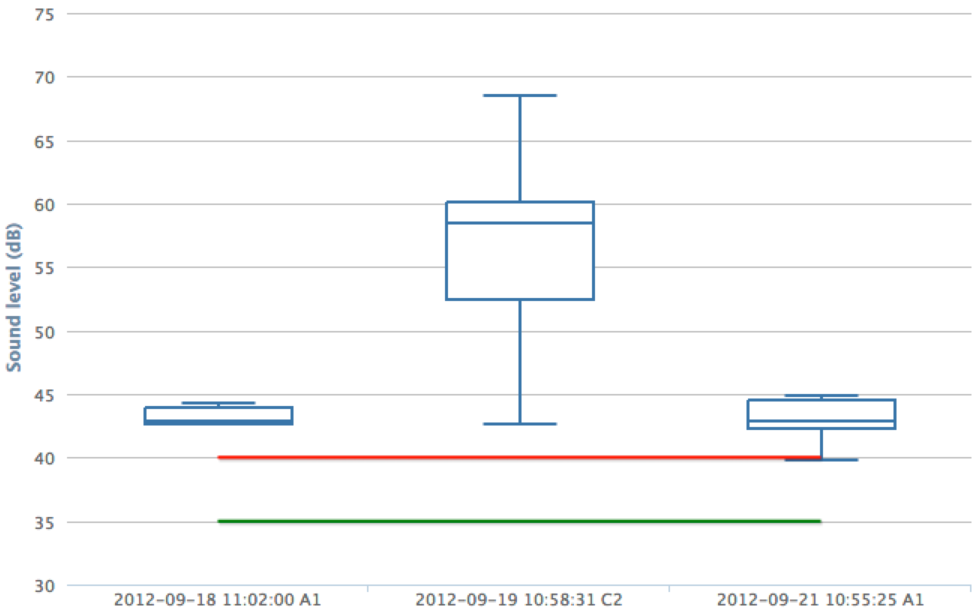
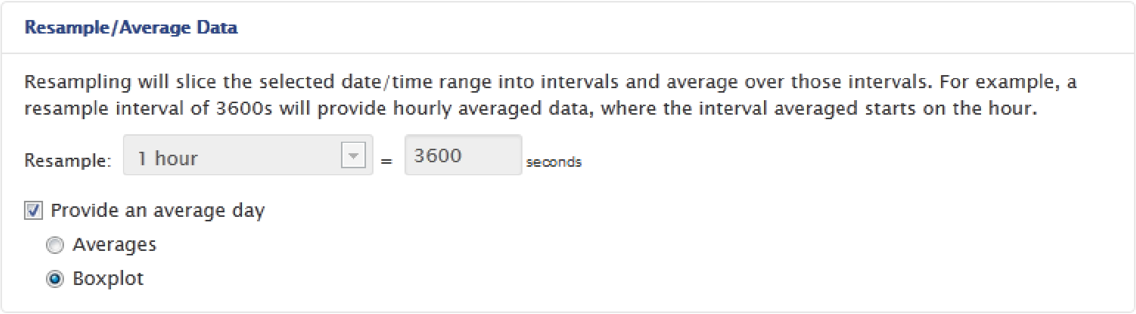


Figure 36: Acoustics example of whole-period analysis boxplot chart

2.2.5.2 Time slices analysis

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. Similar to the whole-period analysis, there are two chart type options: column and boxplot. These behave similarly to the whole-period analysis with an exception for the boxplot chart. The boxplot chart will only show one device at a time because of a current limitation of the charting software. Both chart types will plot up to 24 time slices. The boxplot divides the time slice into 5-minute data which is then summarized by a boxplot. Figure 38 shows a day of hourly averaged lighting values for one ICM from 6:00AM to 6:00PM. The recommended IESNA lighting level for an open plan office with intensive computer use has been selected, with the red line indicating this level.

Like the comfort zone analysis chart for thermal comfort, the time slices analysis method for lighting, acoustics, and IAQ provides an "average day" function, with an additional boxplot feature (Figure 37). This boxplot feature will summarize the hourly data across the days chosen in the temporal filtering section. Figure 39 shows an example in which a week of CO_2 data is shown with a boxplot representing the variation between days for each hour in a day.



Resample/Average Data

Resampling will slice the selected date/time range into intervals and average over those intervals. For example, a resample interval of 3600s will provide hourly averaged data, where the interval averaged starts on the hour.

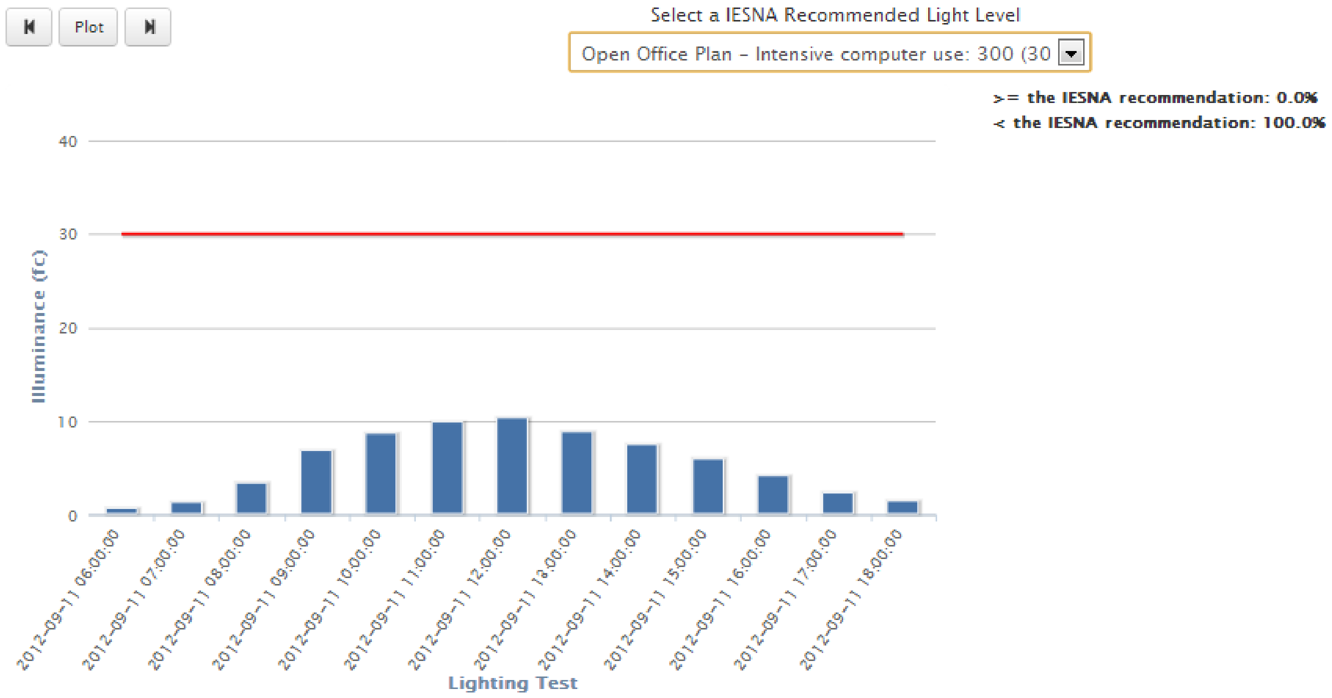
Resample: 1 hour = 3600 seconds

☑ Provide an average day

○ Averages

● Boxplot

Figure 37: Average day boxplot function for time slices analysis



Select a IESNA Recommended Light Level

Open Office Plan – Intensive computer use: 300 (30

>= the IESNA recommendation: 0.0%

< the IESNA recommendation: 100.0%

Figure 38: Example lighting time slices analysis

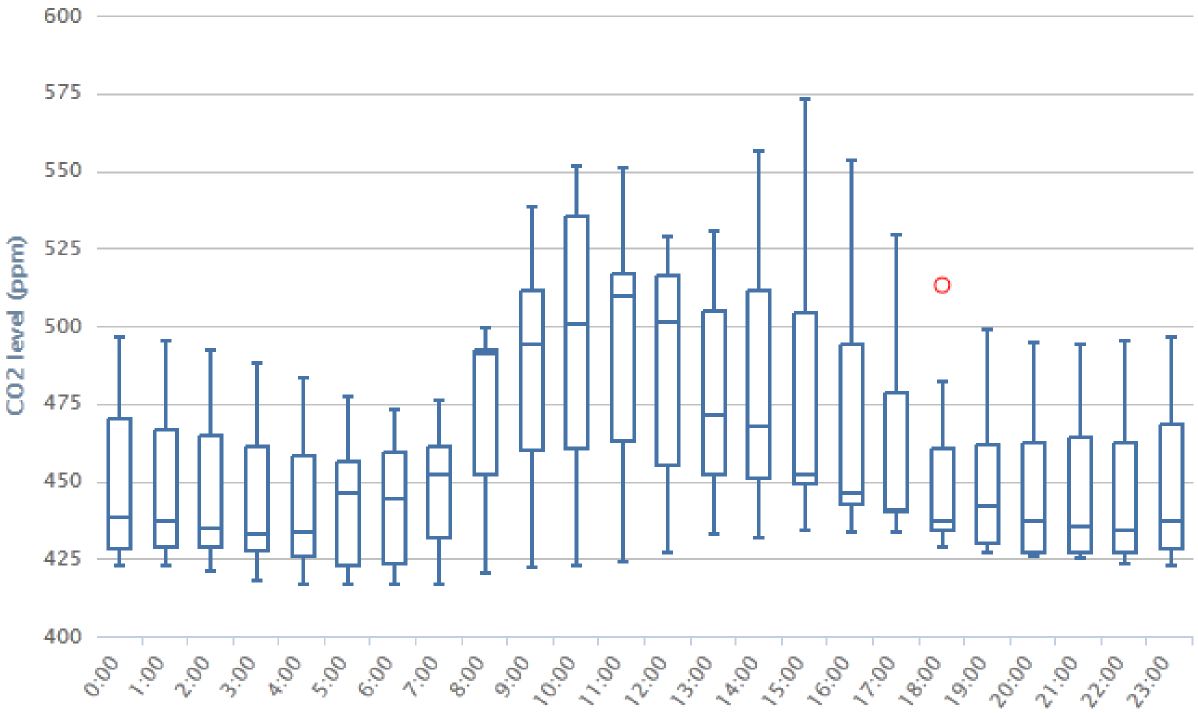


Figure 39: Example of average day boxplot function for time slices analysis

2.2.5.3 Performance summary model

The performance summary model type of analysis is identical to the thermal comfort performance summary model analysis explained in section 2.2.4.4. The different space type conditions are particularly valid for lighting and acoustics as the conditions for each space type vary considerably.

2.2.6 Scorecard and reporting

The performance summary model is the Toolkit implementation of the IEQ models discussed in section 1.5. The model implemented in the Toolkit most closely aligns with Marino et al. 2012, which should be consulted for an in-depth explanation of the mechanics of the model. A basic outline of the process involved in using an IEQ model to generate an IEQ rating is provided in Figure 40. The primary goal of the performance summary model is to divide the selected data into assessment class bins.

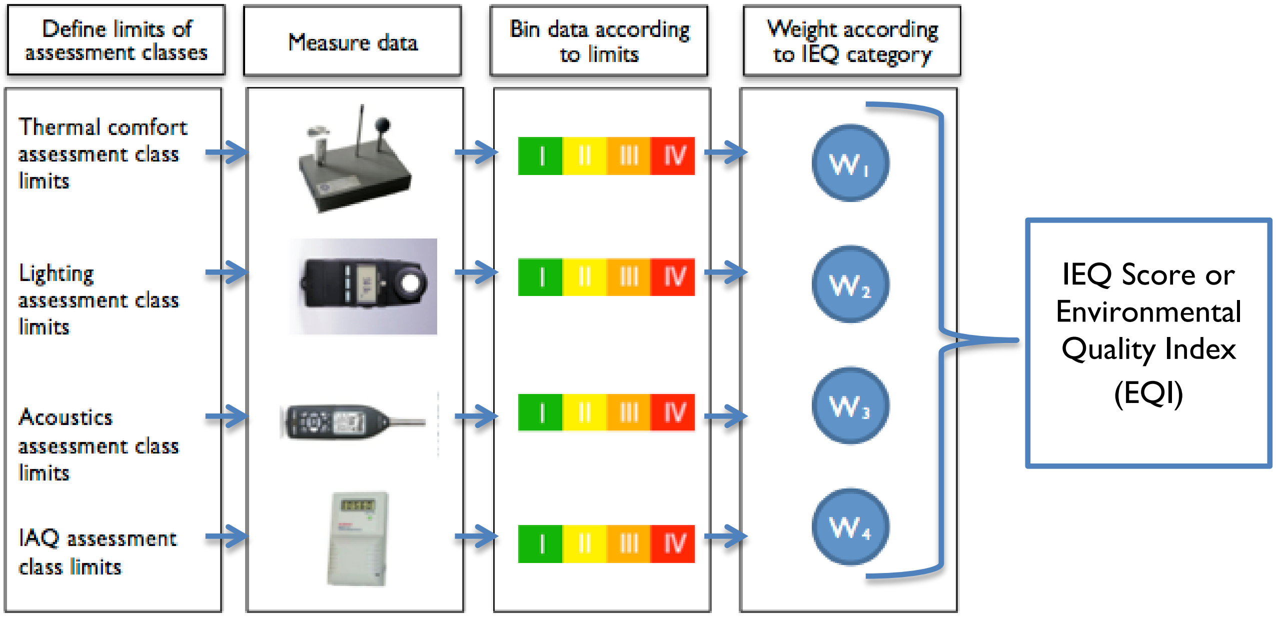


Figure 40: Simplified IEQ scorecard process. Adapted from Marino et al. 2012

In the Toolkit, an IEQ model is defined by both its IEQ category weighting assignments and its assessment class definitions, which are associated with a particular space-type. The process outlined in Figure 40 is applied to each space-type that has a valid model definition and exists in the data set. For example, a user could define a set of assessment class limitations for a conference room to be different from the assessment class limitations for an open-plan office. A default set of assessment class limitations are applied to any space-type that does not have an associated model definition. These bins are defined in the "Setup" section under the "Reporting" section of the Toolkit, shown in Figure 41. The steps involved in defining a complete model are summarized below:

1. Choose a model: the models are defined by the weights assigned to each IEQ category. New models can be added by clicking the "+" button next the model dropdown list.
2. Choose an existing model space definition or create a new one. A model space definition is the set of assessment class conditions for a particular space-type.
3. Define the space-type: choose from a list of space-types.

4. Define the summer start and end months: if a user is interested in defining both summer and winter thermal assessment conditions, then the model needs to know how the user wants to define summer and winter.
5. Define the space-type weight: space-types can be weighted in order to come up with a overall building scorecard that takes space-type weighting into account.
6. Define the assessment class limits for each IEQ category: not all assessment classes need to be completed. The logic for comparison is a nested series of conditionals, if class I is not met, then class II is checked, if class II is not met, then class III is checked, etc. The final class should contain conditions that will capture whatever data is left.

Currently, there are four models that have been implemented in the Toolkit: (1) Marino et al. 2012, (2) Ncube et al. 2012, (3) Chiang et al. 2001, and (4) a proposed PMP-based model described in the next section (2.2.6.1). The conditions for the first three models are given in Table 7 in section 1.5.3. The Marino et al. and Chiang et al. models use measured values for limits, while Ncube uses percent satisfaction based on other models. The proposed PMP-based model uses a hybrid of the two approaches. New models that are defined that do not align with these two model choices will need custom code to enable the correct binning according to assessment class.

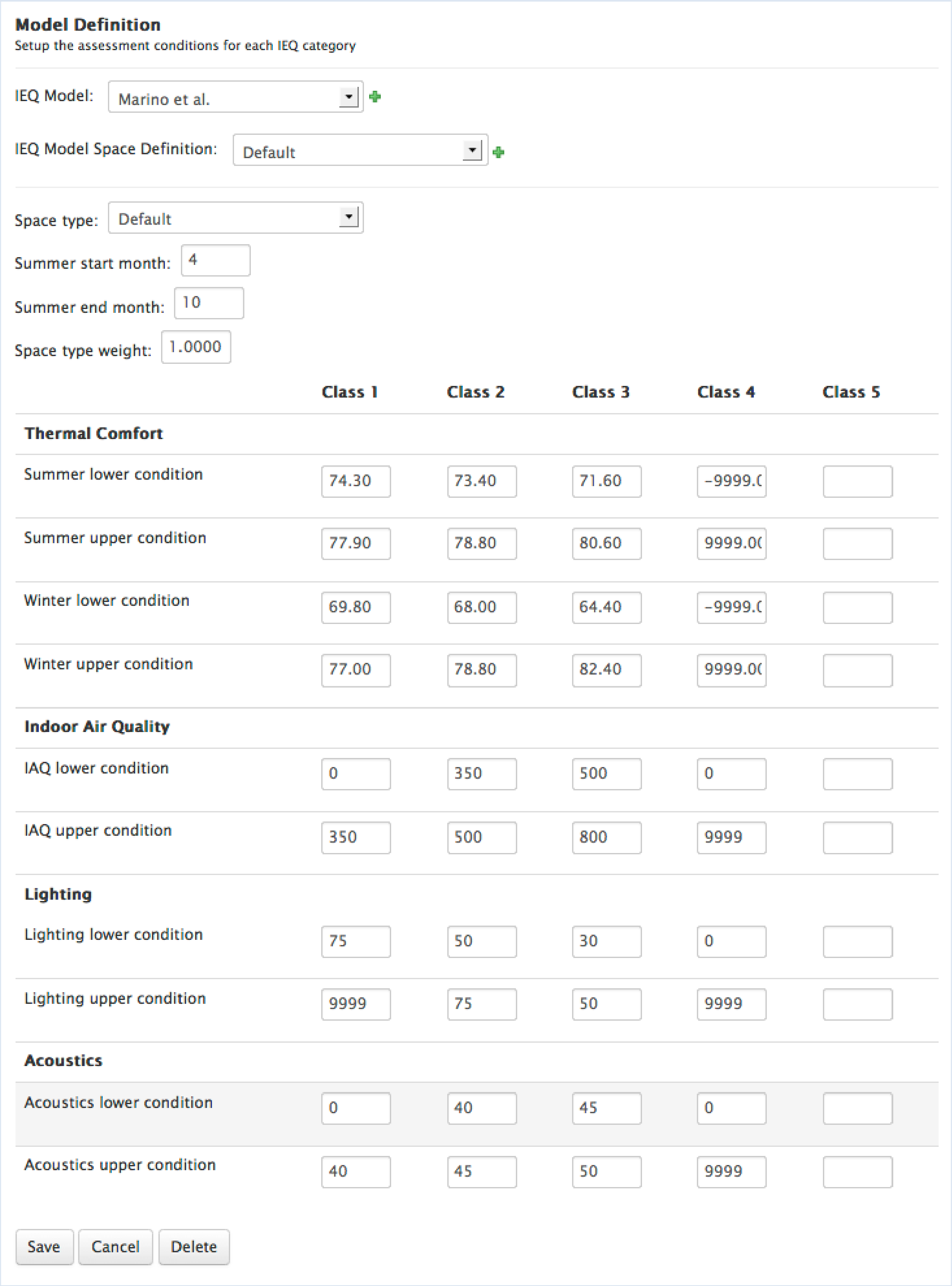
The Toolkit adopts the methods of Marino et al. for generating an "Environmental Quality Index (EQI)" and a "Building Quality Index (BQI)." An EQI is generated for each space-type that is defined in the chosen model and included in the data set according to the steps in Figure 40. Once the data has been binned according to time spent in an assessment class and the IEQ category weights have been applied, the EQI is computed using Equation 3, where f_I, f_{II}, and f_{III} are the fractions of time spent in assessment class I, II, and III respectively.

Equation 3: Computation of EQI

$$\mathrm{EQI} = 100 f_I + 70 f_{II} + 35 f_{III}$$

The BQI is then the weighted combination of each space-type EQI.

The final building scorecard that is produced is a combination of the performance summary models run on each IEQ category. A screenshot of an example scorecard from the Toolkit is provided in Figure 42. In this example, an occupant survey was not conducted, which renders the "Survey" column blank. For the CBE survey, overall satisfaction scores are provided for each IEQ category, which can be entered on the "Setup" page where the IEQ model is defined. The assessment class distribution charts are built from the saved IEQ-model analyses conducted on each IEQ category analysis page. The scorecard page allows the user to select different model results in order to compare how the building is rated differently between models.


Model Definition
Setup the assessment conditions for each IEQ category

IEQ Model: Marino et al.

