METHODOLOGY FOR RATING A BUILDING'S OVERALL PERFORMANCE BASED ON THE ASHRAE/CIBSE/USGBC PERFORMANCE MEASUREMENT PROTOCOLS FOR COMMERCIAL BUILDINGS

A Dissertation

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ABSTRACT

This study developed and applied a field test to evaluate the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE)/Chartered Institute of Building Services Engineers (CIBSE)/United States Green Building Council (USGBC) Performance Measurement Protocols (PMP) for Commercial Buildings in a case-study office building in central Texas. As the first integrated protocol on building performance measurement, the ASHRAE PMP accomplished its goal of providing the standardized protocols for measuring and comparing the overall performance of a building, including energy, water, thermal comfort, Indoor Air Quality (IAQ), lighting, and acoustics. However, several areas for improvement were identified such as conflicting results from different procedures or benchmarks provided in the ASHRAE PMP; limited guidelines for performing the measurements; lack of detailed modeling techniques, graphical indices, and clear benchmarks; and some practical issues (i.e., high cost requirements and time-intensive procedures). All these observations are listed as the forty issues, including thirteen for energy, five for water, and twenty-two for Indoor Environmental Quality (IEQ).

Recommendations were developed for each issue identified. For the selected high-priority issues, twelve new or modified approaches were proposed and then evaluated against the existing procedures in the ASHRAE PMP. Of these twelve new or modified approaches, the following are the most significant developments: a more accurate monthly energy use regression model including occupancy; a monthly water use regression model for a weather-normalized comparison of measured water performance; a method how to use a vertical temperature profile to evaluate room air circulation; a method how to use LCeq – LAeq difference as a low-cost alternative to estimate low frequency noise annoyance; a statistical decomposition method of time-varying distribution of indices; and a real-time wireless IEQ monitoring system for the continuous IEQ measurements.

The application of the forty recommendations and the twelve new or modified approaches developed in this study to the ASHRAE PMP is expected to improve the applicability of the ASHRAE PMP, which aligns the overall purpose of this study. Finally, this study developed a new single figure-of-merit rating system based on the ASHRAE PMP procedures. The developed rating system is expected to improve the usability of the protocols.

I dedicate this dissertation to my father Sooyoung Kim.

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NOMENCLATURE

3-P	Three-Parameter
3-P MVR	Three-Parameter Multi-Variable Regression
4-P	Four-Parameter
ABEL	ASHRAE Building Energy Labeling
AHRI	Air-Conditioning, Heating, and Refrigeration Institute
AHU	Air Handling Unit
AMCA	Air Movement and Control Association International
ASA	Acoustical Society of America
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
ASOS	Automated Surface Observation Station
ASTM	American Society of Testing and Materials
AWWA	American Water Works Association
BASE	Building Assessment Survey and Evaluation
BLS	Bureau of Labor Statistics
BOHS	British Occupational Hygiene Society
BRI	Building-Related Illness
BUS	Building Use Studies
CBE	Center for the Built Environment
CBECS	Commercial Building Energy Consumption Survey
CDWR	California Department of Water Resources
CET	Corrected Effective Temperature
CIBSE	Chartered Institute of Building Services Engineers
CIE	International Commission on Illumination
CO	Carbon Monoxide
CO_2	Carbon Dioxide
COP	Coefficient of Performance
COV	Change of Value
CP	Change-Point
CS	Cooling Slope

CV-RMSE	Coefficient of Variation of the Root Mean Square Error
DAS	Data Acquisition System
DEC	Display Energy Certificates
DOE	Department of Energy
DOL	Department of Labor
ECI	Energy Cost Index
ECWT	Entering Condenser Water Temperatures
ELCAP	End-Use Load and Consumer Assessment Program
ELF	Electrical Load Factor
EMCS	Energy Management and Control Systems
EP	Energy Performance
EPA	Environmental Protection Agency
EPC	Energy Performance Certificate
Eqt	Equivalent Temperature
EqW	Equivalent Warmth
ESI	Equivalent Sphere Illumination
ESPC	Energy Savings Performance Contract
ET	Effective Temperature
EU EPBD	European Union Energy Performance of Buildings Directive
EUI	Energy Use Index
FEMP	Federal Energy Management Program
FOM	Figure-Of-Merit
HCHO	Formaldehyde
HDR	High Dynamic Range
HS	Heating Slope
HVAC	Heating, Ventilation, and Air-Conditioning
IAQ	Indoor Air Quality
IEQ	Indoor Environmental Quality
IES	Illuminating Engineering Society
IESNA	Illuminating Engineering Society of North America
IMT	Inverse Modeling Toolkit
IPLV	Integrated Part Load Value

IPMVP	International Performance Measurement and Verification Protocol
IQR	Interquartile Range
ISO	International Organization for Standardization
LAeq	A-Weighted Equivalent Sound Pressure Level
LCeq	C-Weighted Equivalent Sound Pressure Level
M&V	Measurement and Verification
MCC	Motor Control Center
MRT	Mean Radiant Temperature
NAC	Normalized Annual Consumption
NC	Noise Criteria
NCB	Balanced Noise Criteria
NCDC	National Climatic Data Center
NDB	Net Determination Bias
NEMVP	North American Energy Measurement and Verification Protocol
NIOSH	National Institute for Occupational Safety and Health
NOAA	National Oceanic and Atmospheric Administration
NPLV	Non-Standard Part Load Value
NREL	National Renewable Energy Laboratory
NWS	National Weather Service
OA	Outdoor Air
O&M	Operation and Maintenance
OBE	Office Building Electricity
OEW	Occupational Employment and Wages Survey
OLF	Occupant Load Factor
ORIA	Office of Radiation and Indoor Air
OSHA	Occupational Safety and Health Administration
OT	Operative Temperature
PMP	Performance Measurement Protocols
PMV	Predicted Mean Vote
$PM_{2.5}$	Particulate Matter with a Diameter up to 2.5 micrometers
PM_{10}	Particulate Matter with a Diameter up to 10 micrometers
PPD	Predicted Percentage Dissatisfied

PPHD	Predicted Percentage of Hours Dissatisfied
PRISM	Princeton Scorekeeping Method
R^2	Coefficient of Determination
RC	Room Criteria
RCR	Room Cavity Ratio
RCS	Residential Conservation Service
RS	Right Slope
RT	Resultant Temperature
RTD	Resistance Temperature Detector
SBS	Sick Building Syndrome
SCATs	Smart Controls and Thermal Comfort
SDVAV	Single Duct Variable Air Volume
SPL	Sound Pressure Level
STB	Solar Test Bench
T_{hourly}	Monthly Average of Hourly Outdoor Temperatures
T_{max}	Monthly Average of Daily Maximum Outdoor Temperatures
T_{max_24hour}	Monthly Maximum Daily 24-Hour Average Outdoor Temperature
T_{max_minmax}	Monthly Maximum Daily Min-Max Average Outdoor Temperature
$T_{max\_monthly}$	Monthly Maximum Outdoor Temperature
T_{min}	Monthly Average of Daily Minimum Outdoor Temperatures
T_{minmax}	Monthly Average of Daily Minimum and Maximum Outdoor Temperatures
TLV	Threshold Limit Value
TMY2	Typical Meteorological Year Version 2
TVOCs	Total Volatile Organic Compounds
USGBC	United States Green Building Council, Washington
VCP	Visual Comfort Probability
VDC	Verein Deutscher Ingenieure (The Association of German Engineers)
VFD	Variable Frequency Drive
WBE	Whole-Building Electricity
WCI	Water Cost Index
WUI	Water Use Index

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CHAPTER I
INTRODUCTION

1.1. Background

Currently, buildings consume energy and water to provide comfortable, safe living conditions for their occupants. Recent efforts to design energy and resource efficient buildings that have comfortable, safe, healthy and productive indoor environments have been referred to as green, sustainable, or high-performance buildings. However, many of these claims cannot be verified without an on-site evaluation of the building's performance, including energy, water, and indoor environmental quality (IEQ). Such an on-site evaluation of a building's performance would verify the building's design intent and help to inform ways to reduce a building's consumption of energy and water while maintaining acceptable levels of IEQ. To accomplish this, a standardized and effective protocol is necessary to evaluate a building's performance. One recent effort to develop such protocols is the ASHRAE[1]/CIBSE[2]/USGBC[3] Performance Measurement Protocols (PMP) for Commercial Buildings (ASHRAE 2010a). The use of such protocols could verify many of the claims made by green building designs.