IEQ Model Space Definition: Default

Space type: Default

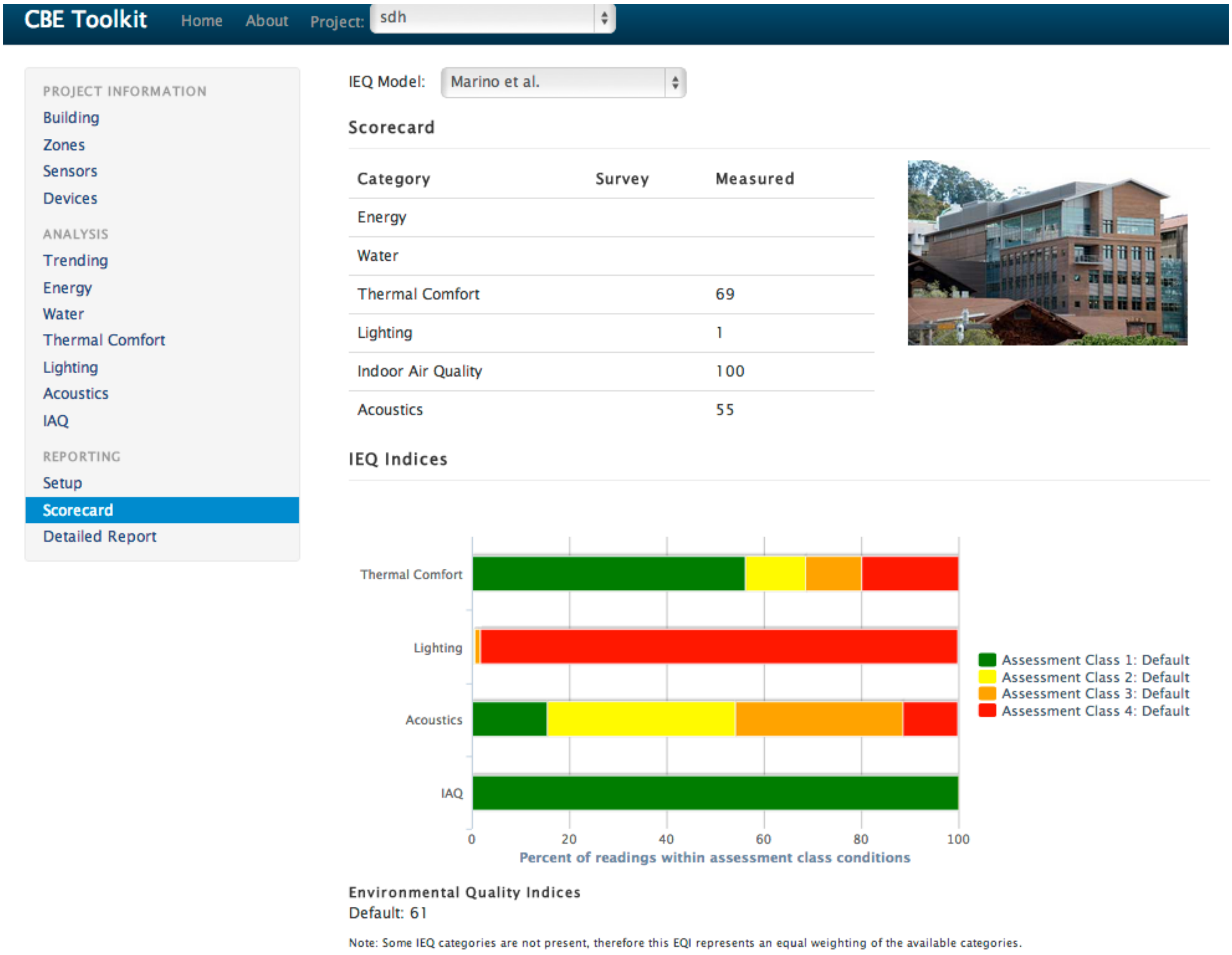
Summer start month: 4

Summer end month: 10

Space type weight: 1.0000

	Class 1	Class 2	Class 3	Class 4	Class 5
Thermal Comfort					
Summer lower condition	74.30	73.40	71.60	-9999.(	
Summer upper condition	77.90	78.80	80.60	9999.0(	
Winter lower condition	69.80	68.00	64.40	-9999.(	
Winter upper condition	77.00	78.80	82.40	9999.0(	
Indoor Air Quality					
IAQ lower condition	0	350	500	0	
IAQ upper condition	350	500	800	9999	
Lighting					
Lighting lower condition	75	50	30	0	
Lighting upper condition	9999	75	50	9999	
Acoustics					
Acoustics lower condition	0	40	45	0	
Acoustics upper condition	40	45	50	9999	

Figure 41: Scorecard setup page where assessment classes are defined for each IEQ category



IEQ Model: Marino et al.

Scorecard

Category	Survey	Measured
Energy		
Water		
Thermal Comfort		69
Lighting		1
Indoor Air Quality		100
Acoustics		55

IEQ Indices

Environmental Quality Indices
Default: 61

Note: Some IEQ categories are not present, therefore this EQI represents an equal weighting of the available categories.

Figure 42: Example of Toolkit building scorecard

2.2.6.1 New IEQ model proposal

While the Toolkit is based on the method described in Marino et al. for creating a building IEQ scorecard, it allows flexibility in defining assessment class limits and weighting factors. There are three main concerns associated with the existing assessment class limits presented in Marino et al. (Table 7):

1. Not all models have limits that are associated with clear occupant satisfaction differences. Arens et al. (2010) suggest that the assessment classes\categories defined for thermal comfort in EN15251 do not align with perceptible changes in occupant satisfaction and may lead to more energy intensive buildings.
2. Space-type differences are not implemented in most of the models. Marino et al. includes a space-type weighting factor though offers no guidance on how such factors may be determined.
3. Inter-category relationships are not considered in the IEQ model framework. None of the models discuss the correlations between IEQ categories, for example, higher thermal comfort is often associated with higher indoor air quality.

The primary danger associated with assessment class models is that tighter parameter bounds will be associated with higher quality buildings and designers will strive for these narrow bounds rather than less-energy intensive but equally satisfactory wider bounds. Similarly, on the operational end, building operators may strive to maintain narrow conditions with the mistaken belief that such narrow bands represent higher quality and greater occupant satisfaction. To this end, we propose only two assessment classes: (I) compliance with the standards and guidelines outlined in the PMP, (II) non-compliance with the standards and guidelines outlined in the PMP. Different space-types are included for the lighting and acoustics categories. Inter-category relationships have not been addressed in this model. Table 12 outlines the conditions for each IEQ category for compliance. The "-" symbol indicates that the Default value will be used.

Table 12: IEQ model based on assessment of occupant satisfaction

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	lx ≥ 300	PPD ≤ 10%
Open plan office with intensive computer use and sound masking	dBA ≤ 45	-	-	-
Open plan office with intermittent computer use and no sound masking	-	-	lx ≥ 500	-
Open plan office with intermittent computer use and sound masking	dBA ≤ 45	-	lx ≥ 500	-
Conference room - televideo conference	dBA ≤ 30	-	lx ≥ 500	-
Lobby / stairway	dBA ≤ 50	-	lx ≥ 100	-
Private office	-	-	lx ≥ 500	-

For this project, thermal comfort is defined only using PPD and there are not currently methods for handling elevated air-speed or adaptive comfort models. These models will be implemented in future work, in which case the thermal comfort section would be compliance with ASHRAE Standard 55.

The PMP does not include a maximum recommended lighting level for illuminance, but we feel that over-illuminance is an issue that needs to be addressed. In future work, we plan to include a tool to associate lighting-controller data with Toolkit zones. This association will then be used to highlight when electric lighting is unnecessarily on during times of sufficient daylight.

In addition to the assessment class limits, the proposed model suggests a new IEQ category weighting scheme. Table 13 provides a summary of IEQ category weighting schemes from the literature, as well as a new proposed scheme. Not all models from the literature used the same four IEQ categories. For these studies, categories weights were adjusted but may not be a completely accurate representation of the data. Without original datasets new regression coefficients cannot be computed. The datasets used in each study varied in size and quality. Chiang et al. used an analytic hierarchy process (AHP) method which sampled 12 professionals to determine the appropriate weights. Wong et al., Cao et al., and Ncube et al. all used multivariate linear regression of occupant responses to determine category weights. Each of these studies regressed IEQ category comfort response against an overall comfort survey response. Marino et al. suggested computed weightings from Bluyssen et al. (2011); however, we are unable to identify which data in Bluyssen et al. that Marino et al. uses. The conclusions of Bluyssen at al. suggest that providing a 'short-cut' to relative importance factors of IEQ categories would not be valid for the dataset (5732 occupant responses from the HOPE project).

The weights proposed in our PMP-based model we computed using a subset of the CBE survey database that was created for use in Frontczak et al., (2012). This subset database only included office buildings—further details of the database are included in Frontczak et al. Occupant responses to satisfaction questions concerning the following variables were regressed against overall workplace satisfaction:

1. Acoustics: average of noise and sound privacy
2. IAQ: air quality
3. Lighting: average of visual comfort and amount of light
4. Thermal comfort: temperature

The multivariate linear regression coefficients were normalized to sum to 1. The results of this regression model suggest that lighting and acoustics are considerably more important than IAQ and thermal comfort. There are many reasons that boiling down an entire database of results into one linear regression is problematic. However, for the purposes of this study, the validity of the specific IEQ category weighting scheme is less important than the comparisons between the models. Future work could apply many of the statistical methods used in Bluyssen et al. to the CBE survey database to develop a more robust set of IEQ category weightings.

Table 13: Summary of IEQ category weighting schemes

Study	Number of occupants surveyed	Acoustics	IAQ	Lighting	Thermal Comfort
1. (Chiang & Lai, 2002)*	12 professionals	0.26	0.27	0.21	0.26
2. (Wong et al., 2008)	293	0.24	0.25	0.19	0.31
3. (Cao et al., 2012)	500	0.224	0.118	0.171	0.316
4. (Ncube & Riffat, 2012)	68	0.18	0.36	0.16	0.30
5. (Marino et al., 2012)*	-	0.25	0.23	0.23	0.29
6. Proposed PMP-based	52,980	0.39	0.2	0.29	0.12

*Adjusted weights

3 Case Study – WSP Flack and Kurtz Offices

3.1 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 43). Their offices are located in sections of the 5th and 6th floors and are serviced by an underfloor air distribution system. The building earned a LEED-EB Platinum rating and a 94 EnergyStar rating. 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 43: 405 Howard St. building

Figure 44: ICM on desktop

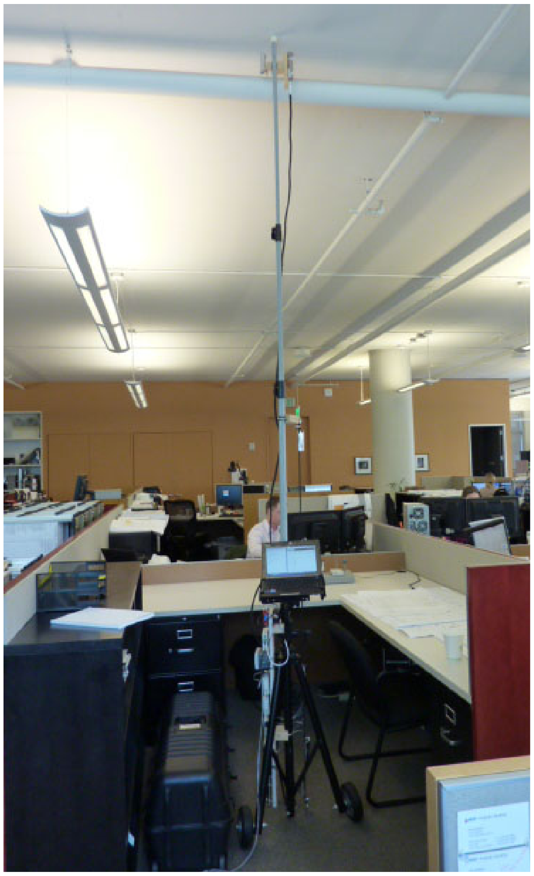


Figure 45: PUCC deployed in open plan cubicle space

This Chapter will begin 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 in a way 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. For the IEQ performance summary model, the proposed PMP-based model discussed in section 2.2.6.1 is used in each of the following analysis sections. Section 3.7 includes a comparison of four IEQ models applied to this case study data, as well as a discussion of temporal sensitivity.

3.2 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 webpages. Figure 46 shows the zoning diagram for the 6th 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 Building Management System (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 44). 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 touchscreen device with cellular connection, which 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 Portable UFAD Commissioning Cart (PUCC) to measure thermal stratification and underfloor plenum pressure (see Figure 45). 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 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 4.3.

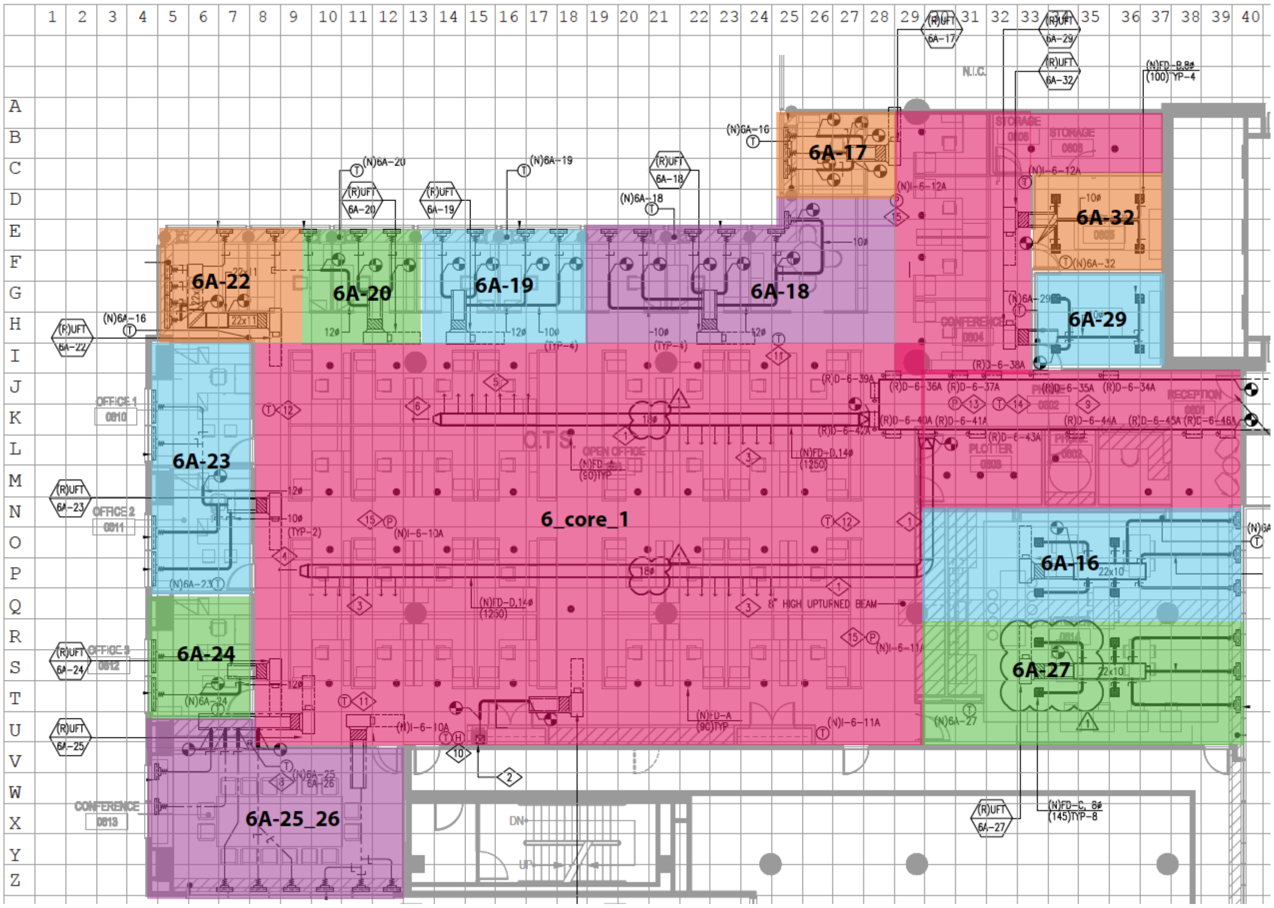


Figure 46: Zoning and grid plan for 6th floor of WSPFK offices

3.3 Thermal comfort

The space occupied by the WSPFK offices is serviced by an underfloor air distribution system (UFAD); 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.

3.3.1 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 47 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°F for all underfloor fan terminals serving the 5th and 6th 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°F. Thus, the negative side of the histogram refers to times when the zone temperature was below 72°F and the positive side of the histogram refers to times when the zone temperature was above 74°F. The bins are defined as *lower bound ≤ x < upper bound*. The majority of readings were within the setpoint range, though the distribution is skewed to the cold side, suggesting overcooling.

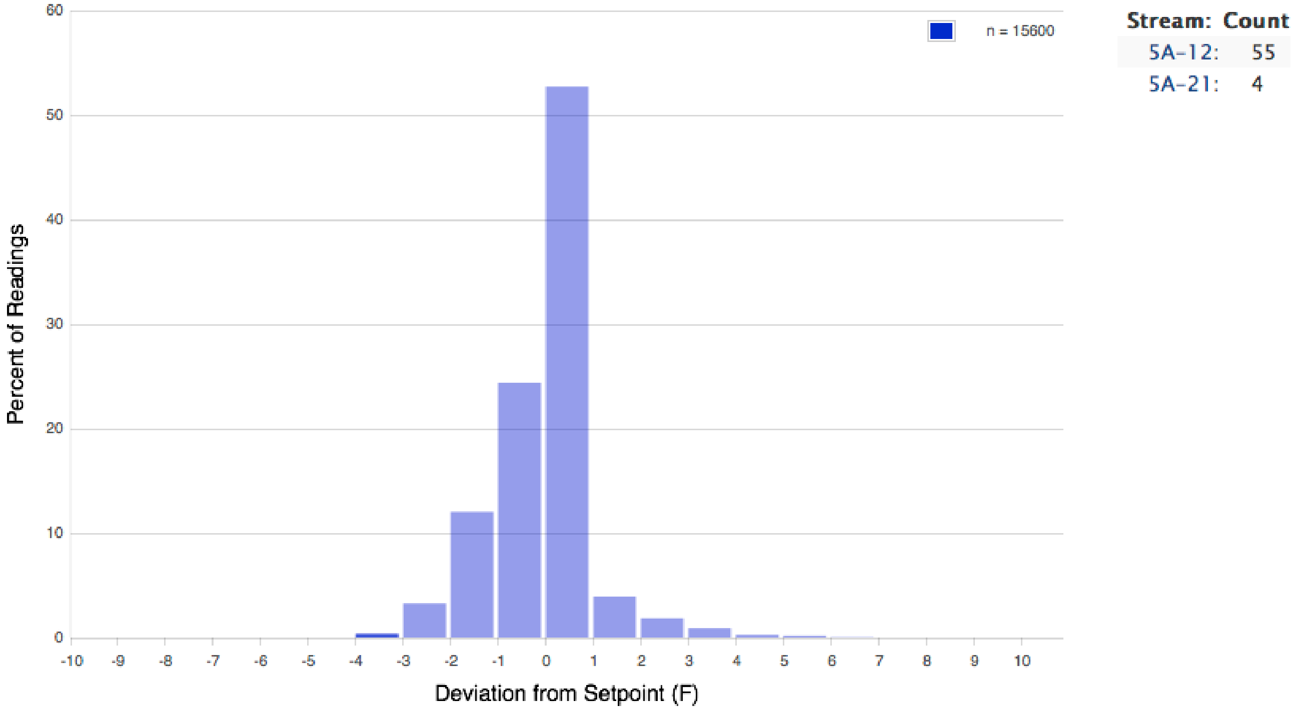


Figure 47: Zone temperature setpoint analysis for all 5th and 6th floor underfloor fan terminals for entire study period

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 47, the coldest bin (-4 to -3°F) has been clicked, showing two potentially problematic overcooled zones: 5A-12 with 55 readings and 5A-21 with 4 readings. Fifty-five, 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% of the readings of this single fan terminal. Figure 48 shows the trend of the 5A-12 fan terminal speed percent and the thermostat reading for that zone. The temperature hovers below 70°F. The red line shows the 69°F line which represents 3°F below a nominal 72°F setpoint. The readings below this line fall into the histogram bin highlighted above. The fan speed trend is constant 30%, 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°F heating, 73°F cooling) than the other zones, but these setpoints do not explain why the zone hovers below 70°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 49 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% minimum flow when air temperature is below setpoint, and ramping up airflow to 100% 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.