A number of guidelines, protocols and standards for building performance measurements have been previously published, including the North American Energy Measurement and Verification Protocol (NEMVP) (DOE, 1996), the International Performance Measurement and Verification Protocol (IPMVP) (EVO 2009; DOE 2002b), ASHRAE Guideline 14-2002 (ASHRAE 2002) for energy, ASHRAE Standard 55-2010 (ASHRAE 2010c) for thermal comfort, and ASHRAE Standard 62.1-2010 (ASHRAE 2010d) for indoor air quality. These guidelines have focused on specific aspects of building performance rather than on an overall performance rating. However, since building systems are interrelated, an occupants' assessment of comfort is often influenced by their experience in a complex indoor environment, including: thermal, indoor air quality (IAQ), lighting, and acoustics. Thus, as the first integrated protocol on building performance measurement, the ASHRAE PMP is expected to be used as a tool to identify building performance-related problems and to verify green building practices.

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[1] American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta, GA.
[2] Chartered Institute of Building Services Engineers, London, England.
[3] United States Green Building Council, Washington, D.C.

However, the ASHRAE PMP is still in its early stages and needs to be tested in a real building to demonstrate its applicability.

In recent years, there have been efforts to label a building's performance to compare the performance of one building with other similar buildings: including the U.S. Environmental Protection Agency (EPA) ENERGY STAR (EPA 2010a); the ASHRAE Building Energy Labeling (ABEL) (ASHRAE 2010b); and the European Union (EU) Energy Performance of Buildings Directive (EPBD) (European Commission 2010). Building energy use disclosure or labeling is already mandatory in several places, including the European Union (EU Directive 2003), Australia (DEWHA. 2009), California (CEC 2007), Washington, D.C. (District of Columbia 2008), and Austin, Texas (City of Austin 2008). However, these labeling programs focus on a single attribute of a building performance, energy use, rather than on an overall building performance. While these single attribute labeling systems allow easy comparisons between peer groups, there remains a need for a new, overall building performance labeling system or methodology that can provide detailed, overall information on building performance, including energy use, water use, and IEQ performance.

1.2. Purpose and Objectives

The purpose of the proposed study is to improve the applicability of the ASHRAE/CIBSE/USGBC Performance Measurement Protocols (PMP) for Commercial Buildings and to develop recommendations for a figure-of-merit for rating a building's overall performance based on the ASHRAE PMP. The objectives of the proposed study are:

1) To develop a field test of the ASHRAE PMP and apply it to a case-study office building;
2) To evaluate the applicability of the three levels of measurement approaches in the ASHRAE PMP using the field test results from the case-study building;
3) To propose new or modified approaches to improve the ASHRAE PMP based on the results of the field test; and
4) To develop recommendations for a figure-of-merit for rating a building's overall performance based on the application of all the ASHRAE PMP procedures.

1.3. Organization of the Dissertation

This dissertation is organized into eight chapters.

Chapter I introduces the background and the purpose and objectives of the research.

Chapter II reviews literature related to this research, including: previous studies on building performance measurements for each performance category (i.e., energy use, water use, thermal comfort, indoor air quality, lighting, and acoustics); a review of the ASHRAE/CIBSE/USGBC Performance Measurement Protocols (PMP) for Commercial Buildings; and a review of several building performance labeling programs for the existing commercial buildings.

Chapter III discusses the significance and the limitations of the research.

Chapter IV describes the methodology used to address each phase of this research, including: Phase I Field test of the ASHRAE PMP; Phase II Proposed new or modified approaches to improve the ASHRAE PMP; and Phase III Recommendations for a figure-of-merit for rating a building's overall performance based on the ASHRAE PMP.

Chapter V presents the results of Phase I Field Test of the ASHRAE PMP for each performance area of each level of the protocols, including: energy use, water use, and IEQ (i.e., thermal comfort, IAQ, lighting, and acoustics).

Chapter VI presents the results of Phase II: Proposed New or Modified Approaches to Improve the ASHRAE PMP, including: an overall summary of findings from the field test with the recommendations for each issue identified; discussions on the applicability of the three levels of measurement approaches in the ASHRAE PMP; and new or modified approaches to twelve selected issues to improve the current version of the ASHRAE PMP.

Chapter VII presents the results of Phase III: Recommendations for a New Figure-of-Merit Rating System, including: a single figure-of-merit rating system based on above-average percentage scores or percentile rank of scores that are separately calculated for six performance areas (i.e., energy use, water use, thermal comfort, IAQ, lighting, and acoustics); and the ideas for a future figure-of-merit rating system based on Predicted Percentage of Hours Dissatisfied (PPHD %) for IEQ instrumented measurements or cost.

Finally, Chapter VIII summarizes this research and discusses the recommendations for the future research.

CHAPTER II
LITERATURE REVIEW

This chapter reviews the previous studies on building performance measurements for each performance category (i.e., energy use, water use, thermal comfort, indoor air quality, lighting, and acoustics), examines the ASHRAE/CIBSE/USGBC Performance Measurement Protocols (PMP) for Commercial Buildings, including comparisons with other existing procedures of building performance measurement, and explores the building performance labeling programs for the existing commercial buildings.

2.1. Previous Studies on Building Performance Measurements

2.1.1. *Energy Use*

2.1.1.1. <u>Overview</u>

With the spread of electricity and natural gas into cities and buildings, the measurement of building energy use started at the end of the 19th century by the energy providers to compensate the cost of its production and distribution (Haberl and Culp 2009). The early history of building energy measurements paralleled the development of measurement and verification (M&V) procedures of building energy use. In the 1970s, the M&V of building energy use was mostly conducted by simply comparing monthly utility bills against bills from previous months under similar weather condition.

In the United States, as a part of the Federal Residential Conservation Service (RCS), extensive home energy audits and retrofit assistance programs for residential buildings were undertaken by utilities beginning in 1981 (Hirst 1984), which accelerated the need for a reliable M&V method of building energy use (Fels 1986).

Early efforts toward standardizing the methods for the evaluation of building energy use were made separately for residential and commercial applications. For residential buildings, one of the most widely recognized techniques developed during this period was the Princeton Scorekeeping Method (PRISM). PRISM is a degree-day-based weather normalization technique that is a widely used method for evaluating the weather-normalized residential heating energy savings from before-after utility billing data (Socolow 1978; Fels 1986). For commercial buildings, multiple approaches have been proposed that use significantly different analysis methods (Rabl et al. 1986; Eto 1988; Haberl and Vajda 1988b; Reiter 1986).

In the earliest of these, Rabl et al. (1986) examined the applicability of PRISM in commercial buildings and found that the PRISM model can be successful for commercial buildings when the base loads do not vary independently of ambient temperature. Eto (1988) also examined the applicability of degree-day-based weather normalization techniques in office buildings and found that these techniques perform well at predicting energy use for the office buildings with an accuracy better than 10%. Haberl and Vajda (1988b) reported daily and hourly methods to account for occupancy variable and showed how to apply these techniques to detect over-consuming practices using two case-study buildings. Reiter (1986) examined the interaction between scheduling and end-use load shapes for commercial applications and showed that scheduling is the key determinants of the commercial building load shapes. MacDonald and Wasserman (1988) reviewed the energy data analysis methods used in 45 published papers and developed five general categories, including: annual total energy and energy intensity comparisons, simple linear regression and component models, multiple regression models, building simulation programs, and dynamic thermal performance models.

There are two main different approaches in commercial building energy performance analysis: forward and inverse modeling. Forward modeling can use a simulation model, based on fundamental engineering principles to predict the hypothetical hourly energy use of a building over a year and is typically used to design the buildings. Inverse modeling is an empirical analysis method using the measured monthly or daily energy data for evaluating energy uses in the existing buildings and building systems. Inverse models have been shown to be an effective analysis procedure in numerous studies (Leslie et al. 1986; Mazzucchi 1986; Rabl and Rialhe 1992; Claridge et al. 1992; Haberl et al. 1998). Hybrid methods that combine forward and inverse approaches have been shown to be useful in actual calibrating simulation models. Haberl and Bou-Saada (1998) reviewed and discussed the procedures for developing calibrated simulation models. Additional details concerning numerous energy estimation and modeling methods, including forward and inverse modeling, are provided in the 2009 ASHRAE Handbook Fundamentals Chapter 19-Energy Estimating and Modeling Methods (ASHRAE 2009a).

2.1.1.2. Measurement protocols

Haberl and Culp (2009) traced the history of M&V protocols in the United States. The NEMVP (DOE 1996) is regarded as the first nationally recognized M&V protocol. It presented three M&V options with expected cost and accuracy, including Option A: end-use retrofits with measured capacity, stipulated consumption; Option B: end-use retrofits with measured capacity and measured consumption; and Option C: whole-facility or main meter before-after measurements. In 1997, the NEMVP was revised and renamed the IPMVP. In the 1997 IPMVP, Option D: calibrated simulation was added. In 2001, the IPMVP was revised again and expanded in two volumes: Volume I for Option A, B, C and D (DOE 2002a) and Volume II for IEQ issues in M&V approaches (DOE 2002b). In 2002, the ASHRAE Guideline 14-2002 (ASHRAE 2002) was published to serve as a technical document for the IPMVP. In 2003, a third volume for new construction (DOE 2003) was released. The IPMVP Volume I has been updated regularly to reflect best practices (EVO 2009). However, the fundamentals of the four M&V options were not changed.

Several efforts were also made to establish a standardized procedure for energy monitoring and reporting (ASHRAE 2007a; Barley et al. 2005; ASHRAE 2007e). The need for a standardized procedure first arose in 1980s (Misuriello 1987). In 1984, ASHRAE Standard 105 (ASHRAE 2007a) was first released to provide a common method of measuring, expressing and comparing the energy performance of both existing and new buildings. However, ASHRAE Standard 105-2007 is limited to basic building energy performance metrics, including an energy use index and an energy cost index.

The National Renewable Energy Laboratory (NREL) Procedure for Measuring and Reporting Commercial Building Energy Performance (Barley et al. 2005) provides two levels of energy performance monitoring procedures: Tier 1 for monthly or annual analysis (i.e., un-instrumented approach using utility billing data) and Tier 2 for hourly or sub-hourly analysis (i.e., instrumented approach typically involving data acquisition system (DAS)).

Finally, the 2007 ASHRAE Handbook HVAC Applications, Chapter 40-Building Energy Monitoring (ASHRAE 2007e) provides overall guidelines for developing building monitoring projects rather than technical details that are discussed in specialized protocols such as the IPMVP and the ASHRAE Guideline 14-2002. The generalized steps contained in the document include project development, field data monitoring, data uncertainty and analysis and data quality assurance procedures.

2.1.1.3. *Instrumentation*

The basic sensors used in early energy monitoring projects, which include temperature, humidity, and water flow meters remain nearly the same as today's instruments. One of the earliest compilations of M&V equipment was the Proceedings of the National Workshop Field Data Acquisition for Building and Equipment Energy-Use Monitoring (1986). This provides an overview of the sensors and data acquisition systems that were used for energy monitoring projects in the 1980s, including the End-Use Load and Consumer Assessment Program (ELCAP) which is the earliest, massive end-use data collection effort (Peterson et al. 1993). For power monitoring, current transformers and watt transducers were used along with watt transformers. For data logging and polling, a data logger was typically used with an analog dial-up modem. Although, the basic instruments used in early energy-use monitoring projects have changed little, several problems were identified in early monitoring projects, including sensor cost and reliability (failure), unreliable remote communications, and manufacturer's reliability (ORNL 1986).

In today's energy monitoring projects, most of the above-mentioned problems in early projects have been solved or improved. Today, an internet connection often replaces a telephone modem for remote communications. In addition, the versatility of data loggers and the programmability of the data logger software have been improved, which allows for easier installation and operation (Barley et al. 2005). For new construction, as Energy Management and Control Systems (EMCS) that can monitor and record the energy use of whole-building and major end-uses became more common for large commercial building applications, the need for installing separate energy monitoring systems was reduced.

However, some of the problems identified by Heinemeier (1994) in the early 1990's energy conservation projects can still exist with today's system. Although most EMCS systems were capable of monitoring energy data, she found limitations in the use of existing EMCS data for energy monitoring, which were mainly related to programming issues, including difficulties in polling or retrieving trend data and an incompatible data format used by EMCS systems such as a Change of Value (COV) format (Heinemeier and Akbari 1993). This COV format for the recorded data has inconsistent time intervals for each channel because data are only recorded when the value changes. This can cause large gaps in the data stream that need to be filled-in.

Instrumentation and calibration requirements used in today's energy monitoring projects can be found in the ASHRAE Guideline 14-2002 (ASHRAE 2002), the NREL Procedure for

Measuring and Reporting Commercial Building Energy Performance (Barley et al. 2005), and the 2009 ASHRAE Handbook Fundamentals, Chapter 36-Measurement and Instruments (ASHRAE 2009b).

2.1.1.4. Summary

In summary, research in building energy performance measurement started in the 1970s. Several M&V and building energy monitoring protocols and procedures have been developed since that time. However, most of today's protocols mainly focus on energy performance although many energy retrofit projects can negatively affect the IEQ performance of the building related to thermal comfort, IAQ, lighting, and acoustics. In addition, there is lack of reliable benchmarking data that includes detailed energy monitoring data (i.e., hourly or sub-hourly energy use of whole-building and major end-uses with the coincident weather data).

2.1.2. *Water Use*

2.1.2.1. Overview

Few studies have been conducted to quantify the water use in buildings. Although studies have investigated the savings from water-efficient products such as plumbing fixtures, the savings were examined at a product-level not a whole-building level. At the whole-building level, most water savings were simply estimated rather than measured (Behling and Bartilucci 1992)[4]. However, there are numerous publications about water conservation in commercial applications. These publications often include recommendations about water auditing or sub-metering as one of the strategies (CDWR 1994; Schultz Communications 1999; Gleick et. al. 2003; EBMUD 2008).