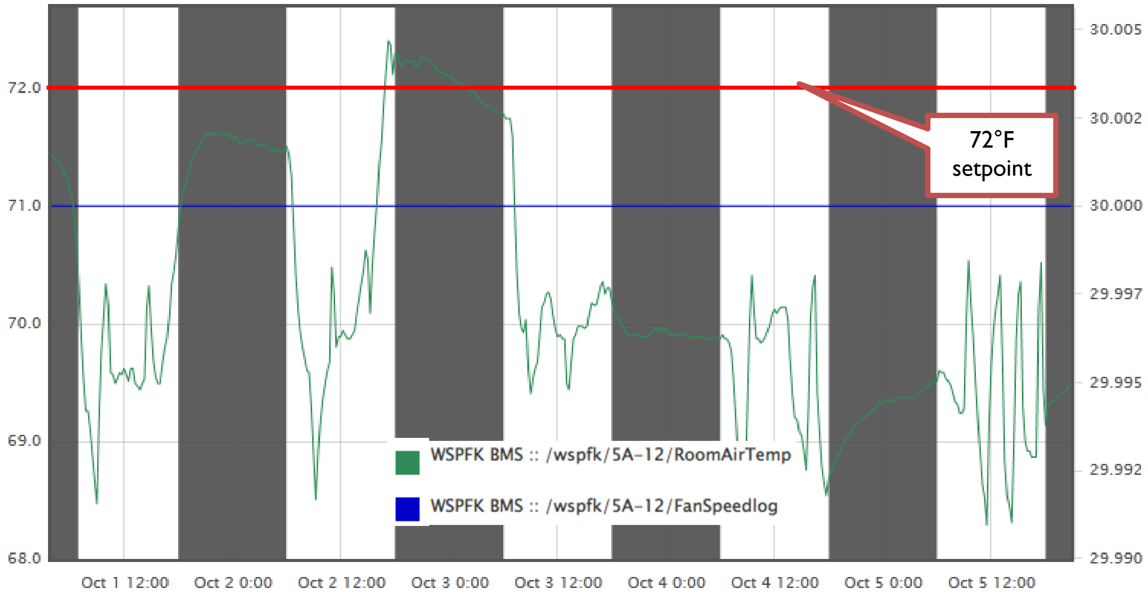


Figure 48: Fan terminal 5A-12 air speed percent and thermostat reading for week of 10/1-10/5/2012

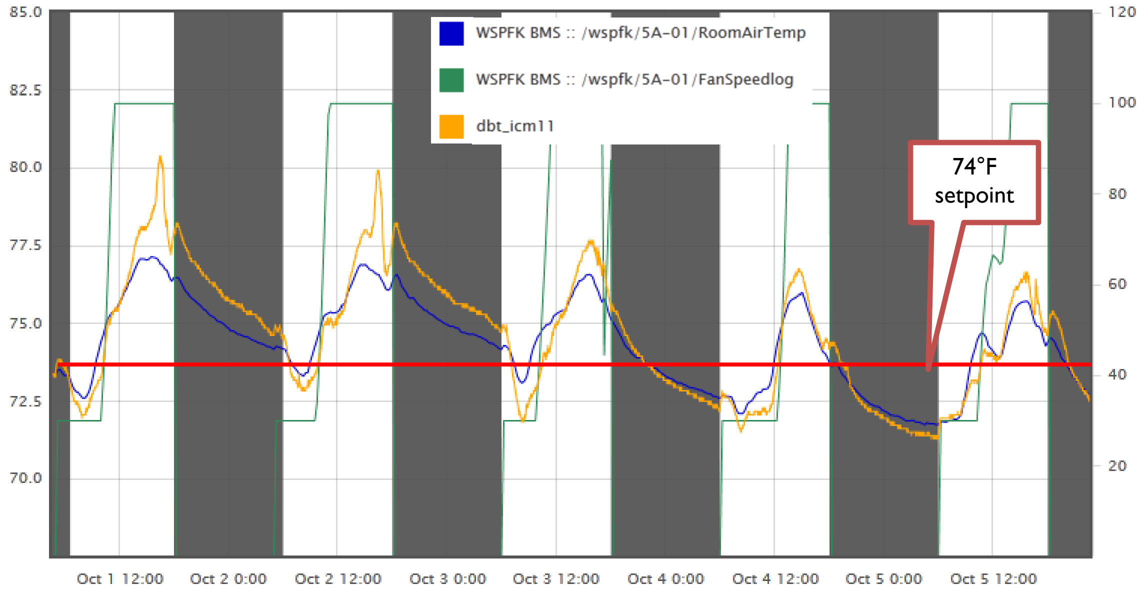


Figure 49: Fan terminal 5A-1 air speed percent and thermostat reading, with ICM11 dry-bulb temperature for week of 10/1-10/5/2012

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.

3.3.2 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, mean radiant temperature (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 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. For this analysis, a metabolic rate of 1.1 met (seated, typing) and a clothing value of 0.8 clo were chosen to define the comfort boundaries. Not everyone in the office was wearing the same level of clothing, though most men wore thick trousers with long sleeve shirts and ties, sometimes with a coat, so the average clothing value in the office is 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 50. 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% of the time and that the average PPD is 8.3%. 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 51 shows the average day data for each ICM in the study (13 points each representing 6:00AM to 6:00PM).

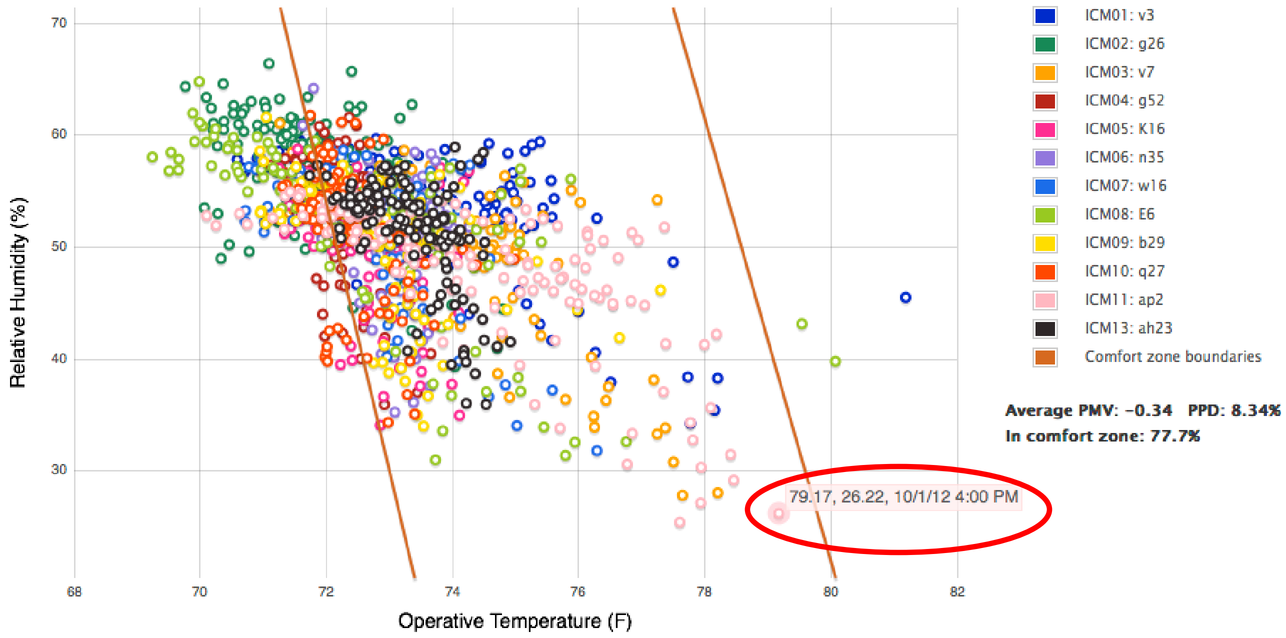


Figure 50: Hourly ICM thermal comfort data from 9/27/12 - 10/10/12 for weekdays 6AM-6PM

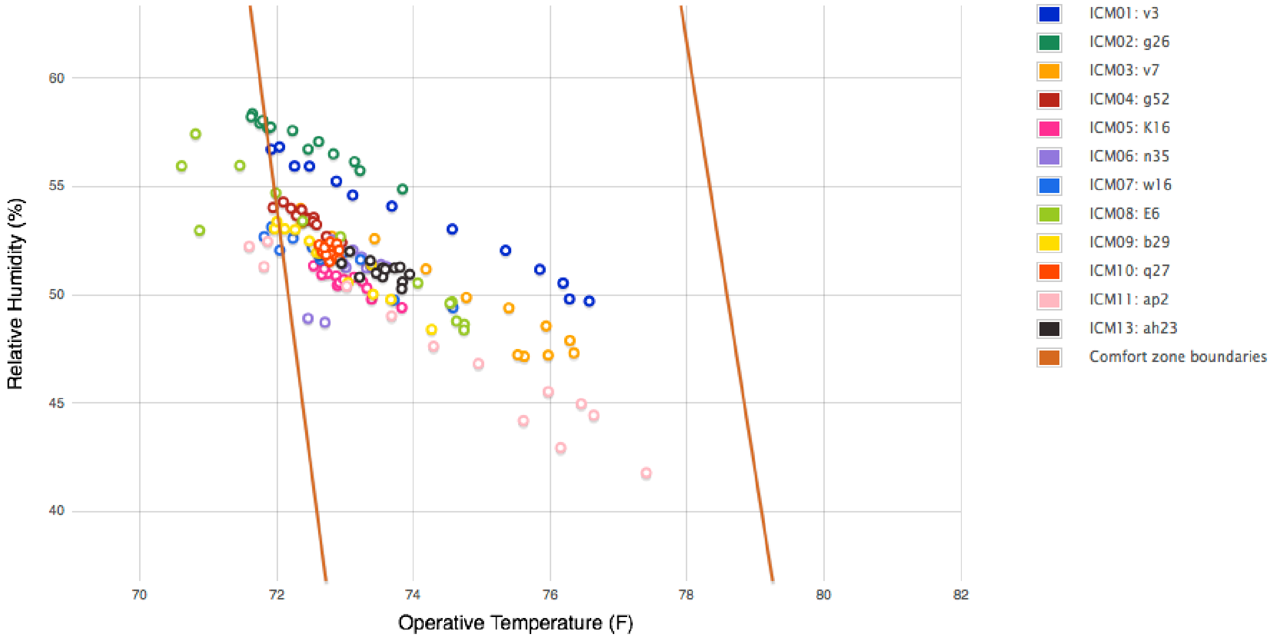


Figure 51: Average of hourly values across all days in study period, representing an "average day"

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. What spatial parameters (windows, orientation, 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 52 (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 50 is 10/1 at 4:00PM), suggesting that the system had difficulty keeping setpoint during this high load period.

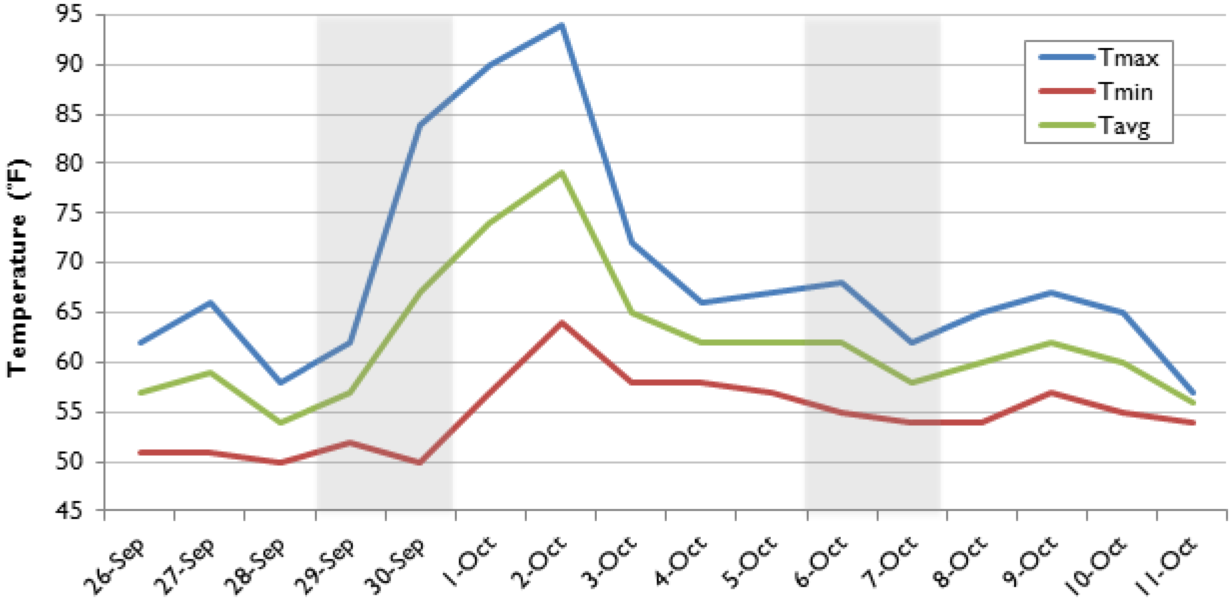
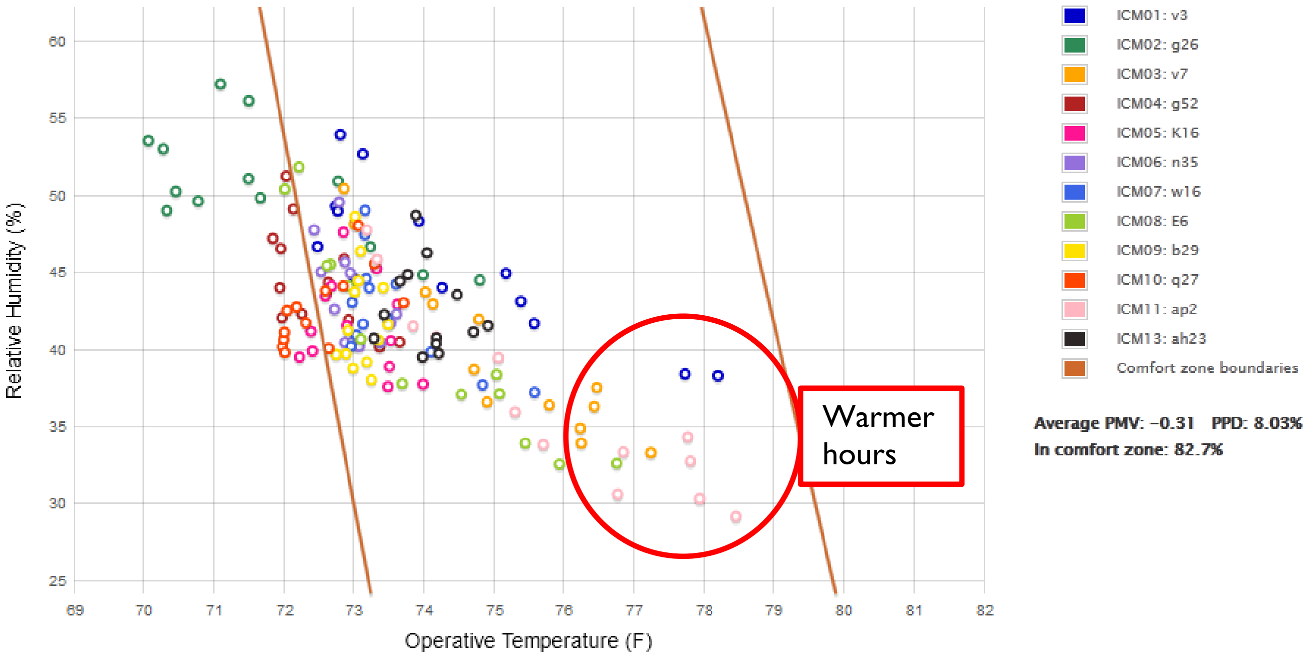


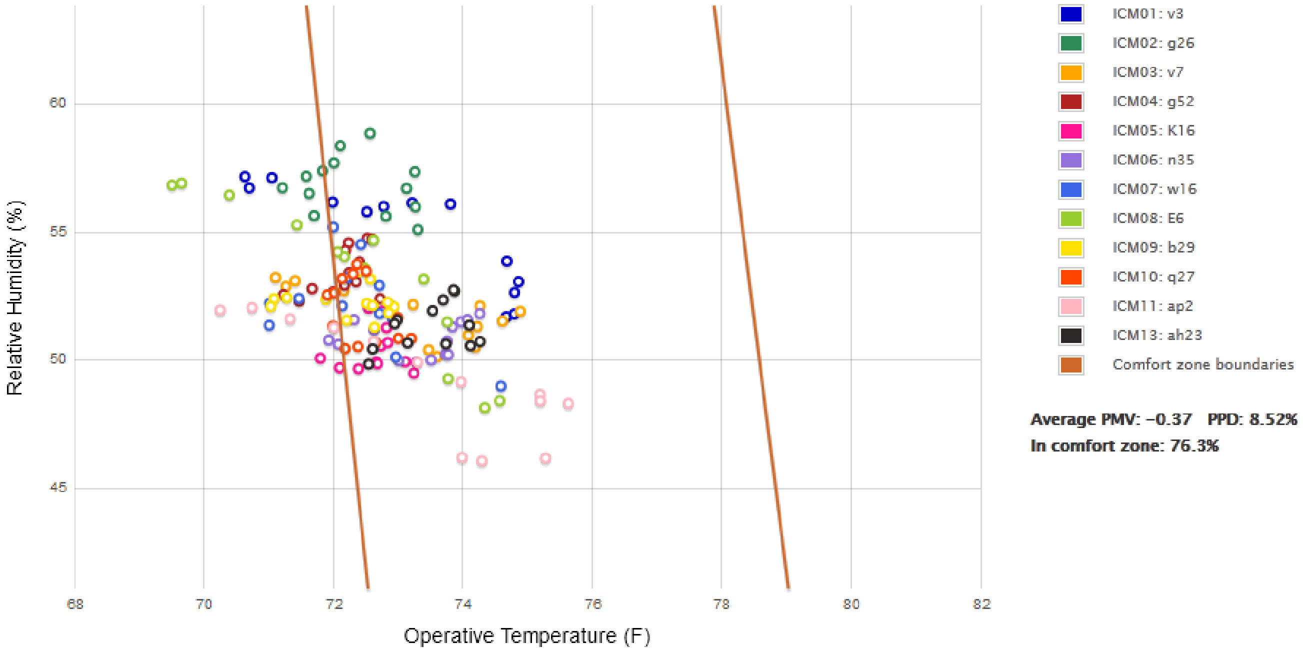
Figure 52: Daily outdoor air temperatures in downtown San Francisco for study period (weekends are shaded)

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 53) showing a hot day (October 2nd) and the second (Figure 54) showing a "normal" day (September 27th) for the study period.



Average PMV: −0.31 PPD: 8.03%
In comfort zone: 82.7%

Figure 53: Hourly ICM thermal comfort data for hot day – 10/2/12



Average PMV: −0.37 PPD: 8.52%
In comfort zone: 76.3%

Figure 54: 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 55 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 51 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.