The publications by California Department of Water Resources (CDWR 1994) and Schultz Communications (1999) provided the water auditing procedures as a part of water conservation strategy. Both publications suggested more than one-year of utility water meter readings and measurements of the amount of water used by major water-consuming equipment using a temporary ultrasonic flow meter or permanent water sub-meters. However, a detailed measurement protocol was not discussed in either publication. EBMUD (2008) suggested a sub-metering of individual unit (tenants), major water-consuming systems or landscaping as a water

[4] Behling and Bartilucci (1992) examined a possible water savings by installing water-efficient plumbing fixtures in the office buildings using a theoretical estimating procedure.

conservation strategy and examined the benefits of sub-metering. However, there were no discussions about procedures for sub-metering.

2.1.2.2. Measurement protocols

Recently the need for a standardized data collection procedure of building water use was identified (EPA 2009). Several efforts to establish a standardized method for quantifying the water use were made in water auditing but from the supply side (AWWA 1999a; Alegre et al. 2002). Since water is also an energy-intensive resource because of its treatment and distribution, water management is now becoming recognized as an integral part of energy management. All water conservation strategies involve reducing the volume of water for a given task to be performed, which results in water savings and energy savings for the pumping, distribution, heating, and treatment to provide supply water as well as treat wastewater from buildings (Tellinghuisen 2009).

The U.S. Department of Energy Federal Energy Management Program (FEMP) (2008) published guidance for determining baseline potable water usage to achieve the water conservation goals of Section 2(c) of Executive Order (EO) 13423, Strengthening the Federal Environmental, Energy, and Transportation Management (2007) in federal agencies. In this guidance, a water use index (WUI) of each agency is suggested as a baseline performance metric of the building's water performance. A brief description of the method of estimating the water use for the unmetered facilities was also provided.

Finally, the IPMVP (EVO 2009) provided M&V procedures for building water use, including the metering instrumentation as a part of an energy management program. However, due to the difficulty of estimating the user behavior of water-consuming equipment, Retrofit Isolation methods with an assumed usage profile are suggested to be used for an estimation of the water savings.

2.1.2.3. Instrumentation

The various instruments for the measurement of water usage were examined by the American Water Works Association (AWWA). The AWWA Manual 33: Flowmeters in Water Supply (2006) provides information on the flow meters commonly used in today's water flow measurements, including: venturi, modified venturi, orifice plate, electromagnetic, turbine and propeller, transit-time ultrasonic, vortex, averaging pitot, and averaging insertable electromagnetic. It also provides principles of measurement and installation and maintenance recommendations. The AWWA Manual 6: Water Meters-Selection, Installation, Testing, and Maintenance (1999b) covers how to select and install an appropriate water meter (i.e., displacement or multi-jet meter) as well as testing and maintenance issues.

2.1.2.4. Summary

In summary, selected efforts to establish standardized procedures for quantifying the amount of water used in buildings or major water-consuming equipment have been made as part of an energy management program and water conservation practice. However, there are few discussions about how to standardize the data collection and how to analyze the data once it has been collected.

2.1.3. *Thermal Comfort*

2.1.3.1. Overview

Research in thermal comfort has been conducted since the 1920s in the United States, England, and France (Houghten and Yagloglou 1923; Vernon 1932; Dufton 1933; Missénard 1935, as cited in McIntyre 1980; Bedford 1936, as cited in McIntyre 1980; Winslow et al. 1937) as it became possible to control indoor thermal environments due to the introduction of mechanical cooling systems (Ackermann 2002). The first thermal comfort standard was developed by the American Society of Heating and Ventilating Engineers (ASHVE) in 1924 (Kwok 1997) to satisfy the need for defining design temperatures for engineers. The main objectives of the early thermal comfort studies were to develop standardized methods for the prediction of human thermal comfort using environmental variables such as air temperature, humidity, radiation, and air speed based upon the laboratory experiments. As a result, a number of thermal comfort indices were developed by numerous researchers, including: the Effective Temperature (ET) by Houghton and Yagloglou (1923); Corrected Effective Temperature (CET) by Vernon (1932); Equivalent Temperature (EqT) by Dufton (1933); Resultant Temperature (RT) by Missénard in 1935 (as cited in McIntyre 1980); Equivalent Warmth (EqW) by Bedford in 1936 (as cited in McIntyre 1980); and Operative Temperature (OT) by Winslow et al (1937). These early thermal comfort indices are discussed in detail by Macpherson (1962) and McIntyre (1980).

In the 1970s, after the first energy crisis, thermal comfort research received much more attention, and extensive studies were conducted, notably by Fanger (1972 and 1973), Gagge et al. (1971), and Humphreys (1974, 1976 and 1978). These studies still form the basis of today's thermal comfort standards. Fanger's Predicted Mean Vote (PMV) and Predicted Percentage Dissatisfied (PPD) index to predict human thermal comfort using four environmental variables (air temperature, humidity, mean radiant temperature, and air speed) and two personal variables (clothing and activity) were later incorporated from the second edition of International Organization for Standardization (ISO) 7730 (1994).

Although the main objectives of the 1970s thermal comfort research was the same as early studies in the 1920s-30s to predict human thermal comfort more accurately, considerable research has been conducted to answer different questions in various disciplines, including, engineering, physiology, medicine, geography, and climatology (Auliciems and Szokolay 1997). For example, Humphreys (1976 and 1978) investigated the correlation of thermal neutralities with outdoor climate conditions using available field data. These studies form the basis of today's Adaptive Model in thermal comfort research. Other researchers investigated human thermo-physiological responses when exposed to certain environmental condition, including Givoni and Goldman (1972 and 1973). They proposed predictive formulas of rectal temperature and heart rate using a given set of metabolic, environmental and clothing conditions.

There are two main approaches in thermal comfort studies: laboratory experiments and field investigations. Laboratory studies are often conducted to find the influences of one or two variables on subjects' thermal sensation, comfort, and productivity mainly under the steady-state conditions (i.e., PMV/PPD). More recently, some researchers investigated thermal comfort under the transient conditions, including Ugursal (2010). He examined transient human thermal comfort in the controlled thermal environmental conditions by varying several thermal comfort variables, including airflow, metabolic rate, and room temperatures, and showed that people have a higher tolerance to high temperatures under the transient conditions.

Field surveys in thermal comfort are usually carried out to evaluate the thermal environments of a specific buildings or systems (McIntyre 1980). In addition, cross-sectional or longitudinal field surveys have been carried out to answer more general questions. For example, many field studies have been carried out world-wide since the late 1980s to validate the thermal comfort indices that form the basis of today's standards such as the PMV/PPD (de Dear and Auliciems 1985; de Dear and Fountain 1994; Kwok 1997; Nicol et al. 1999; Feriadi et al. 2002;

Heidari and Sharples 2002; Mui and Chan 2003; Andamon 2005; Bouden and Ghrab 2005; Goto et al. 2005). Although the PMV/PPD indices were developed using laboratory studies mainly in North America and Northern Europe with college-age students, it has been suggested that they are universally applicable to any building types, climates, and populations (Parsons 1994, as cited in de Dear et al. 1997). However, analyses of field studies showed that people adapt to their environment by modifying their environment to be a more suitable one to feel comfortable over a greater range of temperatures than current standards suggest (Kim 2006). This approach to human thermal comfort is called an Adaptive Model and was incorporated in the revisions of ASHRAE Standard 55-2004 (ASHRAE 2004) for naturally-ventilated spaces with operable windows.

2.1.3.2. Measurement protocols

Principles and measurement protocols of field surveys in thermal comfort have changed little since the 1970s when today's thermal comfort indices were first developed. Such protocols often include a questionnaire survey and simultaneous measurements of several environmental parameters. In 1976, the British Occupational Hygiene Society (BOHS) proposed a procedure for thermal comfort field studies, which is very similar to current practices. The BOHS procedure includes gathering information about: environmental data such as a normal temperature level at the measurement location over a month; the type of heating system; occupants' clothing and activity; comfort votes using a seven-point thermal sensation scale and a three-point thermal preference scale; thermal gradients for non-uniform environmental condition; and a complete set of physical measurements at the time of the comfort survey, including dry bulb temperature, wet bulb temperature, globe temperature, and air speed (McIntyre 1980).

Most of today's field studies in thermal comfort follow the methodology in one of the following two standards: the ASHRAE Standard 55-2010 (ASHRAE 2010c) and ISO 7730:2005 (ISO 2005). These two standards define measurement protocols and metrics for assessing thermal comfort performance mainly for objective, instrumented measures.

de Dear et al. (1997) reviewed and classified field data into three categories (I, II, and III) by evaluating the rigorousness of the procedures and instrumentation (Table 1)[5]. A total of about

[5] The Class I approach is the most rigorous, while the Class III is the least rigorous.

Table 1: Three Categories of Thermal Comfort Field Data (de Dear et al. 1997)

	Class I[1]	Class II	Class III
Measurement Parameters	Air temperature, Humidity, Mean radiant temperature, Air velocity, Clothing level, Metabolic level	Air temperature, Humidity, Mean radiant temperature, Air velocity, Clothing level, Metabolic level	Air temperature, Humidity
Measurement Location	3 points (4 in. (0.1 m), 24 in. (0.6m), and 43 in. (1.1m))	1 point	1 point
Subjective Survey	Synchronous questionnaire	Synchronous questionnaire	Asynchronous questionnaire
Instrumentation Requirements	Laboratory-grade instrumentation, including omnidirectional hot wire anemometer capable of turbulence intensity assessments	Aspirated psychrometer or solid state hygrometer sensors; Directional hot wire anemometer with time constants larger than that necessary for turbulence intensity assessments	No Requirements

NOTES:
1) Fully compliant with ASHRAE Standard 55-1992 and ISO 7730:1994

22,000 sets of field data were collected and cataloged into one of the three categories. Early thermal comfort field studies (Humphreys 1976 and 1978) are the examples of Class III field experiments with simple measurements of air temperature or humidity. Class II field experiments require the measurements of all six variables for calculating the PMV and PDD indices but are less stringent than Class I studies in terms of instrumentation requirements and procedures. Class I field experiments fully complied with ASHRAE Standard 55-1992 and ISO 7730:1994, including a three-point measurement at different heights (4 in. (0.1 m), 24 in. (0.6m), and 43 in. (1.1m)), and require laboratory-grade instrumentation.

Although the measurement procedures for evaluating objective thermal comfort are well defined, there is a lack of validated questionnaire modules to access a building's thermal comfort performance from the perspective of the occupants beyond comfort votes. One effort was made by the Center for the Built Environment (CBE) at the University of California, Berkeley (2008). At the CBE, an occupant IEQ survey has been developed and used for various studies covering all IEQ-related research topics, and a database consists of over 300 buildings. However, the use of this tool also needs to be validated by the third party, including how well it measures occupants' satisfaction and comfort when compared to instrumented measurements.

2.1.3.3. Instrumentation

The instruments in early thermal comfort studies include: an aspirated psychrometer for air temperature and humidity; a globe thermometer (a thermometer with a thin-walled copper sphere painted black surrounding the sensor) for mean radiant temperature (Bedford and Warner 1934); and a kata thermometer for air speed (Hill et al. 1922; Koch and Kaplan 1958). Since then, although the fundamental principles behind the sensors used in thermal comfort studies have not changed, the instruments to measure thermal environments have evolved with advances in electronics that have reduced the response time, improved accuracy, and facilitated improved data recording capabilities (McIntyre 1980).

Although the instruments used in recent thermal comfort field studies have been reviewed, detailed information about the instrumentation was not available from many of the studies. Of the studies reviewed, twenty field studies between 1985 and 1997 that were reviewed by de Dear et al. (1997) and three field studies (Mui and Chan 2003; Mallory-Hill 2004; Andamon 2005) that had detailed instrument information were selected for further review. In these studies, thermistors or thermocouples were widely used to measure air temperatures. Solid-state hygrometers or chilled-mirror dewpoint hygrometers were used for humidity measurements. For globe temperature measurements, thermistors or thermocouples inside a 38 mm diameter table tennis ball painted black or gray were commonly used, and an omni-directional or directional hot wire anemometer was the most commonly used instrument for measuring air speed. Many studies used a data logger for recording and storing the data. Most Class I field experiments used temperature measurements at three heights on a cart-type measurement system where all the sensors, transducers, and a data logger were mounted.

2.1.3.4. Summary

In summary, basic measurement protocols and metrics of thermal comfort were established in the 1970s and are well defined in today's standards: the ASHRAE Standard 55-2010 (ASHRAE 2010c) and ISO 7730:2005 (ISO 2005). Such measurements have been widely used by thermal comfort researchers, including a questionnaire survey with comfort votes, measurements of at least four environmental variables (air temperature, humidity, mean radiant temperature, and air speed) and two personal variables (clothing and activity). However, in all the protocols reviewed, there was a lack of a validated questionnaire module that can access a building's thermal comfort performance from the perspective of the occupants beyond thermal comfort votes. In addition, even less information could be found regarding sampling methods in real buildings and calibration procedures.

2.1.4. *Indoor Air Quality*

2.1.4.1. Overview

The relationship between IAQ and occupant comfort and health received the attention of several early scientists since the late 18th century, including Mr. Antoine-Laurent de Lavoisier of France (Hansen 1999). Lavoisier studied the composition of indoor air and determined that occupants experienced discomfort due to carbonic acid (Bedford 1964). In the middle of the 19th century, a new theory was proposed by Mr. Max Joseph von Pettenkofer in Germany. He argued that discomfort resulted from organic airborne contaminants not from carbon dioxide (CO_2), and that the concentration of CO_2 could be used as an indicator of indoor air quality (Pettenkofer 1862, as cited in Hansen 1999). Pettenkofer proposed 1,000 ppm of CO_2 as an indicator of acceptable indoor air quality (Sundell 2004). Following Pettenkofer, many researchers examined the anthropotoxin theory[6] to find scientific evidence of toxic effects on discomfort (Bedford 1964). However, these early studies failed to demonstrate the causal relationship between toxic effects of organic airborne contaminants and human discomfort and adverse health effects (Sundell 2004).

In the early 20th century, several researchers argued against the anthropotoxin theory. In the late 1920s, Hill and his colleagues claimed that human discomfort was due to excessive warmth rather than an elevated CO_2 concentration (Angus 1968). Yaglou et al. (1936) proposed a quantitative criterion for ventilation requirements based on the chamber experiments of perceived odor of visitors rather than CO_2 levels. After Yaglou's experiments, it was believed that body odor was the main source of indoor air pollution and became the criterion for a ventilation standard (Sundell 2004).

Until the 1970s before the first energy crisis, outdoor air quality was of primary concern due to the emissions from automobiles and industrial processes. After the Great Smog of 1952 in

[6] The theoretical belief that some poisonous volatile compounds existed in expired air was termed anthropotoxin theory (Rovenstine 1936).

London[7], the first legislation regarding outdoor air pollution was initiated, including the Air Pollution Control Act of 1955 in the United States (EPA 2008) and the Clean Air Act of 1956 in England (Guissani 1994). Thus, the early IAQ monitoring studies before 1970s focused on indoor concentrations of outdoor pollutants, including sulfur dioxide, nitrogen dioxide, ozone, carbon monoxide, and total suspended particles (Nagda et al. 1987).