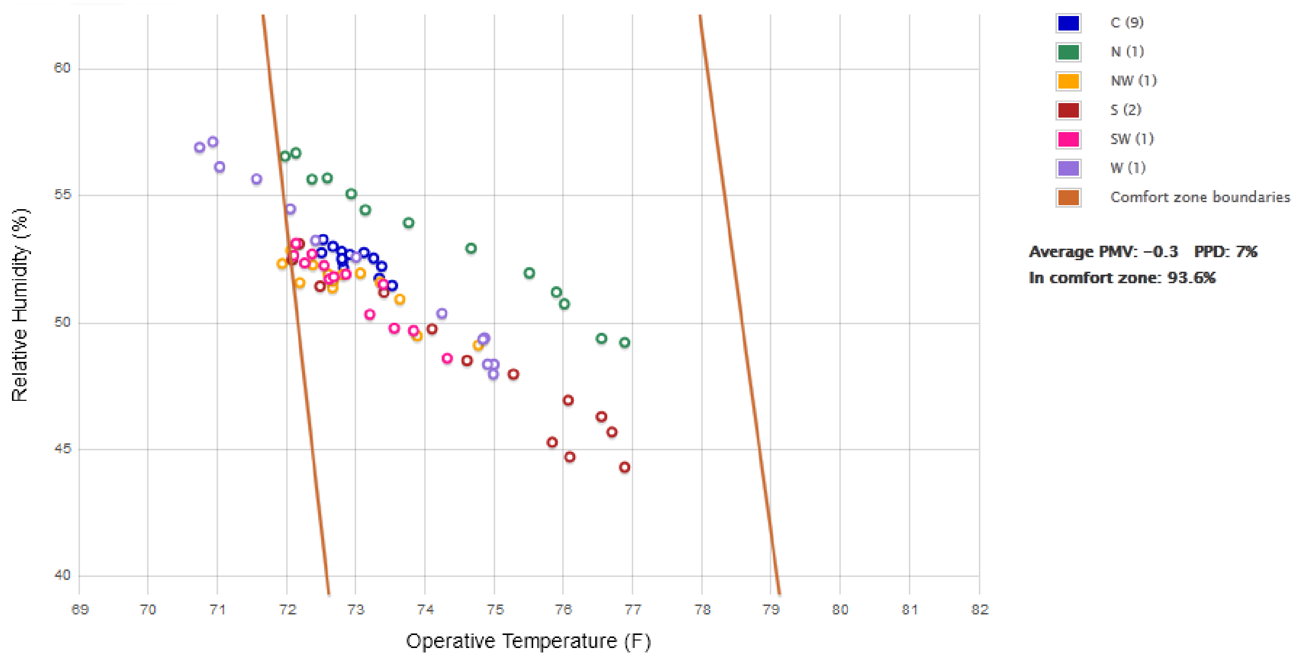


Figure 55: ICM thermal comfort data aggregated by orientation for entire study period, showing "average days"

The ICM comfort zone analysis shows that the building tends to fall nicely into the comfort zone for a clothing level of 0.8 and metabolic rate 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 56 shows the summary model based on the assessment class conditions of the "proposed" model explained in section 2.2.6.1. 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 percent persons dissatisfied (PPD) is ≤ 10%, indicating compliance with the PMV/PPD model of ASHRAE Standard 55. Assessment class 2 represents any PPD above 10%. In the proposed model case, the percent persons *satisfied* (100-PPD) is computed instead of PPD. Figure 57 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% or more of the occupants 100% of the time.

Figure 56: Thermal comfort summary performance model of entire study period and all ICMs

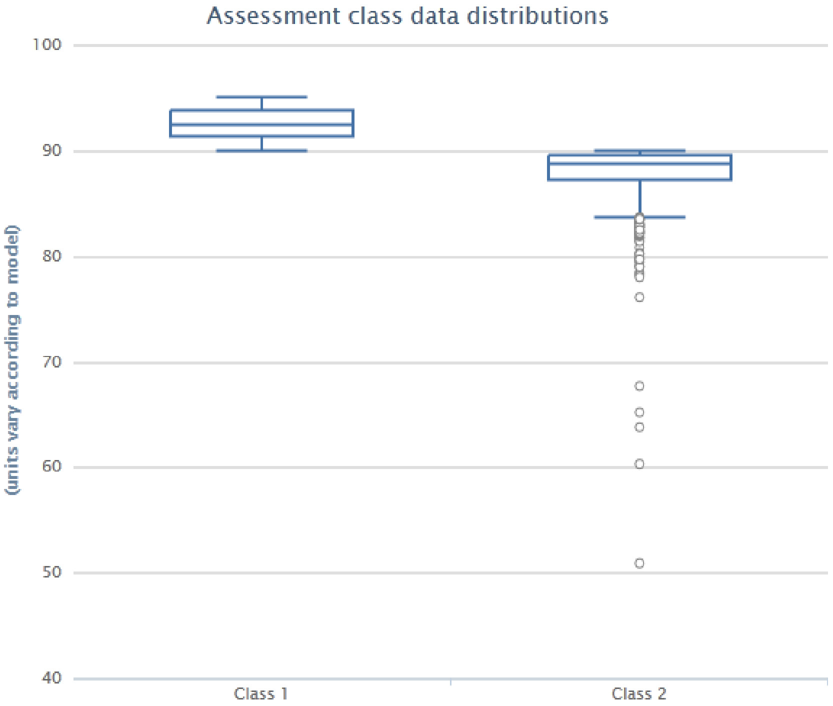


Figure 57: Distribution of the data for each assessment class for the default space type shown in Figure 56

3.3.3 PUCC analysis

The portable UFAD commissioning cart was used to analyze the performance of the underfloor air distribution 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 (see section 2.2.4.3 for a detailed explanation of these variables). Figure 58 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°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 61.

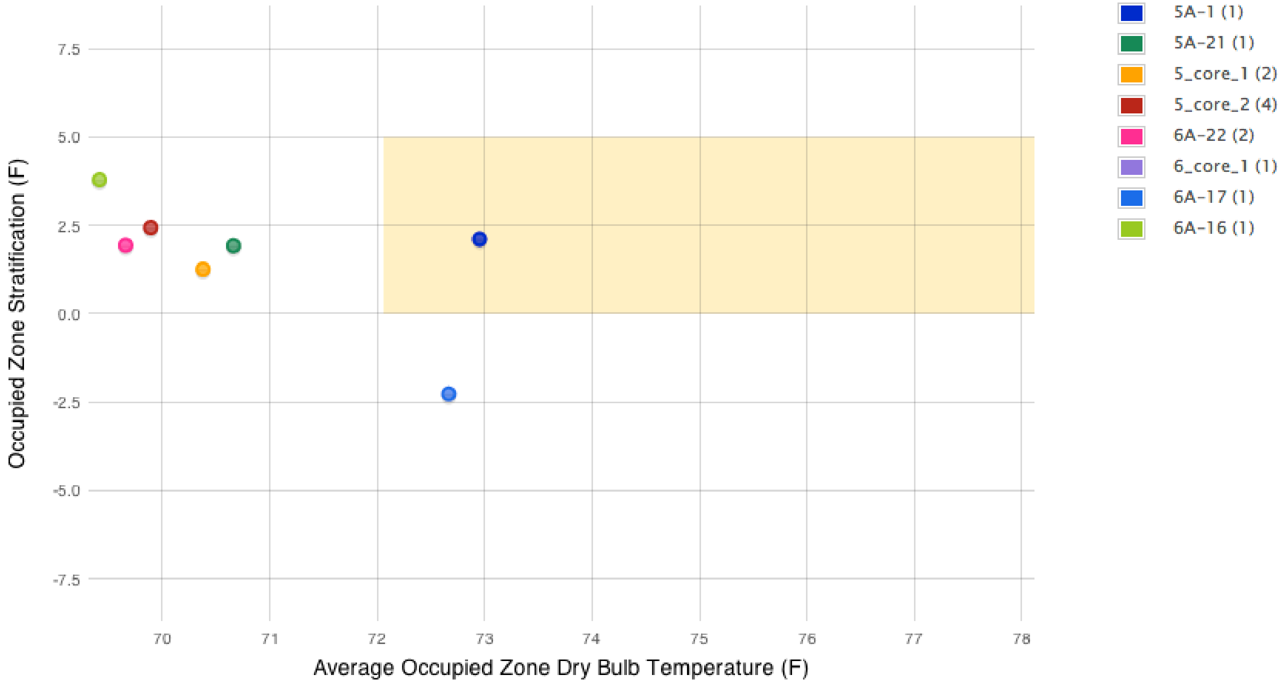


Figure 58: Comfort/stratification summary chart of cart measurements aggregated by zone

Room-air-stratification (RAS) charts provide a further level of detail for analyzing stratified systems. Figure 59 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°F to 68.5°F. These floors are served by four air-handling-units (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°F to 65°F with two air handlers in sync, but not necessarily with the other two handlers (Figure 60). 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°F. Even the temperature directly below the ceiling (152") is still quite cool, at 72°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.

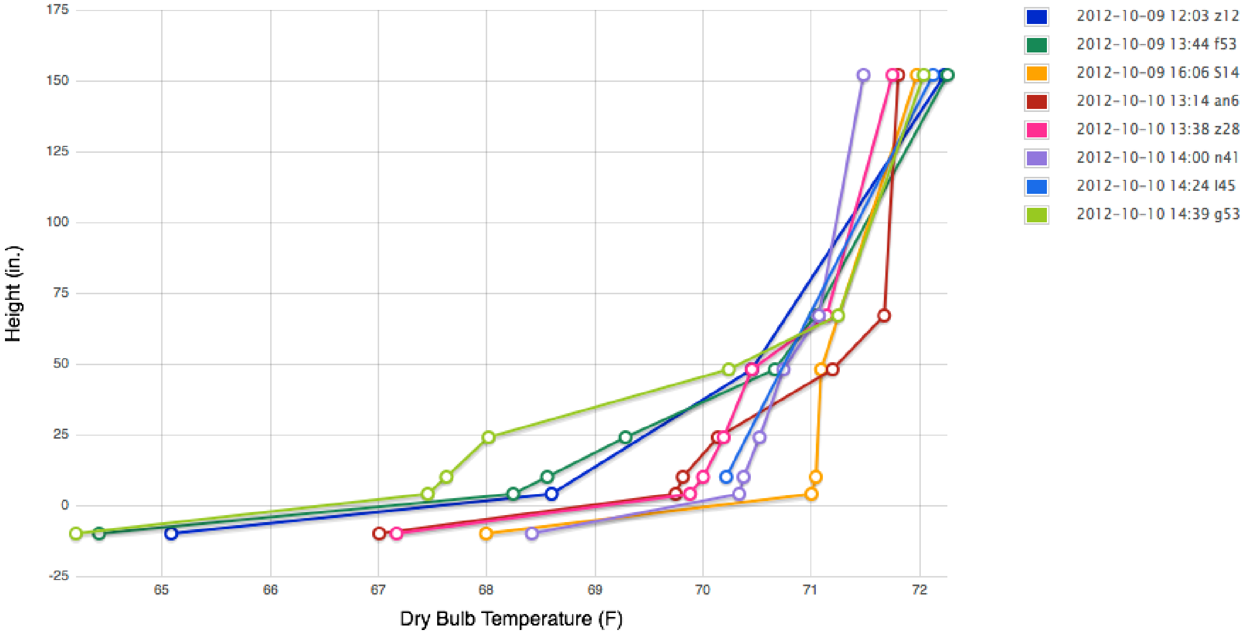


Figure 59: Room-air-stratification chart for interior cart measurements

The perimeter cart measurements are shown in Figure 61. 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 strange 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.

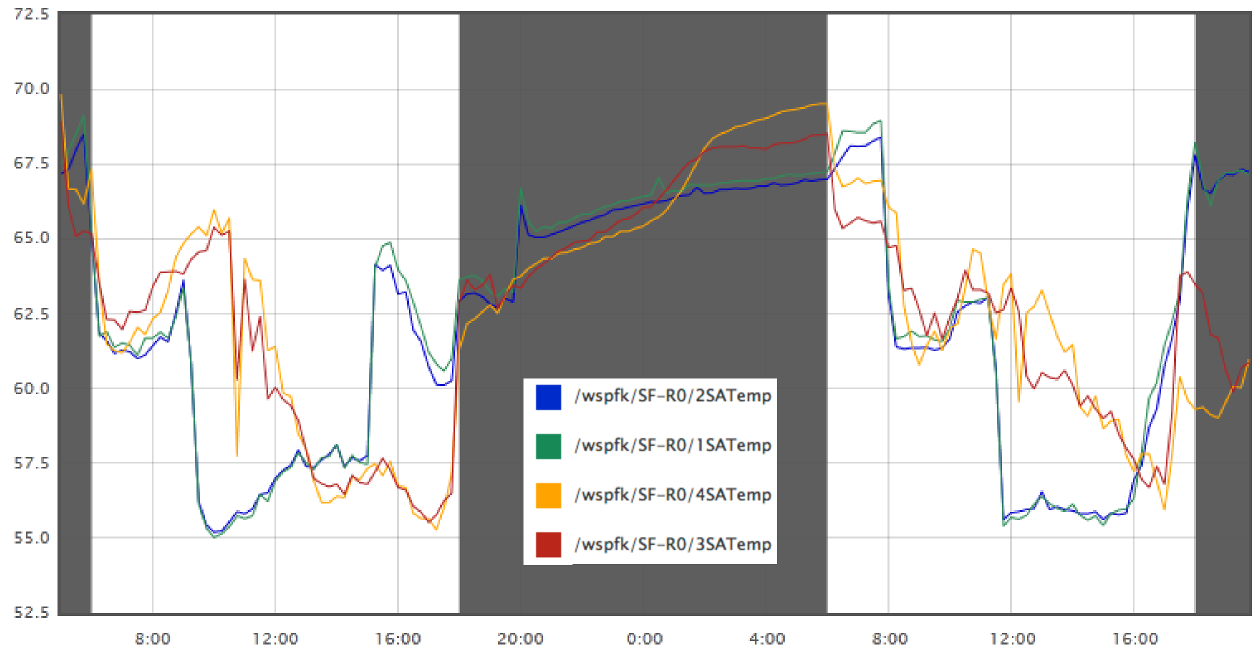


Figure 60: Air handling units supply air temperature for 10/9 - 10/10/2012 (non-operational hours are grayed out)

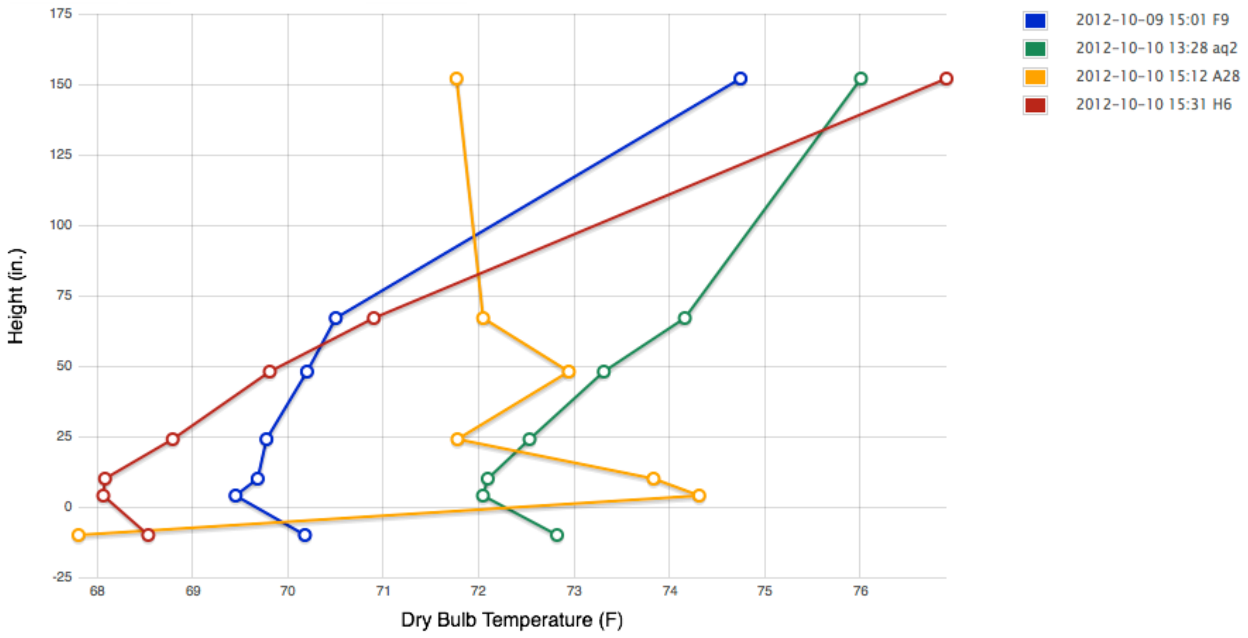


Figure 61: Room-air-stratification chart for perimeter cart measurements aggregated by zone

3.4 Lighting

The office has daylighting features, including auto-dimming perimeter light fixtures controlled by light-sensors and motion detectors. There were two concerns 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, there is usually a blind 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 the boxplot distribution. Figure 62 shows this style of analysis for one of the illuminance meters in the 6th 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 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 63 shows the hourly data that corresponds with the circled outliers in Figure 62. In this case, the outliers happened within the same 24-hour period. Note that the data in Figure 64 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.

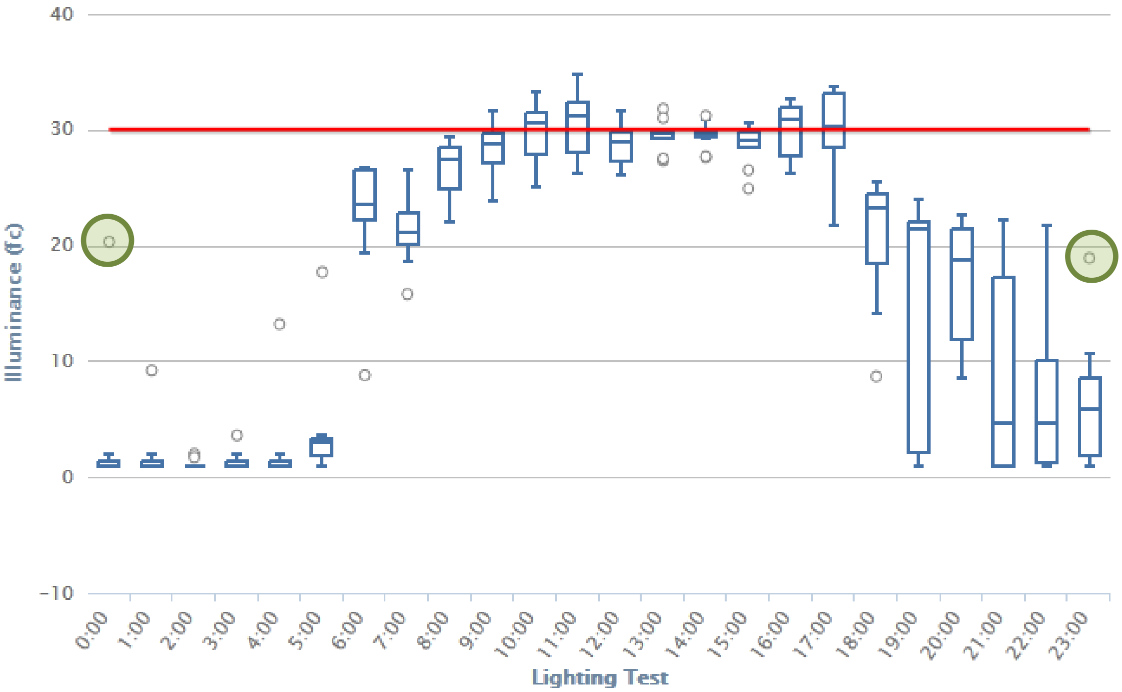


Figure 62: Boxplots of hourly light levels across study period weekdays for ICM05 in the 6th floor core zone

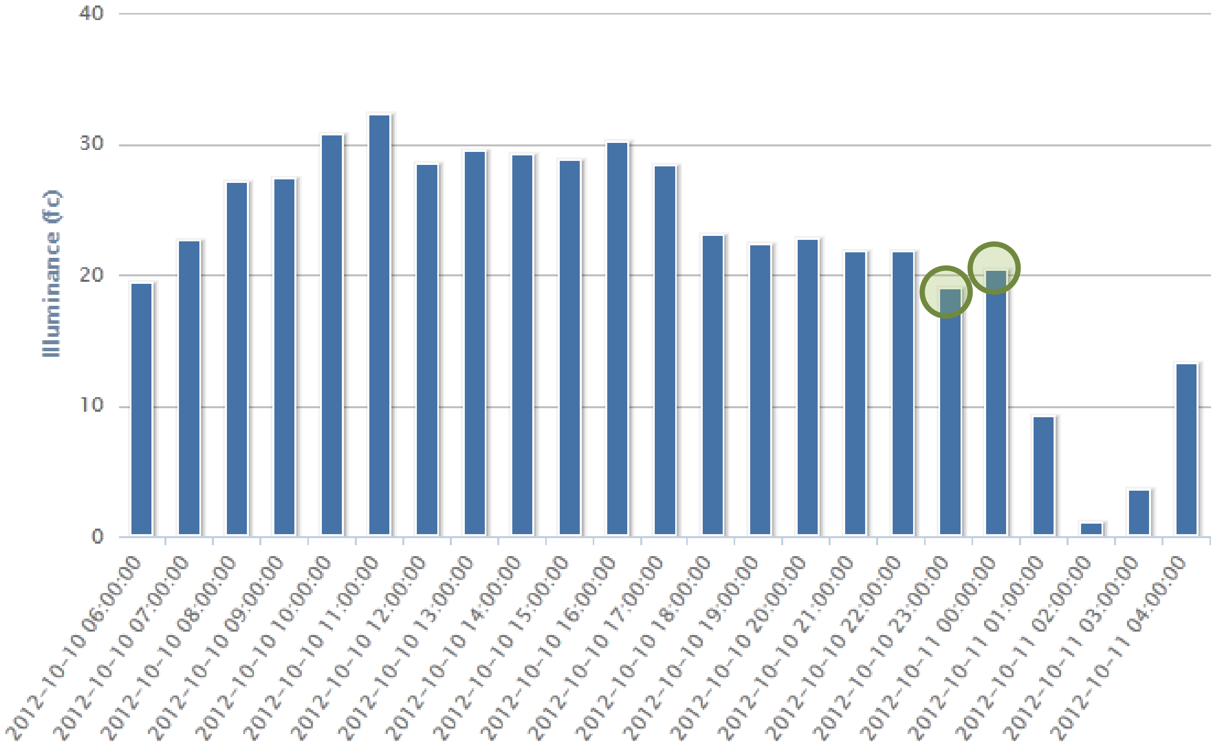


Figure 63: Hourly light levels for 6th floor core zone ICM05 for Thursday 10/10/2012

Figure 64 and Figure 65 show the boxplot "average day" analysis for two perimeter zones on the 6th floor. ICM09 (Figure 64) was placed on a bookshelf approximately 10 feet 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 65) 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.