After the first energy crisis in the early 1970s, a major shift took place in IAQ research. To reduce the energy costs associated with heating and cooling, building managers decreased outdoor air intakes for ventilation, and buildings were constructed tighter to reduce air infiltration (Spengler et al. 2001). Unfortunately, at the same time materials that produced airborne volatile organic compounds (VOCs) were seeing increased use in buildings, including synthetic materials for interior finishes and furniture as well as chemicals for cleaning products and office supplies (Hansen 1999).

With these two potential causes, occupants' complaints and adverse health symptoms associated with poor indoor air quality were increasing. As a result, two building-associated illnesses were defined: sick building syndrome (SBS) and building-related illness (BRI) (ASHRAE 2009c). Shortly thereafter, numerous IAQ assessment field studies were performed across North America and in European countries to better understand the problem for possible remedies (Burge et al. 1987; Skov et al. 1990; Wyon 1992; Zweers et al. 1992; Fisk et al. 1993; Menzies et al. 1993; Sundell 1994; Daisey et al. 1994; Jaakkola and Miettinen 1995; Bourbeau et al. 1997; Milton et al. 2000; Wargocki et al. 2000; and Marmot et al. 2006).

The main goal of these studies is to examine the relationship between the reported SBS symptoms against the selected characteristics of a building and workplace (i.e., HVAC system, ventilation rate, indoor environmental quality, etc.) as well as psychosocial factors (i.e., gender, job satisfaction, etc.). Many studies reported an increased occurrence of the symptoms with low outdoor air ventilation rate (Mendell 1993; Sundell 1994; Jaakkola and Miettinen 1995; Milton et al. 2000; Wargocki et al. 2000; Sundell et al. 2011), although some studies did not find any significant association between the two factors (Wyon 1992; and Menzies et al. 1993). Some studies found an increased prevalence of the reported SBS symptoms in air-conditioned buildings compared to the naturally ventilated buildings, including: Burge et al. in the U.K. (1987), Zweers et al. in the Netherlands (1992), and Fisk et al. in the U.S.A. (1993).

[7] The Great Smog of 1952 in London was a severe air pollution episode that followed by an elevated mortality and morbidity (Bell et al. 2004).

2.1.4.2. Measurement protocols

The need for a standardized IAQ assessment procedure began in the late 1980s. In 1991, the National Institute for Occupational Safety and Health (NIOSH) and the U.S. Environmental Protection Agency (EPA) jointly developed a practical guide for maintaining good indoor air quality based on the experiences gained from more than 600 IAQ investigations in office buildings (EPA 1991). It contained an IAQ investigation procedure to diagnose the problems, and this procedure included measurements of CO and CO_2 as indicators of indoor air contaminants. The sampling locations, durations, time of day, and benchmark guidelines were also provided.

In 1994, a more standardized approach was proposed by the U.S. EPA entitled "A Standardized EPA Protocol for Characterizing Indoor Air Quality in Large Office Buildings (EPA 2003)." This protocol was created to be used in the U.S. EPA's Office of Radiation and Indoor Air (ORIA) Building Assessment Survey and Evaluation (BASE) study, and was revised twice since then, once in 1999 and once in 2003. A BASE study is a cross-sectional study initiated to characterize baseline IAQ in public and commercial office buildings (Womble et al. 1995). It measured core IAQ parameters of a building over a week either in the summer or in the winter using the proposed EPA protocol. The EPA protocol provides very detailed procedures to investigate IAQ performance of a surveyed building, including: sampling methods for study areas, monitoring locations, sampling periods, performance metrics, instrumentation, an occupants' questionnaire survey, and data validation (EPA 2003).

Two types of performance metrics were defined in the EPA protocol: core and augmentation parameters. The measurements of core parameters consisted of continuous monitoring of indoor temperatures at four heights (0.1 m, 0.6 m, 1.1 m, and 1.7 m) and single-level measurements of relative humidity, CO_2, CO, sound level, and horizontal illuminance as well as integrated samplings of $PM_{2.5}$, PM_{10}, VOCs, Formaldehyde (HCHO), bioaerosols, and radon. The procedure also included the measurement of several coincident outdoor air parameters, including outdoor temperature, relative humidity, CO_2, CO, $PM_{2.5}$, PM_{10}, VOCs, HCHO, and bioaerosols. The collected, continuous monitoring data are then required to be reduced to 5 minute averages for reporting purposes. However, the protocol does not provide any procedures for data analysis beyond this simple data reduction method.

2.1.4.3. Instrumentation

Because of the wide variety of potential indoor air pollutants, a number of measurement techniques and instrumentation have been used in IAQ studies. Different sampling methods (either active or passive) and approaches (either a real-time analyzer or sampling collectors) were used for each pollutant of interest. Nagda et al. (1987) reviewed commercially available IAQ instruments in the late 1980s for the following indoor pollutants: asbestos, bioaerosols, CO, HCHO, particulate matter, nitrogen dioxide, ozone, radon, and sulfur dioxide. A relatively large number of instruments were available for the measurements of CO, nitrogen dioxide, ozone, and sulfur dioxide, partly because these pollutants were required to be monitored by the U.S. EPA National Ambient Air Quality Standards. However, since they were intended for ambient air quality monitoring, many of them lacked the mobility required to perform indoor assessments. As a result, portable or personal instruments were developed for indoor air monitoring using electrochemical oxidation cells, but they lack the sensitivity needed to identify low concentrations of the pollutant of interest. Shortly thereafter, the U.S. EPA proposed standardized sampling and analysis techniques, including calibration requirements for VOCs, nicotine, CO, CO_2, air exchange rates, nitrogen dioxide, HCHO, Benzopyrene and other polynuclear aromatic hydrocarbons, acid gases and aerosols (NO_x, SO_x, and NH_3), particulate matter, and pesticides (Winberry et al. 1993). Although the fundamental operational principles of these instruments have not changed since their use in the 1980s-1990s, the instruments have become more compact and portable. In addition, the utility of a real-time graphical interface and increased sensor sensitivity has also improved all at a fraction of the cost of the original equipment used in the 1980s-1990s.

2.1.4.4. Summary

In summary, there are a number of well-established performance metrics in IAQ research for a wide variety of indoor air pollutants. However, CO_2 and CO have been widely used as basic indicators of IAQ. The U.S. EPA has provided a very detailed IEQ investigation protocol for most indoor air pollutants of interest today. However, since the protocol was specially designed for the high accuracy requirements of the BASE study, its practicability and cost-effectiveness needs further study. For example, the procedure requires one mobile and five fixed monitoring systems per each building. The monitoring systems needs to be equipped with multiple sensors and instruments, including: indoor temperatures at four heights (0.1 m, 0.6 m, 1.1 m, and 1.7 m) and single-level measurements of relative humidity, CO_2, CO, sound level, illuminance, $PM_{2.5}$, PM_{10}, VOCs, Formaldehyde (HCHO), bioaerosols, and radon, which results in high implementation costs. In addition, the measurement of indoor air speed and flow was not addressed.

2.1.5. *Lighting*

2.1.5.1. Overview

Research into lighting performance started in the early 1900s with the developments in photometry to access the quality (i.e., quantity of illumination) of various light sources and luminaires (i.e., gas lighting and incandescent lighting) as the competition between various forms of lighting intensified at the end of the 19th century[8] (Dilaura 2006). Professional lighting societies were soon launched as the importance of illumination was acknowledged. For example, the Illuminating Engineering Society of North America (IESNA) was founded in 1906 to provide scientific lighting recommendations, and in 1911, the International Commission on Illumination (CIE) was formed to establish a standardized vocabulary of lighting measurements (Loe and McIntosh 2009).