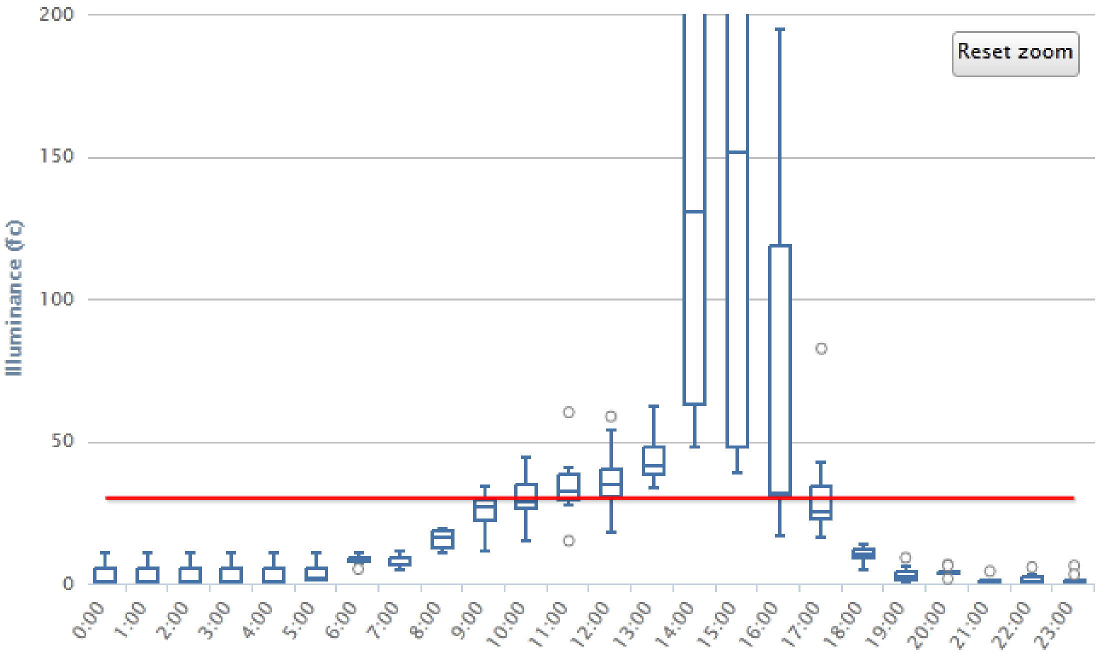


Figure 64: Hourly light levels across study period weekdays for ICM09 in the 6th floor perimeter zone 6A-17

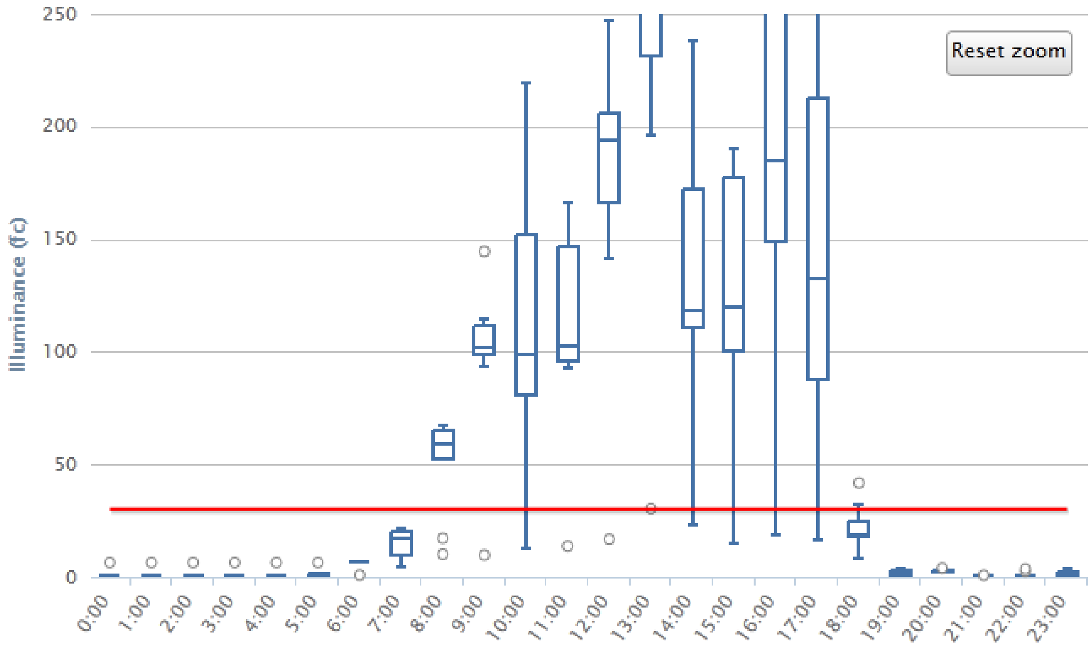


Figure 65: Hourly light levels across study period weekdays for ICM08 in the 6th floor perimeter zone 6A-22

To summarize the performance of the lighting system we can look at the lighting performance summary model. Figure 66 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 lx (28 fc) in order to meet assessment class 1 and comply with PMP recommendations. The spaces monitored reached this level nearly 70% 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 to correlate high light levels with electric light operation. In the absence of this electric lighting data, we can study the distribution of data for each assessment class in Figure 67. Here we clearly see that while 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).

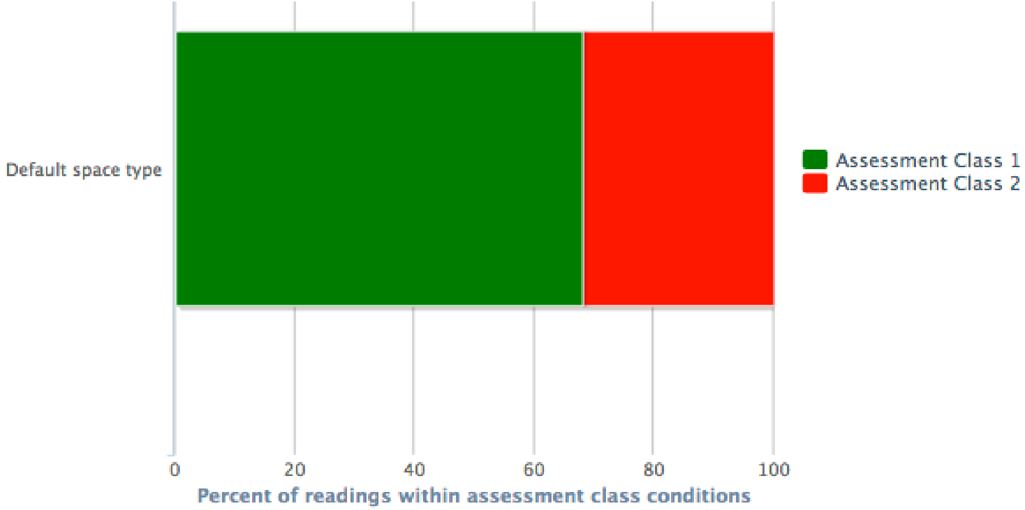


Figure 66: Lighting performance summary model for all illuminance sensors

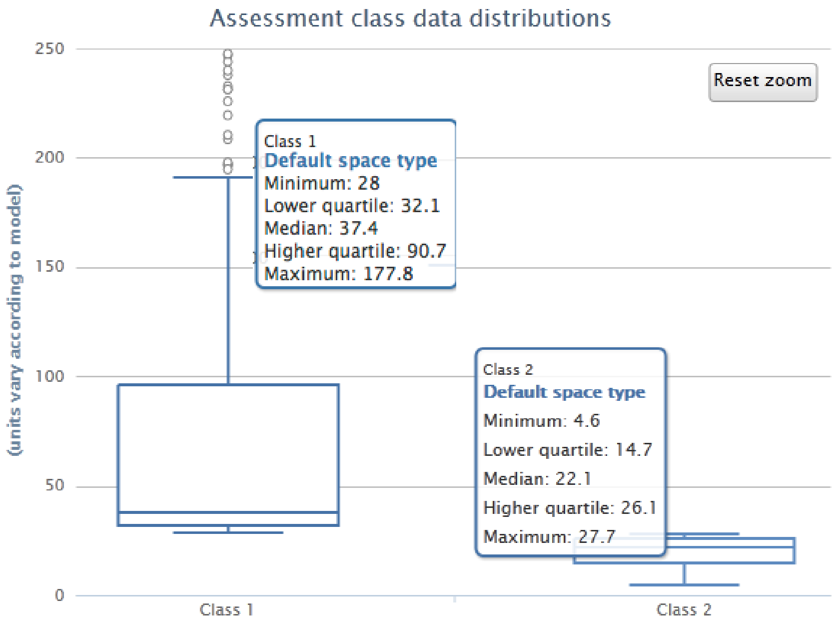


Figure 67: Assessment class data distributions for lighting performance summary model

3.5 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 90% 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 68 shows the boxplot summary sound level measurements for each half hour from 8:00AM – 3:30PM for the open office portion of the 5th floor. These measurements represent A-weighted sound pressure levels averaged every five minutes and summarized over each half-hour period. The ASHRAE/ASA/ANSI/CEN recommended (green – 35 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 HVAC system running. A long-term test such as the one in Figure 68 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.

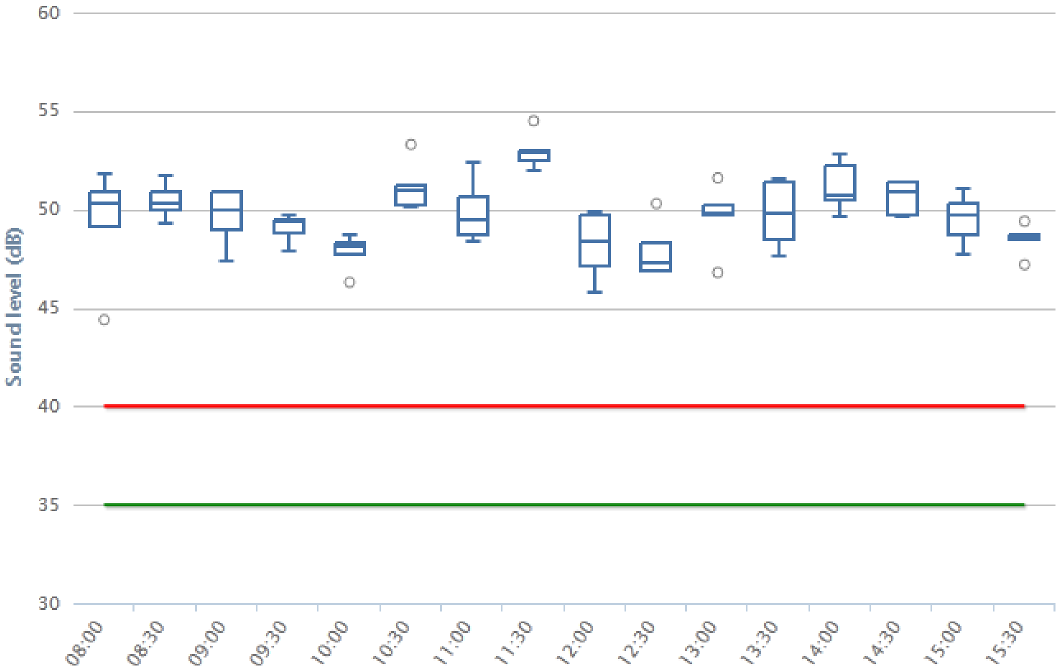


Figure 68: Long-term sound level test on 10/9/2012

Short-term tests (5-minute averages) were taken in two conference rooms and in the open-plan office on the 6th floor. The tests taken in the open-plan office were consistent with the levels shown in Figure 68. Figure 69 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.

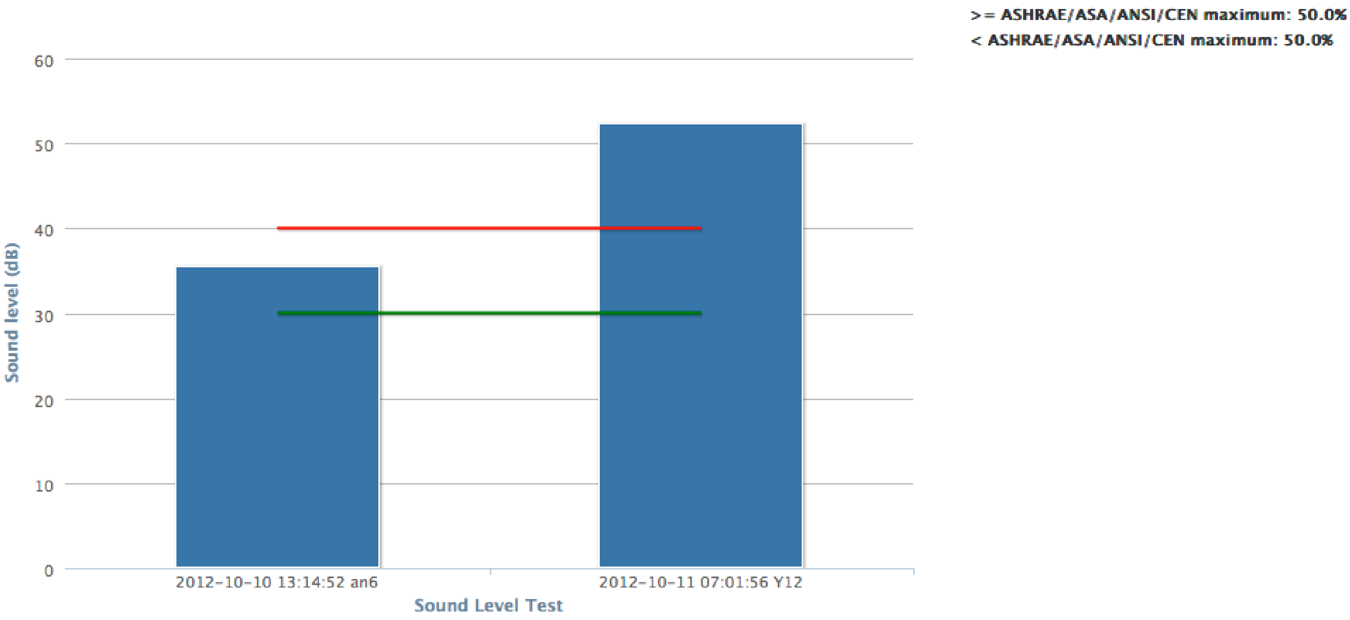


Figure 69: Short-term sound level tests for conference rooms

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 70 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 ≤ 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 70: Acoustics performance summary model for short-term tests taken on 10/10/2012

3.6 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 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 71 shows a boxplot analysis of the hourly CO_2 levels across days in the study period for a core zone on the 5th 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% 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 72 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 71 and its corresponding data point is highlighted in Figure 72.

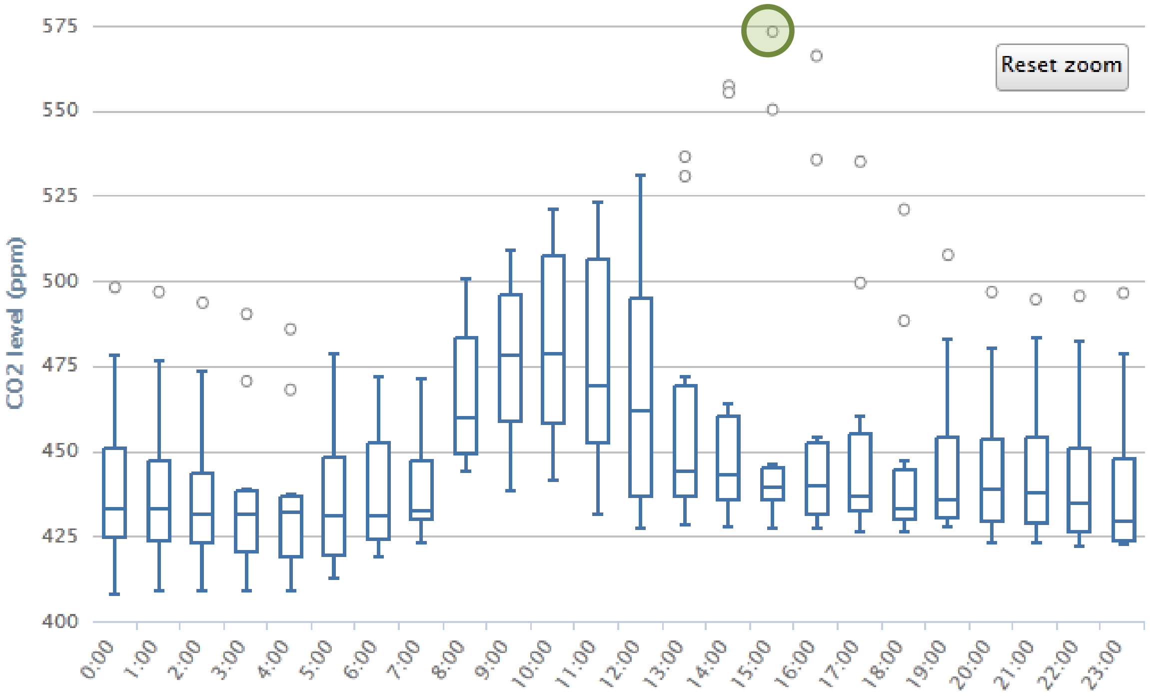


Figure 71: Hourly CO_2 levels across study period weekdays for ICM12 in a core zone cubicle on the 5th floor

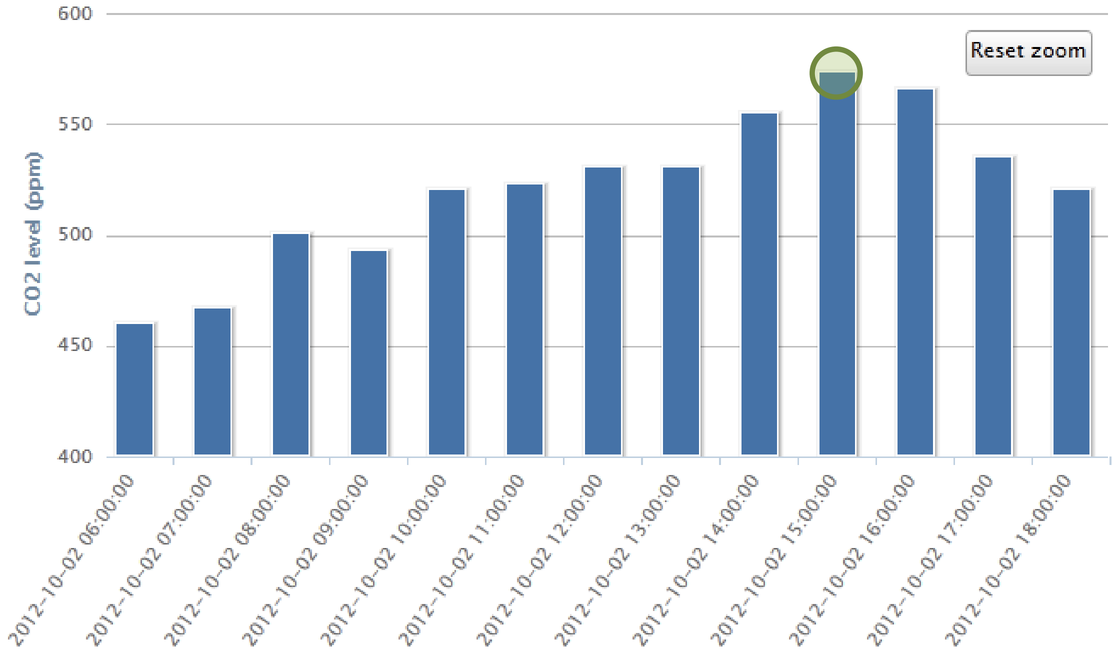


Figure 72: Hourly CO_2 levels on 10/2/2011 for ICM12 in a core zone cubicle on the 5th floor

Figure 73 shows the boxplot analysis of the hourly CO_2 levels across the study period for an ICM in a conference room in the 5th 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 74 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 which 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.

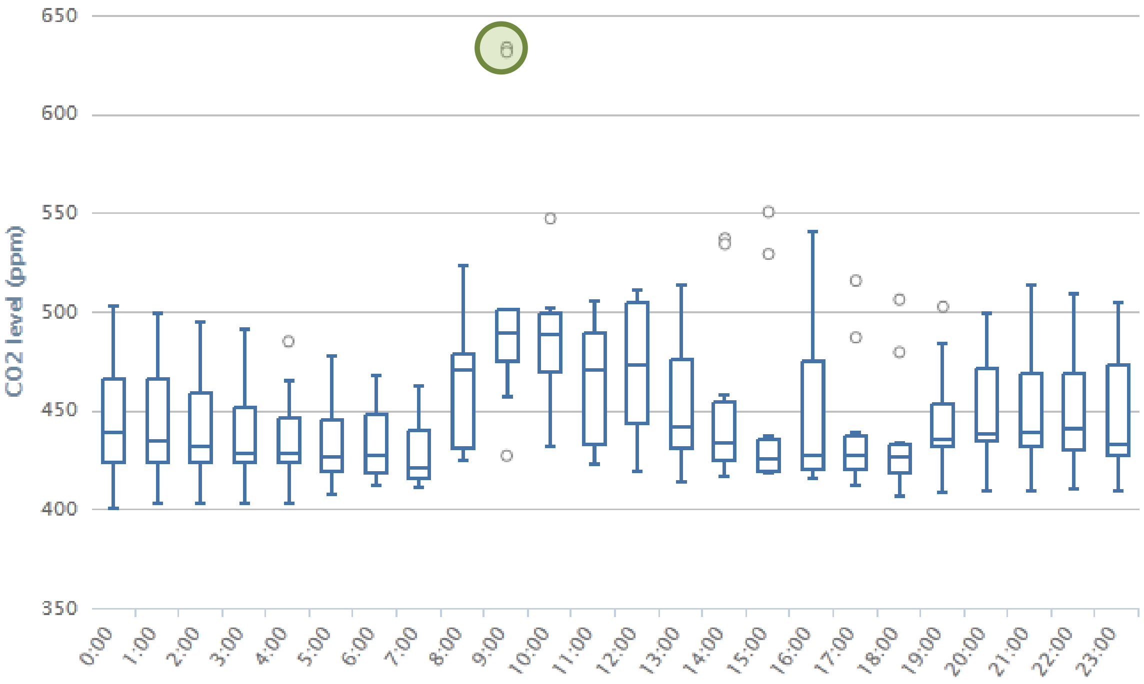


Figure 73: Hourly CO_2 levels across study period weekdays for ICM15 in a conference room on the 5th floor

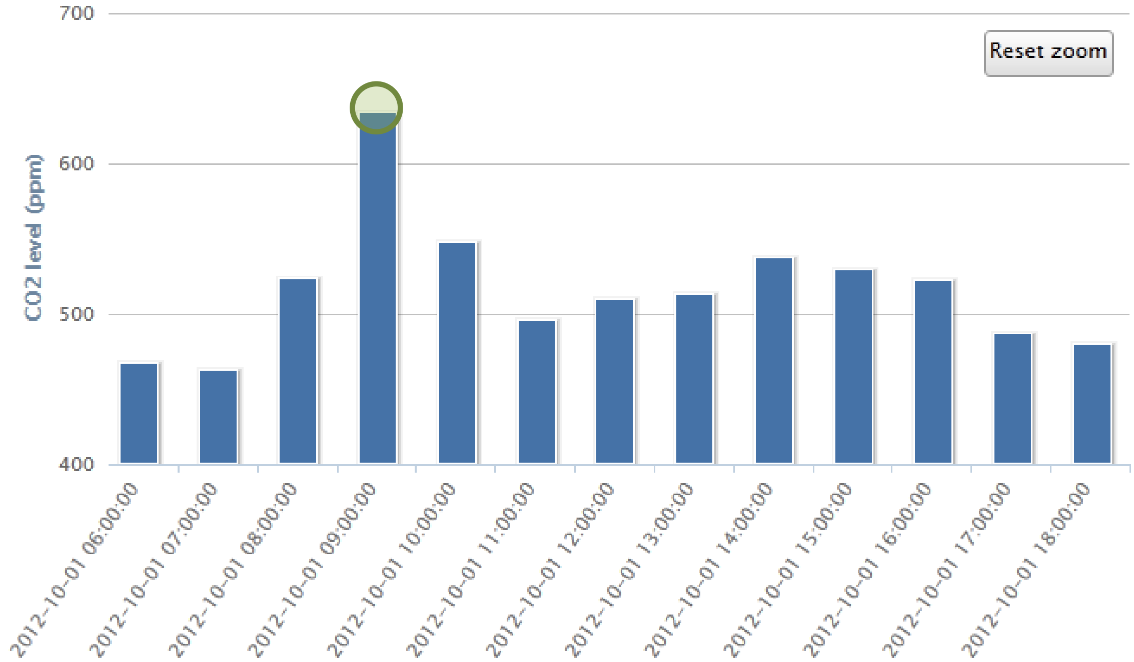


Figure 74: Hourly CO_2 levels on 10/1/2012 for ICM15 in a conference room on the 5th floor

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% 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 (see section 4.4).

3.7 IEQ performance summary model comparisons

The IEQ performance summary models are designed to summarize a large amount of data and provide a course indication of IEQ performance. The two weeks of data collected for this case study is not intended to be a representative sample of the entire year. Thus, the scores provided by the IEQ models presented in this section are used primarily as a method for comparing the models as opposed to a true evaluation of the performance of the WSPFK offices. There are four major sensitivities involved in the IEQ models that will be discussed in this section: (1) assessment class definitions, (2) length of study, (3) spatial density of instrumentation, and (4) IEQ category weights.

3.7.1 Assessment class definitions sensitivity

The data for each IEQ category were run through four models: (1) Marino et al., (2) Ncube et al., (3) Chiang et al., (4) Proposed PMP-based. The operational hours of the full study period was chosen with a day taken off each end to account for any missing data (9/27 – 10/11/2012, weekdays 6:00AM-6:00PM), and 15-minute averaged data was used. Reasonable acoustics measurements were only taken on 10/10/2012, so only that day of data was used for the acoustics category of the models. Table 14 shows an overall Environmental Quality Index (EQI) score for each of the models as well as a score for each of the four IEQ categories. For the first three models, the EQI was computed using Equation 3. For these three models Equation 3 was also used to compute a score for each IEQ category. For the proposed PMP model, the scores were based on compliance only.

Thus, the EQI for the proposed model is a weighted average of the individual IEQ compliance scores. The individual category scores for model 4 represent the percent of time that a particular category was in compliance.

Table 14: Summary of IEQ model scores

IEQ Model	Acoustics	IAQ	Lighting	Thermal Comfort	EQI
1. Marino et al.	46	100	37	44	62
2. Ncube et al.	97	100	62	100	93
3. Chiang et al.	50	100	95	99	86
4. Proposed PMP-based	18	100	68	79	56

The assessment class breakdown results for each model are provided in Figure 75. From Table 14 and Figure 75 we can clearly see major differences in how each model interprets the same dataset. All of the models agreed that IAQ quality was good—based purely on low CO_2 levels—but IAQ is the only category where all models agreed. Marino et al. have the strictest assessment class criteria, which are aligned with EN15251, resulting in the second lowest EQI. The proposed PMP-based model produced the lowest EQI, largely because of the low acoustics score. In this model, the acoustics category is weighted the highest (0.39) and the data are based solely on background noise measurements that were not taken according to the PMP protocol. Ncube et al. and Chiang at al. produced similar EQIs though not for the same reasons. In the Ncube et al. model, the lighting score is based on a regression equation based on the work of Saunders (1969), which ends up heavily penalizing lower light levels. Their acoustics score is also developed from previous literature, linking occupant satisfaction to background noise levels, which does not penalize high sound levels as much as the other models. Further discussion of the different models is provided in section 4.2.

While the differences in EQI scores can be understood through the individual IEQ category scores, interpretation of the EQI alone is not clear-cut. The resolution of the EQI scale (0-100) is too high for appropriate interpretation. For example, a score of 65 would not be interpreted any differently than a score of 63. Marino et al. suggest assigning EQI ranges to create “indoor quality classes” in increments of 15 points except for the highest class which is 10 points wide. Using their indoor quality classes, the building would be either a Class C (models 1 and 4), Class A (model 2), or a Class B (model 3) building. Though, as noted before, the reasons behind each models final EQI score are all unique.

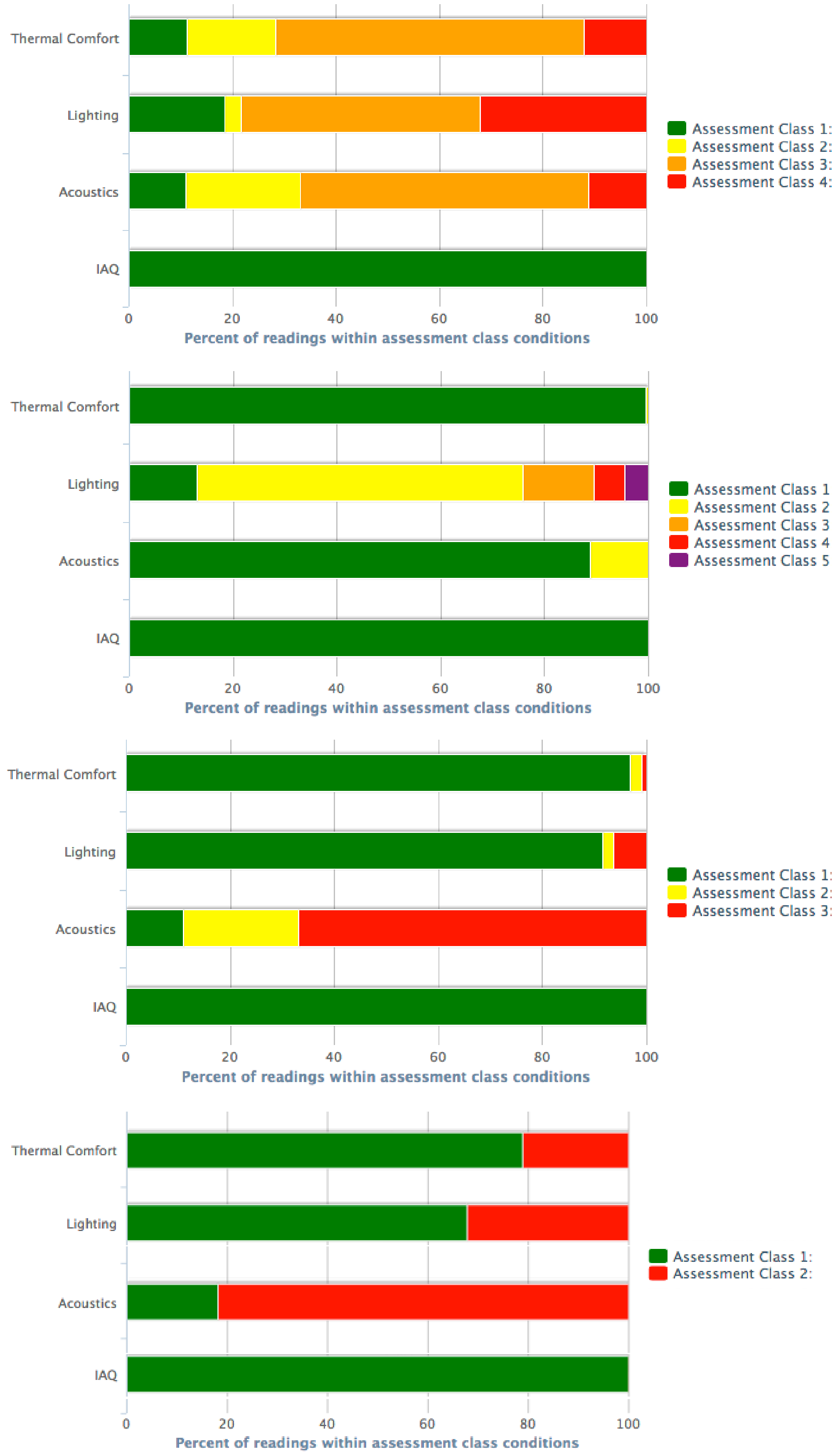


Figure 75: Performance summary models for case study data (1) Marino et al. (2) Ncube et al. (3) Chiang et al. (4) Proposed

3.7.2 Study period length sensitivity

This two-week study covered a relatively wide range of temperatures for the normally consistent San Francisco area, but is still quite temporally limited in scope. There is little agreement in the literature for appropriate study lengths, except that longer studies with higher resolution data are best. The studies and guidelines previously discussed in section 1.6 and summarized in Table 9 range from one day to 5 years in length, with most in the one day to one week range. Because IEQ scores are designed to provide an overall summary of building IEQ performance, it is important that a representative sample of data is collected. Ideally a full year of data would be collected in order to assess how the building performs over the full range of outdoor conditions; however, such monitoring lengths are often expensive. In order to briefly assess the impact of different monitoring period lengths, four different study period lengths were chosen and run through the proposed PMP-based model only. Table 15 shows the results of the different study period length tests.

Table 15: Proposed PMP-based IEQ model results for different study period lengths

Study period length	Acoustics	IAQ	Lighting	Thermal Comfort	EQI
1 day (10/9/2012)	18	100	77	86	56
2 days (10/9 - 10/10/2012)	18	100	75	77	54
1 week (10/1-10/5/2012)	18	100	63	90	53
2 weeks (full study)	18	100	68	84	54

Because the acoustics measurement period was the same in each of the tests and the CO2 level was never unacceptable, the only categories that changed during the changing time periods were lighting and thermal comfort. While there are differences between the results of the different study period lengths, these differences are not stark enough to produce different EQIs and the maximum difference within an IEQ category is 14 for lighting and 13 for thermal comfort. A study of a long term dataset, using statistical sampling methods would be required to draw conclusions concerning the length of study period required to produce a representative sample for IEQ performance summary methods. Further discussion of study period length sensitivity is provided in section 4.3.

3.7.3 Spatial density of measurements sensitivity

In addition to study length, spatial density of measurements also plays an important role in gathering a representative sample of data to run through IEQ models. While dense measurement networks are ideal, instrumentation is expensive in both material and in-field setup labor costs. The studies and guidelines previously discussed in section 1.6 and summarized in Table 9 provide a muddy picture of appropriate measurement density, depending on the parameter being studied. Because this case study covered large areas over two floors the spatial density of measurements was not high, though most space-types, all orientations, and both perimeter and interior zone-types were measured. Given the sparse density of ICMs, there is not a clear spatial breakdown (e.g. one ICM per orientation or space-type) that could be used to analyze the sensitivity of the IEQ model to spatial density. There are two ways to attempt to assess whether the spatial density of the ICMs provides a representative sample of the space: (1) compare distributions of temperature data between a large set of BMS data and the smaller set of ICM data, (2) study variation in temperature between ICMs throughout the space and within a single zone. The first method requires that the BMS sensors are calibrated. The thermostats at WSPFK were calibrated three years ago, but will be calibrated again this year, at which point this type of analysis can be completed.

The second method for assessing the spatial representativeness of the ICMs is to look at how measurements varied spatially and intuit how density may affect IEQ model results. Figure 76 shows boxplot distributions for each hour of the day representing the distribution of operative temperature across the spaces that were measured. This analysis takes the "average day" of the study period for each ICM and computes the boxplot distribution of the 15 ICMs operative temperature measurements for that hour of their average day.

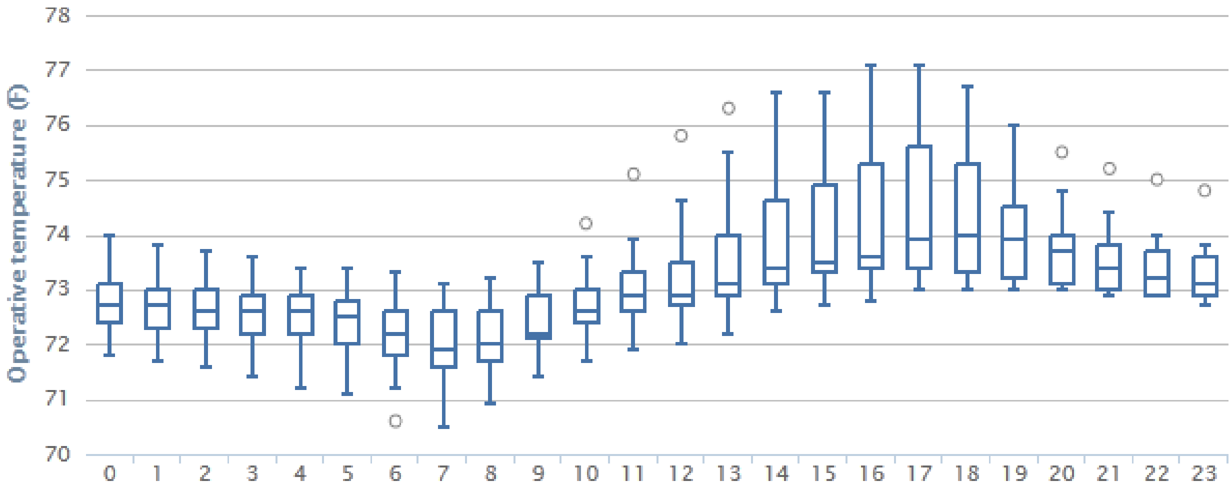


Figure 76: Spatial variation of operative temperature over study period for all ICMs

We can see that during off-hours and morning hours, the range of operative temperatures across the floor plates (both floors are represented here) are tighter than the afternoon hours, with an inter-quartile range of 1°F and range of 2°F. During the afternoon, the distribution begins to spread with inter-quartile ranges approaching 2°F and ranges near 4°F. From these boxplots we can see that the temperature can vary significantly across the floor plates, though this does not address the question of the required density within one zone. In one of the large core zones on the 5th floor, three ICMs were used. Figure 77 shows the distribution of temperatures for that one zone, using the same method as used for Figure 76. The distributions are much tighter, suggesting relative uniformity across this one large zone. The removal of one or two of the ICMs in this zone would not change the IEQ model results significantly. While this result is true for this particular zone of this study, we cannot conclude that similar behavior would exist in all zones in all buildings. One way to approach spatial density questions would be to start with high density, analyze the data, and move sensors to other locations if the variation within a zone is small.

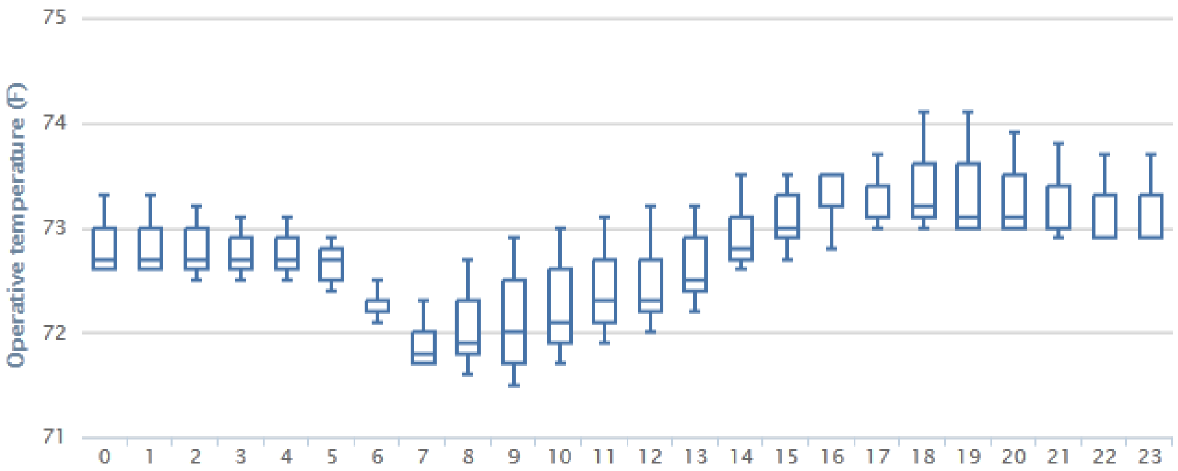


Figure 77: Spatial variation of operative temperature over study period for one zone (5_core_2)

3.7.4 IEQ category weighting sensitivity

There has been a significant effort in the literature to assess the relative importance of different IEQ categories. Thus, in order to briefly assess the impact of different IEQ category weighting schemes, four different schemes were chosen and run through only the proposed PMP-based model for the entire study period length. Table 16 shows the results of the different IEQ category weighting schemes.