In the early 1910s, the need for a lighting code arose to ensure worker's safety (Osterhaus 1993). About the same time, several studies examined the relationship between inadequate lighting condition and the occurrences of industrial accidents (Simpson 1914 and 1918; Alger 1913). In the 1915 IES Transactions, the first lighting code entitled "Code of Lighting Factories, Mills and Other Workplace" (IES 1915), was published. This code defined minimum and recommended lighting intensities on a horizontal plane for several different types of workplaces. By 1930, the code was revised several times to cover more types of work spaces with different lighting requirements and glare issues. In 1942, the code was divided into two codes: the American Recommended Practice of Industrial Lighting (IES 1942a) and the Recommended Practice of Office Lighting (IES 1942b). The recommended illuminance levels increased significantly (i.e., from 3 footcandles in the 1915 edition to 25 footcandles for ordinary tasks in

[8] The commercially practical incandescent light bulb was first invented by Thomas Edison in 1879 (Beals 1999).

offices). In those days, high illumination levels of 75 to 100 footcandles became common practice, due in part to the invention of fluorescent lamps[9] (Osterhaus 1993).

In all these early standards, the main lighting performance metric was the quantity of illumination (i.e., illuminance level on a horizontal plane), but as the importance of visual comfort was acknowledged, a number of studies examined discomfort glare (Harrison 1945; Luckiesh and Guth 1949; Hopkinson 1957; Guth 1963). Based on these studies, the Visual Comfort Probability (VCP) method to evaluate the glare and the Equivalent Sphere Illumination (ESI) method to evaluate veiling reflections were added to the 1973 edition of the lighting code entitled "the American National Standard Practice for Office Lighting" (IES 1973) as one of the methods to evaluate lighting performance.

Research into acceptable lighting levels has been carried out almost continuously since the 1900s. These studies often include subjective assessment as well as mechanical tests of visual performance (i.e., speed of error detection) under various lighting conditions. As a result, numerous preferred illuminance or luminance ranges in office spaces have been reported (Bodmann 1962 and 1967; Saunders 1969; Nemecek and Grandjean 1973; Bean and Hopkins 1980). The effects of lighting on visual performance and productivity have also been one of the main topics in lighting research up through the present day (Simonson and Brozek 1948; Boyce 1973; Smith and Rea 1978, 1982 and 1987; Odemis et al. 2004; Juslén 2007).

2.1.5.2. Measurement protocols

For the field measurement of illuminance, there are two methods frequently referenced: the methods in the IES Lighting Handbook (IES 2000) and the methods in the CIBSE Code for Interior Lighting (1994). Both methods are based on the grid methods, but different approaches were taken to position a grid of measurement points. In the IES method, the grid positions are decided by the locations of luminaires. Whereas, in the CIBSE method, a full grid is used that divides the space into a number of equal areas. One of the advantages of the IES method is its reduced number of measurement points. However, the IES method is limited to six different types of room shapes with varying luminaire configurations.

The IES method is based on the uniform field survey method "How to Make a Lighting Survey" (1963) developed by the IESNA in 1963. This survey included a detailed description of:

[9] In 1901, Peter Cooper Hewitt patented the first mercury-vapor lamp (Hewitt 1901), but its commercial applications were limited. The commercially practical mercury-vapor lamp (i.e., fluorescent lamps) was introduced in the market by General Electric (GE) scientists in 1938 (GE 2012).

the space (i.e., interior surface reflectance, room dimensions, etc.); the lighting system (i.e., type, age, wattage, etc.); and the instruments to be used. It also provided detailed instructions for illuminance and luminance measurements. To compare the proposed IESNA method with other survey methods, comprehensive illuminance measurements were performed in 11 different rooms under actual conditions of use. These studies showed the reported accuracy of IESNA method was ±10 %. However, the errors tend to increase for spaces with unusual room cavity ratios (RCR)[10] or highly non-uniform illuminated spaces (IES 2000) such as in corridors for emergency lighting applications (Ouellette et al. 1993).

2.1.5.3. Instrumentation

Dilaura (2006) has summarized the early instruments used in photometry. By 1930, photometry was a vision-based assessment process of trained human observers based on Johann Lambert's photometric system, which was laid out in 1760. The metric used to assess the quality of luminaires was the luminous intensity in candlepower. In the 1930s, a light sensitive electronic device that generated an output current proportional to the amount of incident light was developed, and eventually replaced human observers. To cope with differences in the spectral sensitivity of photoelectric cells versus human eye, special filters were developed to be used with the new electronic meters. With this new calibrated photoelectric detector, portable illuminance meters, which are similar in configuration to today's illuminance meters, became available in 1932. In 1987, the CIE published a guide for illuminance and luminance meters (CIE 1987). It contained important performance parameters of illuminance and luminance meters and the corresponding error values. For both meters, the spectral bias is dealt with as a special parameter, as well as cosine corrections for illuminance meters.

Illuminance and luminance meters are still widely used to evaluate the lighting performance of buildings. However, the measurement processes using these meters are time-consuming and laborious. Recently, high dynamic range (HDR) photography has been suggested as an alternative to tedious illuminance and luminance measurements. HDR photography can be created using a series of images with different shutter speeds. HDR photography allows capturing images that closely represent human vision. Using HDR photography, the luminance

[10] The room cavity ratio (RCR) is defined as: RCR = 5 x (room height) x (room width + room length) /(room width x room length) (IES 2000).

distribution of a space and discomfort glare can be accurately evaluated with a number of reduced measurements (Inanici and Galvin 2004).

2.1.5.4. Summary

In summary, the basic measurement metrics (i.e., illuminance, luminance and luminance ratio, and discomfort glare) to evaluate lighting performance in buildings have been established and widely investigated in many studies since the 1900s. However, there remains a lack of standardized field measurement procedures to continuously access a building's lighting performance over all hours of the day, across different seasons of the year. Efforts to develop a standardized field measurement methods by the IES and the CIBSE have produced measurement protocols. However, both methods do not include an occupant's subjective assessment of their lighting environment and have limitations. For example: the IES method is limited to illuminance measurements in six different types of room shapes with varying luminaire configurations; and the CIBSE's full grid method, although more accurate, is not cost-effective.

2.1.6. *Acoustics*

2.1.6.1. Overview

Research into architectural acoustic performance started at the end of 19th century, notably by Mr. Wallace Clement Sabine of the United States (1922). Based on thousands of measurements using a stop watch and pipe organs, Sabine defined the reverberation time as the time needed for the sound in an enclosure to decay by 60 dB, and derived an equation that calculated the reverberation time as a function of room parameters including the room volume and the sound absorbing characteristics of a space in 1898. Sabine's reverberation time is still one of the most common acoustic performance metrics to assess speech communication issues of spaces[11].

Since the 1930s, several researchers (Fletcher and Munson 1933; Churcher and King 1937; Robinson and Dadson 1956) examined metrics for acoustic loudness. Fletcher and Munson (1933) developed equal-loudness contours that charted the human ears' different

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[11] Several studies have subsequently investigated the measurement methods used to measure reverberation time (Schroeder 1965; Davy 1989; Sato et al. 2008). Sabine's equation has also been revised by researchers (Eyring 1930; Millington 1932). Finally, the use of the reverberation time has been examined under a number of different spaces (Carvalho 1994; Neubauer 2001; Beranek 2006).

response over the sound frequency spectrum based on subjective estimations of listeners. Fletcher and Munson’s contours substantially improved acoustic performance measurement capabilities. In 1936, A-weighting (40 phon) and B-weighting (70 phon) curves were developed based on Fletcher and Munson’s contours and used in the first American standard for sound level meters entitled “American Tentative Standards for Sound Level Meters (Z24.3-1936) for Measurement of Noise and Other Sounds” (1936). Since its development in the 1930s, A-weighted sound pressure level (dbA) has been regarded as the most basic acoustic performance metrics due to its easy applicability. However, many studies (Hellman and Zwicker 1987; Persson and Björkman 1988; Kuwano et al. 1989; Schomer et al. 2001) have examined potential problems of using A-weighted sound pressure level measurements since it does not provide information on spectral distribution and tends to underestimate the loudness of sound at low frequencies.