Table 16: Proposed PMP-based IEQ model results for different IEQ category weighting schemes

IEQ weights	Acoustics	IAQ	Lighting	Thermal Comfort	EQI
1. Default proposed PMP-based	0.39	0.2	0.29	0.12	56
2. Equal	0.25	0.25	0.25	0.25	65
3. Marino et al.	0.19	0.34	0.23	0.24	71
4. Ncube et al.	0.16	0.3	0.18	0.36	72

The weighting schemes are listed in order of decreasing acoustics and lighting importance and conversely increasing IAQ and thermal comfort importance. The low acoustics score has the largest effect on the EQI—as the acoustics weight decreases, the EQI rises. The maximum difference in EQI scores is 18 points, which corresponds to a shift in IEQ class assignment (from class D to class C in this case). The extent to which the weighting scheme ends up playing a role in the overall interpretation of IEQ performance depends in large part on the differences in the individual IEQ category results. For example, if the acoustics score had been 80 instead of 6, the differences in EQIs with different weighting schemes would be significantly less than shown in Table 16.

3.8 *Survey results*

A CBE survey was given to the occupants at WSPFK and 50 responses (out of 114, 44%) were collected. The summary results are provided in Figure 78, 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.

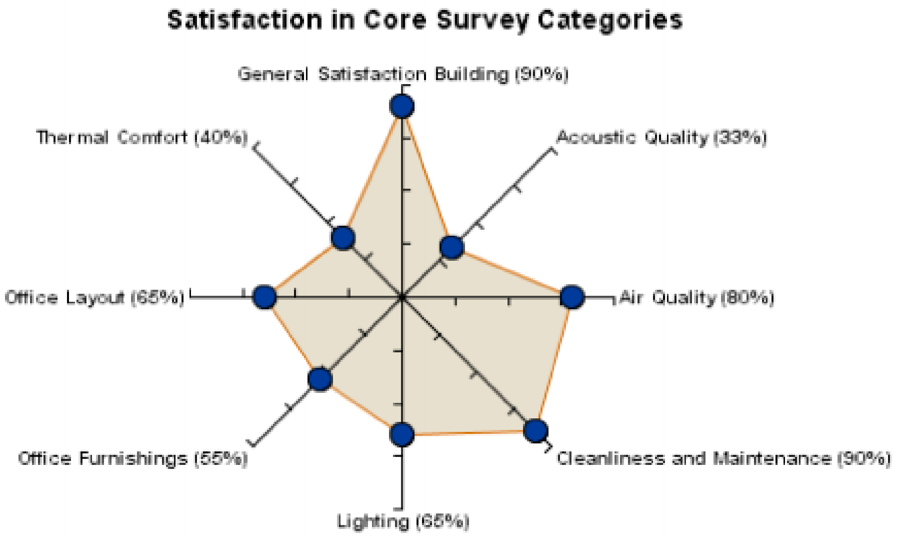


Figure 78: CBE survey summary results

3.8.1 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, which 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.

3.8.2 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% of respondents (3 people) were slightly unsatisfied with air quality. Unfortunately these respondents did not provide further information concerning the nature of their dissatisfaction.

3.8.3 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.

3.8.4 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% and 22% respectively). The cold complaints are consistent with the measured data which showed that the building was controlling to the colder end of the comfort range.

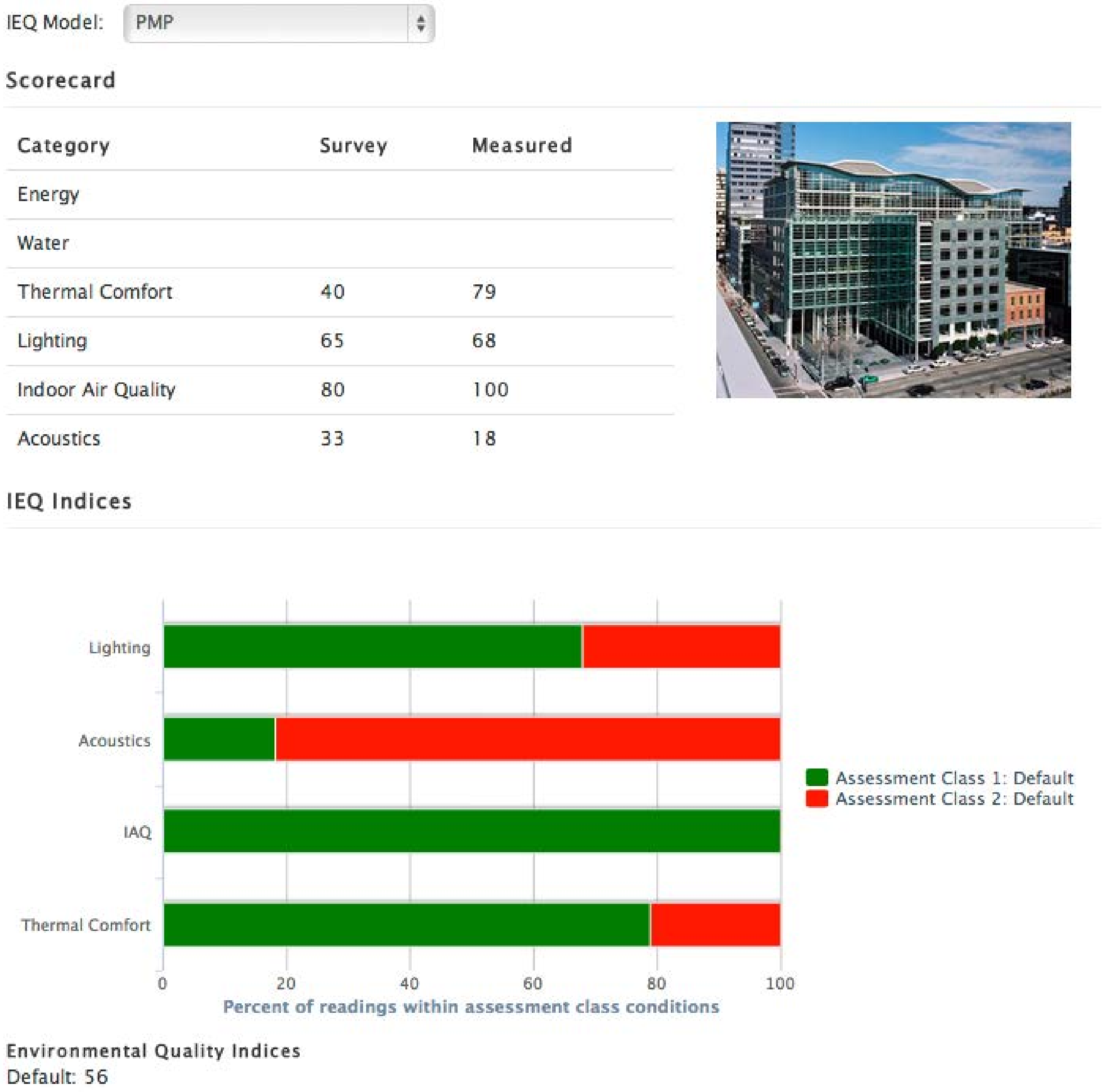
3.9 Case study conclusion

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 79 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 79: 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 Discussion

4.1 PMP critique

The Performance Measurement Protocols for Commercial Buildings represents a strong collection of methods, procedures, and knowledge surrounding evaluation of building performance. Measurement of building environmental parameters is complex and not easily proceduralized in a manner that covers all commercial buildings. Nevertheless, the existence of such protocols is an important step toward realizing a goal of increased building performance across the building stock. This section will highlight some of the specific issues with the IEQ sections of the PMP, as well as discuss how the new Best Practices Guide (BPG) (ASHRAE, 2012) serves to address some of these issues.

4.1.1 PMP vs. Best Practices Guide

The stated goal of the PMP is to facilitate appropriate comparison of measured energy, water, and IEQ performance data of commercial buildings. There are four major sections for each IEQ category at each level (Basic, Intermediate, and Advanced):

- Objective: this section provides an overview of the section objectives
- Measurement methods: this section details the type and accuracy of sensor to use, the temporal and spatial resolution to use, and how to appropriately operate the sensor.
- Metrics: this section details the specific measured or computed values that are used for evaluation.
- Evaluation/benchmarking: this section details standards or guidelines that metrics should be evaluated against or databases for benchmarking performance.

In addition to these sections there is an extensive background section that communicates the larger intent of measurements for each IEQ category. Each section of the PMP was written largely independently by experts in a particular field and tied together after-the-fact. This lack of cohesiveness becomes apparent in the varying levels of difficulty and specificity provided in the above major sections between IEQ categories, though part of this non-uniformity can be attributed to inherent complexity differences between IEQ categories. Specifically, the temporal and spatial resolutions for measurements are not typically detailed enough for practical purposes. For example, the suggestion at the Basic level of the acoustics section to measure all occupied spaces (all spaces where a human ear may hear noise) is simply untenable for a large building and a short-term study.

The Best Practices Guide (BPG) builds upon the PMP to provide facilities and operations staff processes and tools to make measurement, verification, and correction easier (ASHRAE, 2012). The guide has not been published, though a 90% draft was reviewed for the purpose of this thesis. The BPG succeeds in its goal to provide a clearer framework for implementing the processes outlined in the PMP. Like the PMP, the BPG is setup in three levels (Basic, Diagnostic, Advanced). In the BPG, the Basic IEQ sections are combined, providing a more consistent framework for evaluating performance. The Basic level is performance evaluation driven, using walkthrough checklists and surveys as the primary tools. The IEQ categories are split out at the Diagnostic and Advanced levels, which serve to supplement findings at the Basic level. Through flowcharts, checklists, and more detailed discussion, the BPG improves on the PMP in consistency and direct application as a protocol to be implemented by practitioners. However, the length and scope of some checklists are quite deep, potentially leading to a large set of documents that are not easily analyzed as a whole. Additionally, there is some overlap between checklists and an unclear recommendation for organizing and mining the data contained in the lists.

The next four sections provide a discussion of specific weaknesses in each IEQ section of the PMP, as well as whether such weaknesses are addressed in the BPG. These critiques focus on the Basic and Intermediate levels of the PMP taken together as one set of procedures for evaluating building IEQ performance.

4.1.2 Acoustics

The acoustics category requirements are in many ways the most difficult to accomplish. The acoustics category is the only category at the Basic level to require spot measurements of all occupied spaces (with an expensive tool), as well as the collection of detailed descriptive information (room finishes, location of all noise sources) for the entire building. The procedures outlined at the Basic level are also largely untenable in most situations, including the suggestion of emptying the spaces of occupants, turning off all computers, and running the HVAC system at three different levels. Additionally, the acoustics category is the only category at the Intermediate level to require a professional consultant to perform the measurement procedures. The acoustics category does not align well with the other categories in terms of relative difficulty for Basic and Intermediate procedures. If the measurement requirements at the Basic level were shifted to the Intermediate level and the Intermediate level to the Advanced level, the difficulty levels would be more consistent. This shift was implemented in the BPG, providing a more reasonable difficulty level for the intermediate steps. In fact, the Diagnostic level of the BPG appears to be nearly identical to the Basic level of the PMP. Additionally, the importance of different acoustical parameters needs better explanation (background noise vs. reverberation time vs. speech privacy). According to the CBE survey, speech privacy ranks as a top concern, and a recent CBE study suggests that it can be measured with reasonable accuracy using a simplified method (Salter & Lawrence, 2012). Such methods may allow practitioners to address occupant concerns over speech privacy without hiring an acoustical consultant.

4.1.3 IAQ

The IAQ category requirements are largely based on the verification of ASHRAE Standard 62.1 (2007) compliance. The PMP requires that ventilation rate be measured at the outside air intake of each air handler, though there is not clear guidance on proper procedures. The PMP references Fisk et al. (2006), which provides details on the accuracy of measuring outdoor air ventilation rates and suggests that some commercially available systems can provide outdoor air rate with error of 20% or less. Additionally, Fisk et al. (2008) suggests that practical accuracy of outdoor air rates of 15% can be achieved with electronic air speed probes placed between the outdoor air intake louvers or at the outlet face of the louvers. While there is literature to help practitioners measure outdoor air, the accepted recommended procedures should be detailed in the PMP, especially given that the procedures are not simple and range widely in accuracy. Unfortunately, the BPG also does not provide a reference method for measuring outdoor air.

In the summary Table 2-1 in the PMP, the Intermediate “instrumented measures” section of

IAQ suggests to measure outdoor air quality if local ambient pollutant source is suspected. However, in the written Intermediate IAQ section, the document suggests determining outdoor air quality by accessing local air quality data, which is significantly easier than measuring outdoor air quality. While minor, this table should be edited to reflect the actual requirements (the relevant tables in this thesis were edited accordingly). Additionally, in the Advanced section of this same table, the acronym "CoC" is used for contaminant of concern, which is not a standard acronym for non-IAQ experts. This same acronym is used in the IAQ sections without explanation. The introductory background section of the PMP is the only place where this acronym is defined.

Another minor point is that the *Metrics* sections of IAQ category are different than the other category *Metrics* sections in listing required measurement and reporting tasks rather than simply the parameters to be measured. The metrics sections across IEQ categories are the least consistent in information and format.

4.1.4 Lighting

One of the main concerns with the lighting sections is the lack of discussion regarding overlighting. A discussion of overlighting occurs in the energy section of the PMP, but not in the lighting sections. As daylighting mixed with advanced controls becomes more prevalent (especially in high-performance buildings), methods for assessing proper control operation need to be detailed. Illuminance measurements in the PMP are included to establish minimum light levels without discussion of maximum light levels. Luminance measurements help address occupant comfort with lighting, but again there is no mention of using luminance measurements to test for situations in which electric lighting is enabled during times of adequate daylight. Further discussion of techniques that can be used to address visual comfort and overlighting in heavily day-lit spaces are available in Konis (2012). While the PMP titles the section Daylighting/Lighting, the Lighting Checklist on page 77 and the corresponding section in the lighting appendix are the only locations where daylighting issues are addressed.

The difficulty of the Basic level of the lighting category aligns well with other categories, but the Intermediate level is overly detailed. The Intermediate level requires full-grid illuminance and luminance measurements with little justification or reasoning behind such a level of detail. The lighting appendix offers clear instruction on measurement procedures, but there is little guidance in the PMP on how to summarize and evaluate the extremely detailed nature of these measurements. Additionally, there is little guidance on handling the temporal variation of lighting in a space. While temporal and spatial parameters are recorded in detail, what to do with this information at the time of analysis is missing. Kim and Haberl (2012) suggested that continuous measurement of illuminance offers a way of addressing temporal variation in lighting quality and requested more guidance on such measurement techniques. We agree that continuous measurement offers good insight, and that such measurement is incompatible with the suggestions of the PMP, as clearly full-grid continuous measurement of illuminance and luminance is not feasible.

Finally, the nuances inherent in lighting could be communicated more effectively. The subjective and objective sections do not reference each other and discussion of occupant preference in light levels occurs only in a short discussion concerning the interpretation of survey results. A reliance on horizontal illuminance and glare discomfort ratios without corresponding occupant preference feedback can lead to a shallow interpretation of lighting performance and the potential for unnecessary recommendations. While the BPG puts the illuminance and luminance measurements into better perspective in relation to the survey results at the Basic level, it still provides a similarly cumbersome method at the Diagnostic level with little nuance and discussion of interpretation beyond IESNA recommendations.

The lighting portion of the background section of the PMP is the shortest of the IEQ categories, providing a minimal introduction to the complex subject of lighting quality, focusing on a scientific explanation of illuminance, luminance, and glare. Future editions could expand this section to reflect the complex relationships of lighting variables, which could also help provide better guidance toward interpreting measurements.

4.1.5 Thermal comfort

The thermal comfort category sections suffer some of the same issues as the other categories, including vague guidance on spatial and temporal distribution of measurements. While continuous measurement is required at the Intermediate level, no guidance is given on the required length of the study period. The Basic level provides some guidance concerning locations to measure, but the Intermediate level does not mention spatial distribution except to provide a range of possibilities (detailed workstation level measurements or BMS thermostat points). These issues are also present in the BPG.

The *Metrics* sections of the thermal comfort sections are different in scope from the other categories, providing detailed background information on the metrics and instrumentation used to capture those metrics. Other IEQ categories typically only list the specific measured variables and instead use the *Measurement methods* section to explain instrumentation and procedures. While a minor point, this lack of consistency between sections is detrimental to readability.

4.1.6 PMP critique conclusion

The PMP and upcoming BPG represent a wealth of information concerning IEQ measurement procedures; however, there is still much to improve. The critiques above come from the vantage point of a practitioner and user of the guides. Practitioners are not experts in each IEQ field, and as such, this thesis does not purport to suggest many alternatives to the procedures outlined in the PMP. Where criticisms have been made, they primarily refer to usability and feasibility of the procedures. As with all guides, the protocols will inevitably develop over time and certain experts will disagree with whichever protocol is accepted in that publication round.

All IEQ category procedures suffered to varying degrees from a lack of spatial and temporal distribution specifics. This lack of specificity is consistent with the lack of large-scale, long-term, and detailed studies that would be required to develop robust procedures with specific guidelines. The tools and methods outlined in this thesis will help make such studies possible in the future. Short of having the results of such studies, Table 17 provides a breakdown of suggested IEQ objective measurements with minimum spatial and temporal resolutions for different user needs based on our field study measurement experience. In the table, “continuous” refers to a measurement interval of at most 15 minutes, with 1 minute measurement interval preferred.

Table 17: Suggested IEQ objective measurements with minimum temporal and spatial measurement resolutions for different applications

		Commissioning agents	Designers/Operators	Owners/Raters
Intent/goal		To determine if building systems are operating as designed	To determine if system design is providing high occupant satisfaction	To determine how well the building is performing compared to other buildings and ensure high occupant satisfaction.
Acoustics	Spatial	• Background noise level (dBA_{eq}): in representative zones. In locations near noise sources (near HVAC equipment, operable windows near streets) • Speech privacy and reverberation times: in zones specified by owner/client as high priority	• Background noise level (dBA_{eq}), speech privacy, reverberation time: in zones where occupants have expressed dissatisfaction, every 20' x 20' for large zones (for background noise level)	• Background noise level (dBA_{eq}): in representative zones, every 20' x 20' for large zones. In locations near noise sources (near HVAC equipment, operable windows near streets)
	Temporal	• Background noise level (dBA_{eq}) and speech privacy: 30 second measurement periods • Reverberation time: according to PMP protocol	• Background noise level (dBA_{eq}) and speech privacy: 30 second measurement periods • Reverberation time: according to PMP protocol	• Background noise level (dBA_{eq}): 30 second measurement periods
	Comments	Background noise level is the only measurement that is required for overall evaluation. Speech privacy and reverberation time are optional tests for commissioning agents and designers/operators if there are known issues or the client wants to verify proper acoustic performance in high priority areas.		
IAQ	Spatial	• CO_2 and TVOC: in representative zones, no fewer than 20% of zones on a floor, capturing unique space types (conference room, open plan, private office, kitchen, lobby, etc.), multiple floors only if known source pollutant differences between floors (major occupancy differences, operable windows, off-gassing furniture) • Outdoor air flow: at all air handler intakes	• CO_2: in zones already monitored for demand response ventilation. In zones where occupants have expressed dissatisfaction • Outdoor air flow: at all air handler intakes	• CO_2, $PM_{2.5}$, PM_{10}: in representative zones, no fewer than 20% of zones on a floor, capturing unique space types (conference room, open plan, private office, kitchen, lobby, etc.), multiple floors only if known source pollutant differences between floors (major occupancy differences, operable windows, off-gassing furniture) • Outdoor air flow: at all air handler intakes
	Temporal	• CO_2 and TVOC: continuous measurement for 2 weeks • Outdoor air flow: series of one-time spot measurements	• CO_2: continuous measurement as long as building is operational • Outdoor air flow: series of one-time spot measurements to be repeated if HVAC system changes or is rebalanced	• CO_2, $PM_{2.5}$, PM_{10}: continuous measurement for three, 2 week periods (cooling, heating, no heat/cool seasons) • Outdoor air flow: series of one-time spot measurements

		Commissioning agents	Designers/Operators	Owners/Raters
	Comments	TVOC is included only in the commissioning agents section because total VOC concentration provides limited information about health factors, but can be useful for determining when new carpet, furniture, painted surfaces have moved beyond their off-gassing phase. PM$_{2.5}$, PM$_{10}$ are relatively expensive to measure accurately but are the most important when considering health and should thus be part of any rating system for IAQ, though are not required for normal building operation or design feedback.		
Lighting	Spatial	• Illuminance: in representative spaces, capturing all unique space types, lighting types (direct, indirect, direct/indirect, task, skylight, window, etc.), and orientations (direction glazing faces)	• Illuminance and luminance: in spaces where occupants have expressed dissatisfaction	• Illuminance and luminance: in representative spaces, capturing all unique space types, lighting types (direct, indirect, direct/indirect, task, skylight, window, etc.), and orientations (direction glazing faces)
	Temporal	• Illuminance: spot measurement (30 seconds) during nighttime with different lighting conditions (overhead light only, overhead + task light) and on a sunny day, following sun around the building as it hits different exposures (e.g. E, S, N, W)--for as many days as required to get spatial coverage (may only take one day and one night)	• Illuminance: continuous measurement for 2 weeks • Luminance: hourly HDR photographs for 2 weeks	• Illuminance: continuous measurement for four, 2 week periods (one period per season) • Luminance: hourly HDR photographs for three, 2 week periods (cooling, heating, no heat/cool seasons)
	Comments	HDR photography for capture and analysis of luminance data is recommended because it provides the simplest method for capturing a large amount of easily interpreted/analyzed data. Because illuminance measurements have a limited connection to occupant satisfaction, luminance measurements must also be part of any rating system. However, luminance is typically outside of the scope of normal lighting system commissioning, so is not included for commissioning agents.		
Thermal comfort	Spatial	• Air temperature: all thermal zones • Relative humidity (RH): no fewer than 10% of thermal zones • Globe temperature: all thermal zones for buildings with active radiant systems, and representative perimeter zones for buildings with >60% window-to-wall ratio • Air velocity: in representative zones in buildings with operative windows, no fewer than 20% of zones, multiple floors if stack effect in use	• Air temperature: all thermal zones • Globe temperature, RH, and air velocity: in zones where occupants expressed dissatisfaction	• Air temperature: all thermal zones • Globe temperature, RH, and air velocity: for buildings with active radiant systems, and representative perimeter zones for buildings with >60% window-to-wall ratio, or in other situations where air temperature and radiant temperature are different or air velocity is potentially high
	Temporal	• Indoor/outdoor air temperatures, RH, globe temperatures and air velocity: continuous measurement for three, 2 week periods (cooling, heating, no heat/cool seasons)	• Indoor/outdoor air temperatures: continuous measurement for as long as building is operational • Globe temperatures, RH, and air velocity: continuous	• Indoor/outdoor air temperatures, RH, globe temperature, and air velocity: continuous measurement for three, 2 week periods (cooling, heating, no heat/cool seasons)

		Commissioning agents	Designers/Operators	Owners/Raters
			measurement for 2 weeks in the season during which the occupants expressed dissatisfaction	
	Comments	Air temperature is typically measured in all zones continuously through the building control system. Globe temperature is used to get mean-radiant-temperature (MRT) and air velocity is used for both MRT and determining comfort conditions, especially with the adaptive comfort standard. RH tends to not vary much within the building.		

4.2 IEQ models

The concept of scoring a building according to its indoor environmental quality has not been previously well explored. This thesis has begun to scratch the surface of this exploration, but there is much more to be explored. This section will highlight issues with the IEQ models in the literature, as well as suggest further areas of research.

There are two main concerns with IEQ models as they have been presented in the literature and implemented in the Toolkit. Some of these concerns were addressed previously in section 2.2.6.1 but will be discussed in more detail here:

1. There are limited guidelines on appropriate use of IEQ models.
    a. What measurement protocols need to be followed, including temporal and spatial resolution and sensor accuracy?
    b. How should the results be interpreted—can results between buildings be directly compared?
2. Assessment class limits are not always aligned with occupant satisfaction and justification for certain limits is often minimal.

4.2.1 Limited guidance on appropriate use of IEQ models

An important component in appropriate use of IEQ models is the establishment of accepted measurement protocols. The PMP has provided a strong starting point for such protocols. However, in its current state, there are large holes when looked at from the perspective of a cohesive set of protocols for the purposes of strict evaluation of IEQ via a model approach such as those explored in this thesis.

Clear and consistent temporal and spatial measurement resolutions need to be established and proceduralized in order to ensure representative datasets are used for analysis through IEQ models. These procedures will require development over time through large, long-term studies of IEQ parameters that are matched to occupant survey data. In the PMP, summary tables of instrumentation accuracy and calibration requirements should be developed in order to ensure high quality instrumentation. Such information is available in each corresponding section of the PMP, though there is not a quick way of obtaining this information without going through the entire book. Without a cohesive set of measurement protocols, IEQ models cannot be appropriately compared between buildings. While IEQ models are still useful for providing an overall evaluative picture of a building, they cannot yet be reliably used as a true scorecard, rating, or to build a database for benchmarking, such as EnergyStar.

4.2.2 Assessment class limits are controversial

The problems associated with assessment class limits have been discussed at length in this thesis (sections 1.4.1, 1.4.3, 1.5.2, 2.2.6, 3.7.1). Class limits provide a method for summarizing large amounts of data by creating large bins to separate the data into. A recent application and evaluation of EN15251-2007 categories of IEQ assessment (classes) suggests that the bins are not intended to force the operation of a building into certain class limits, but rather to evaluate how the distribution of performance among classes changes over the course of a year (Raimondo, Corgnati, & Olesen, 2012). Regardless of the intention, binning data raises the problem of the decisions involved in defining the bins and the conclusions that will be drawn from those decisions. Divorced from evaluative meaning (e.g. class I = highest quality or tightest control), there appears to be little value in the use of assessment class binning. The binning is too coarse and separated from temporal and spatial information to provide any meaningful analysis of changing conditions over a year except to say that conditions do change over the year. At this point, not enough guidance exists in the IEQ standards/guidelines or research community to justify the definition of precise boundaries for assessment classes.

The studies previously discussed and summarized in Table 7 all made decisions on how to define the limits of assessment classes—many based on previous attempts to correlate objective measurements to occupant preferences. However, such regression models can lead to the creation of class limits with expensive measurement accuracy requirements (such as the < 0.15 m/s air speed requirement in the Marino et al. model). A direct link to occupant satisfaction is indeed the most promising approach to assessment classes; however, sufficient research has not been conducted to be able to reliably link objective measurements to subjective satisfaction responses—which makes sense. Occupant satisfaction is a complex mix of inter-related variables that are not easily segmented, categorized, and measured objectively. Research has come a long way into understanding and predicting occupant satisfaction through the use of objective variables (environmental and cultural parameters), though recent research has trended towards broadening the limits of acceptable conditions rather than tightening (adaptive comfort standard, decreasing IESNA illuminance recommendations, increased prevalence of open plan offices without acoustical privacy). In understanding that conditions that are acceptable to occupants will encompass a range of values for most environmental parameters, there seems to be more value in agreement on the division of acceptable and unacceptable conditions rather than gradations of both. Such thinking informed the decision to make our proposed IEQ model based solely on compliance with the relative standards or guidelines outlined in the PMP.

IEQ models have potential to be a motivator for designers, operators, and building owners. IEQ measurement can help discover and correct problems, but when such measurements are implemented in a standardized fashion, IEQ models have the power to transform the measurements into scores that can be used in ratings and standards. Such standardized procedures that would enable more appropriate use of IEQ models are not necessarily far off with improved revisions to the PMP and REHVA Indoor Climate Quality Assessment guidebooks. That said, designers, operators, and owners will gain more from the analyses that such data collection enables, which is why the effort to develop an easy-to-use, powerful, and cost-effective toolkit has been the primary focus of this project and is further discussed in the next few sections.

4.3 Toolkit

The development of the Toolkit represented the bulk of the work of this thesis project. The next few sections detail some of the issues surrounding the hardware and software elements of the Toolkit. Additionally, there is a short discussion of the steps that would need to be taken to make the Toolkit viable as a product.

4.3.1 Hardware and procedures

The Toolkit hardware was designed to be easy to use, accurate, and reliable. The wireless mesh network system is the key component to making sensor deployment and data collection fast. In an open plan office, the density of wireless devices does not need to be high because there is little radio frequency (RF) interference. However, the density of devices required to maintain a robust network in a more challenging environment tends to align with the density of sensors that would be ideal for achieving good spatial coverage for performance measurement. In other words, the RF interference is largely not an issue in the deployment of these sensor networks. There are two key exceptions to this observation: (1) moving sensors, (2) underfloor diffusers that are metal cages. In the case of moving sensors (the PUCC and the sound level meter), when the device is moved to a new location, the onboard wireless motes may need time to associate themselves with the motes in the network that are closest. This adjustment of the network can happen seamlessly, but may require intervention from the user, increasing deployment time and potential for lost data (e.g. if the PUCC operator does not realize that connection has been lost after movement). The case study at WSPFK and others not mentioned in this thesis provide ample evidence that this issue of network rearrangement is not an insurmountable issue. For underfloor systems, wireless motes have difficulty making connection through metal floor diffusers because of a Faraday cage effect. Previous experience suggests that hanging the motes from the bottom of the diffuser cage (using a hook or wire) solves the problem.

Cost is 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 are now offering wireless versions of their sensors. Onset's wireless sensors come at a premium of approximately $100 over their logging counterparts. Solutions with combined sensors on one wireless device are ideal, and a four-channel wireless device from Onset is $220 at the time of this publication, which represents a reasonably priced solution for building ICM or PUCC devices ("Wireless HOBO Data Loggers & Sensors: ZW Series by Onset," n.d.). We believe that ICM and PUCC wireless devices could be made at quantity for reasonable cost. Consulting firms interested in the Toolkit suggested that an overall price of $10,000 would be a reasonable investment for the purposes of IEQ performance evaluation. We feel that a system with 20 ICMs and 10 standalone motes could be built within this budget. The intent of this section is not to outline the viability of such a business proposal, but rather to estimate that the cost of such a system is within range of what companies suggest they are willing to pay for.

The procedures involved in the Toolkit deployment were largely successful at reducing deployment overhead. Through defining device instances at the time of deployment, all metadata is captured in the database and metadata/data relationships can be used during the analysis phase. While defining device instances at the time of deployment has the advantage of being a one-step process, we still choose to record the same information on paper versions of the gridded zoning map during deployment as a backup. Even with this double recording of metadata information, significant time is saved by the built in structure that relates the wireless sensors to the correct spatial/temporal metadata. In a traditional logging system, the metadata must be recorded when the logger is placed, and then associated with the specific file that is later downloaded from the device. This procedure generally takes the form of a network of Excel or CSV files that must be assembled into one database, which can take a considerable amount of time.

Map-based metadata entry is the one element of the Toolkit procedures that was not implemented in time for this thesis. This feature is discussed in section 4.4. Its functionality rests upon the metadata/data relational database that was designed as the backbone for the Toolkit procedures, but provides a more convenient method for defining the location of sensors rather than the manual grid method described in section 2.2.2. Current work on building imaging systems could also play a role in future Toolkit-like deployments to assist with map-based procedures (T. Liu et al., 2010).

4.3.2 Software

The Toolkit web analysis and reporting components were designed to minimize the time it takes to reach conclusions from data analysis. The Toolkit succeeds in providing a framework for quick analysis through a standardized method of retrieving, filtering, and charting data. The analysis component is not meant to be generalized analysis software that relies on the user to design charts, but rather a set of charts that are tailored to quick analysis of the data that is collected using the Toolkit hardware. In this sense, the analysis capabilities of the Toolkit are inherently limited, though additional analysis types could (will) be easily added in the future.

In the case study at WSPFK, multiple issues with the Toolkit software were discovered and fixed. Additionally, improvements were made based on suggestions from the users. Most of these issues were bugs in the software that needed to be corrected, but others included usability suggestions, such as the ability to create default templates for use in defining zones. A more detailed compilation of user opinions and suggestions will be provided in a separate report on this project, but was not complete in time for the publication of this thesis.

There are many improvements and feature additions that can be made to the Toolkit software in the future. One of the least developed sections of the Toolkit web interface is the scorecard section. The goal of the scorecard page is to provide the ability to quickly generate a PDF or print of a scorecard with enough background information to communicate a summary of the building's performance that users can decipher and use. While the current page is a step toward this goal, more work needs to be done to clarify and supplement the information that is currently provided. Additionally, the automation of the creation of a detailed performance report needs to be designed and implemented. Other potential improvements to the Toolkit software are discussed in the next two sections. Additionally, a list of bugs and feature requests are available at the source-code repository: http://code.google.com/p/cbesmap/issues/list.

4.3.3 Steps 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 look at some of the immediate needs on a path toward commercialization. The primary driver toward commercialization is ensuring that features add value for the users. A primary barrier to IEQ measurement as standard practice has been unclear value for owners. With decreased hardware costs and labor costs associated with data collection and analysis, we feel that IEQ measurement systems such as the Toolkit have potential to generate market interest. Future work showing connections between occupant satisfaction with indoor environmental quality and productivity and retention rates would help drive market feasibility. Other avenues toward improving market feasibility include required IEQ monitoring in high performance building rating systems, as well as solutions that enhance the workflows of building operators and commissioning agents. To move toward these goals, the primary steps involve improving ease-of-use, reliability, and cost of the Toolkit.

Ease-of-use

- Provide help links on all major elements of the Toolkit frontend. Also provide detailed documentation and video help tutorials for hardware devices.
- Obtain feedback from users of the software and implement desired feature requests and fixes. Different user types (commissioning agents, designers, operators, raters, and owners) will have different needs that need to be addressed. What features make each job workflow easier?
- Fail intelligently—error messages that direct a user to what might have happened wrong.
- Create smaller devices that can run for extended periods of time with a subset of sensors on battery power only.

Reliability

- When a sensor fails (runs out of batteries, reads garbage values, etc.) the system should recognize these events and fail intelligently (alert the user, flag entries in the database, etc.)
- When a network connection is lost, the software should buffer appropriately and upload data when connection is reestablished. This feature exists now, but a manual step is required upon reconnection.
- Steps for recovery from a failure should be simple (e.g. click a button to reset) and well-documented.
- Establish a detailed protocol for keeping sensors calibrated, including schedules and procedures.

Cost

- Reductions in cost come with scale as well as moving more sensors to be chip-level components. There are tradeoffs between accuracy, cost, size, and power usage that need to be analyzed by experts in sensor technologies.

4.4 Future work

The primary objective of this project was to develop a toolkit that could be used in the analysis and evaluation of commercial building indoor environmental quality. This objective has largely been met, though there are still many avenues for future work.

One of the most pressing needs for future development is to continue work into reducing the burden of collecting metadata. Collection of sensor data has been greatly simplified through the use of wireless systems and the sMAP web-based collection system coupled with BMS data. However, collecting the metadata that describes such sensor data still requires steps that could be eliminated. An immediate future work task is to implement a map-based input system for sensor metadata similar to the one described by Loftness & Aziz (Loftness & Aziz, n.d.). Such a system eliminates the manual process of finding a grid location on a map and entering that location in the database. Instead, this process is done by touching the location on the map where you want to add a sensor. Map-based methods also allow improved analysis and visualization capabilities. Automated contour maps of sensor data across a floor plan can greatly enhance a quick understanding of spatial and temporal variation of a parameter.

In addition to map-based input and output methods, there is room for future work in automating relationship building between building control components. While mechanical plans can be studied to understand how air handling units, fan coil units, and variable air volume boxes work together, these relationships are often opaque in BMS control point lists. Recent work in the computer science field aims to tackle this issue (Krioukov, Fierro, Kitaev, & Culler, 2012). Future progress in this research could enable simpler and more powerful analysis of relationships between building control elements and environmental conditions.

There is also a need for development work to bring both software and hardware platforms created for this project beyond a prototype phase. The web-based software was designed to be easily configurable and improved. The analysis methods currently in place are powerful, but important methods are missing (e.g. percentile analysis of acoustics results) and the reliability and usability of current methods could be improved. The hardware components of the Toolkit are one-off designs that need development to reduce cost and size. For the ICMs, developing boards with embedded sensors could easily reduce cost and size. Hardware development is an expensive process and the level of development completed for this project is likely enough to pass onto large data collection hardware manufacturers like Onset to develop further.

Beyond software and hardware enhancements for improving data collection and analysis processes, the protocols for the what, when, and where of IEQ parameters needs further research. The issues of temporal and spatial resolution requirements need extensive exploration. Additionally, in its current implementation, the Toolkit has limited capabilities for evaluating lighting, acoustics, and indoor air quality. Further exploration of some of the more complex procedures outlined in the PMP (and beyond the PMP) with the explicit goal to simplify and streamline could greatly enhance the capabilities of the Toolkit in these IEQ categories. The work of Konis (2012) for evaluating lighting and daylighting comfort, quality, and energy needs to be studied more carefully and implemented into the Toolkit framework.

This thesis has focused almost exclusively on objective measurements, though the PMP includes extensive descriptive information collection requirements as well as subjective measurement requirements, especially at the Basic level. This background descriptive information about a building is often critical to understanding the operation and performance, but can be difficult to obtain and keep organized. Future work will include better methods for storing such descriptive information and better adherence to these PMP requirements, including the addition of “right-now” survey data linked to objective measures. The upcoming Best Practices Guide provides a better model for collecting and organizing such descriptive data.

Finally, perhaps the most promising avenue of future research lies in ongoing development and analysis of IEQ models. Sensitivities need analysis using large datasets and multiple building comparisons need to be completed. Assessment class limits need further exploration alongside a wider discussion with building sector constituents.

5 Conclusion

There were four main objectives for this thesis:

1. Develop a hardware and software toolkit for facilitating the evaluation of IEQ performance in commercial buildings based on the ASHRAE/CIBSE/USGBC Performance Measurement Protocols
2. Evaluate the success of the Toolkit through a case study
3. Explore IEQ models as a method for rating IEQ performance
4. Provide an example implementation of the PMP and suggestions for improvement

A toolkit with both hardware and software elements was designed for practitioners around the requirements of the PMP. This toolkit was evaluated through a case study at the San Francisco office of WSP Flack and Kurtz. This case study highlighted strengths and weaknesses of the toolkit and led to suggestions for improvement and areas for future research. As part of the toolkit and case study, multiple IEQ models were implemented and explored as a method for reducing data for the purposes of a scorecard or rating system. Finally a thorough investigation, implementation, and critique of the Performance Measurement Protocols were performed.

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7 Appendix A - ICM sensors

- Thermistors:
  - Manufacturer: US Sensor Corp
  - Part number: USP12574
  - Specifications:
    - Resistance: 10,000 Ω
    - Accuracy: ± 0.10°F (± 0.056°C)
- Humidity
  - Manufacturer: Mamac
  - Part number: HU-921
  - Specifications:
    - Accuracy: ± 3% over 30-70% RH, temperature compensated
    - Power: 12-40 VDC
    - Output: 0-10 V
- CO2 sensor:
  - Manufacturer: CO_2Meter.com
  - Part number: K-30 SE-0018
  - Specifications:
    - Warm-up time: < 1 min
    - Range: 0 -10,000 ppm_{vol}
    - Response time: 20 sec diffusion time
    - Sensitivity: ± 20 ppm ± 1% of measured value
    - Accuracy: ± 30 ppm ± 3% of measured value
    - Pressure dependence: ± 1.6% reading per kPa deviation from 100 kPa
    - Power input: 4.5-14 V
    - Current consumption: 40 mA average
    - Digital/Analog conversion accuracy: ± 2% of reading ± 20 mV
- Illuminance sensor:
  - Manufacturer: Licor
  - Part number: LI-210
  - Specifications:
    - Absolute calibration: ± 5%
    - Sensitivity: 30 μA per 100 klux
    - Linearity: Maximum deviation of 1% up to 100 klux
    - Stability: < ± 2% change over 1 year
    - Cosine correction: Cosine corrected up to 80° angle of incidence
- Anemometer:
  - Manufacturer: Cambridge AccuSense, Inc.
  - Part number: AVS-1000 (AVS1012D0N161)
  - Specifications
    - 10-16 VDC supply
    - Non-directional
    - 0 -2.5 m/s calibration range
    - 0-5 V output

8 Appendix B – PUCC sensors

- Thermistors:
    - Manufacturer: US Sensor Corp
    - Part number: USP10850
    - Specifications:
        - Resistance: 10,000 Ω
        - Accuracy: ± 0.10°F (± 0.056°C)
- Pressure:
    - Manufacturer: Setra
    - Part number: 267
    - Specifications:
        - Accuracy: ± 1% FS
        - Non-linearity: ± 0.98% FS
        - Non-repeatability: 0.1% FS
        - Output: 0-10 V
        - Power input: 13-42 VDC
- Infrared temperature:
    - Manufacturer: Omega
    - Part number: OS137
    - Specifications:
        - Temperature range: 0-100°C
        - Accuracy: @22°C 1.5% of reading or 2°C whichever greater
        - Repeatability: 1% of reading or 1°C whichever greater
        - Field of view: 10 to 1
        - Power: 12-24 VDC @ 50 mA
        - Output: 0-10 V