Since the 1950s, other sound rating systems have been developed, including the noise criteria scale (NC) by Beranek (1957), the room criteria scale (RC) by Blazier (1981), the balanced noise criteria scale (NCB) by Beranek (1989), and the RC Mark II scale by Blazier (1997). Generally, these rating systems consisted of several criterion curves over the audible frequency spectrum that consider the spectral distribution of measured sound with the rating determined by a comparison of measured sound with these criterion curves. Each method was intended to be used in different applications. While the RC and RC Mark II rating methods were developed to be used for the evaluation of HVAC system related noise, NCB was intended to evaluate room sound. In addition, the RC, NCB, and RC Mark II rating systems included a method for the evaluation of sound quality as well as the loudness of the sound. The details of these rating systems are provided in the 2009 ASHRAE Handbook Fundamentals, Chapter 8-Sound and Vibration (ASHRAE 2009d) and the 2007 ASHRAE Handbook HVAC Applications, Chapter 47-Sound and Vibration Control (ASHRAE 2007f).

2.1.6.2. *Measurement protocols*

To evaluate acoustical performance of a building enclosure or HVAC system component, a number of standards on measurement and test methods have been published by the Air Movement and Control Association International (AMCA) for fans and ducts; the Air-Conditioning, Heating, and Refrigeration Institute (AHRI) for air terminals and outlets; American Society of Testing and Materials (ASTM) for partition, insulation, and whole-HVAC system background noise; and the Acoustical Society of America (ASA) for general noise sources. However, at a building level, fewer standards have been developed. The current standards in use include: the ANSI/ASA S12.2 (ASA 1995), the ANSI/ASA S12.60/Part1 (ASA 2010), and the ASTM E1573-09 (ASTM 2009) for sound level measurements and the ISO 3382-2:2008 (ISO 2008) for reverberation time measurements. The 2009 ASHRAE Handbook Fundamentals, Chapter 8-Sound and Vibration (ASHRAE 2009d) provides useful guidelines about the measure of sound pressure level in occupied spaces.

The ANSI/ASA S12.2 Criteria for Evaluating Room Noise provides several methods to evaluate room noise, including NCB and RC rating systems. The ANSI/ASA S12.60/Part 1 American National Standard Acoustical Performance Criteria, Design Requirements, and Guidelines for Schools covers various acoustical performance issues in school buildings, including design requirements and guidelines and benchmark criteria. It also provides measurement protocols in the Appendix to verify whether the space conforms to the performance criteria suggested by the standard. The ASTM E1573-09 Standard Test Method for Evaluating Masking Sound in Open Offices Using A-Weighted and One-Third Octave Band Sound Pressure Levels was developed to evaluate the masking sound spectrum and levels in open offices. Finally, the ISO 3382-2:2008 describes a standardized procedure for the measurement of reverberation time in ordinary rooms. It also covered the necessary instruments and data analysis methods.

2.1.6.3. Instrumentation

The fundamental operational principles of a sound pressure level meter have not changed since its use in early noise measurement projects (Peterson and Beranek 1953; NPL 1955). The basic construction of a sound level meter includes a microphone to transform a sound pressure level (i.e., force per unit area of acoustical sound waves to air particles) into an electrical signal, signal amplifiers, and an output display. To modify the frequency spectrum, special filters were developed to be used with the sound level meter, including: A-weighting and C-weighting filters or octave and 1/3 octave band filters. The first portable sound level meter was developed in 1960, which is similar in configuration to today's sound level meters (Christensen 2010). There are several standards that describe instruments specifications, including the ANSI S1.4-1983(R2006) (ANSI 2006a) and the ANSI S1.43-1997 (ANSI 1997) for sound level meter; the ANSI S1.11 (ANSI 2004) for octave and 1/3 octave band filters; and the ANSI S1.40-2006

(ANSI 2006b) for the sound level meter calibrators. The ANSI S 1.4-1983 American National Standard Specification for Sound Level Meters specified the performance requirements of Type 1 and Type 2 sound level meters. The required accuracy of Type 1 and Type 2 meter is ±1.0 dB over 50-4000 Hz and ±1.5 dB over 100-1000 Hz (ASHRAE 2009d).

2.1.6.4. Summary

In summary, basic measurement protocols and metrics (i.e., A-weighted sound pressure level, NC, RC, BNC, RC Mark II, and reverberation time), instrumentation, and calibration requirements to evaluate acoustical performance in buildings are well established and have been widely investigated in many studies since the early 1900s. However, most methods focus on quantitative measurements of sound levels and do not include an occupant's subjective assessment of their acoustical environment based on a questionnaire survey.

2.2. ASHRAE/CIBSE/USGBC Performance Measurement Protocols for Commercial Buildings

Although a number of studies on building performance measurements have been conducted and numerous efforts have been made to develop a standardized building performance measurements procedures for the respective fields of study (i.e., energy use, water use, thermal comfort, IAQ, lighting, and acoustics), there remained a need for an integrated protocol for building performance measurement, which would include energy use, water use, thermal comfort, IAQ, lighting, and acoustics. In 2005, the U.S. Green Building Council (USGBC) approached ASHRAE to fill in this gap by developing performance measurement protocols for commercial buildings. A preliminary literature survey was performed by the ASHRAE working group (Haberl et al. 2006), and it was proposed that a protocol, entitled "ASHRAE/CIBSE/USGBC Performance Measurement Protocols (PMP) for Commercial Buildings" be developed.

The purpose of the ASHRAE PMP is to provide a standardized set of protocols for measuring and comparing the operational performance of occupied commercial buildings, including: energy use, water use, and IEQ. The ASHRAE PMP has been developed at three levels of cost/accuracy, Basic (Indicative), Intermediate (Diagnostic) and Advanced (Investigative), for the following six performance categories: energy use, water use, thermal comfort, indoor air quality, lighting and acoustics. For each of three levels, the ASHRAE PMP identifies the performance metrics (i.e., the quantities to be measured) and measurement and evaluation methods, including the appropriate benchmarks to be used for comparisons and the cost information. The three levels allow the users to make a realistic choice for consistent performance characterization of the building based on their need and specific objectives.

2.2.1. *Overview*

2.2.1.1. Level 1: Basic

The Basic Level 1 protocol is intended to provide a quick, inexpensive characterization and evaluation of a building's overall performance. Since this Basic Level is expected to be applied to much of the existing building stock, all six performance categories are presented in one chapter to help users navigate more easily. The performance metrics required at the Basic Level are categorized into the three types of measures as follows:

- Descriptive Information: Basic building performance-related building/system characteristics;
- Subjective Measures: Occupant IEQ satisfaction survey; and
- Instrumented Measurements: Annual whole-building energy use and cost indices; annual total site water use and cost indices; and spot measurements of several IEQ parameters, including: temperature, humidity, radiation (i.e., globe temperature, mean radiant temperature or operative temperature), air speed, outside air flow rate, illuminance, and sound pressure levels.

For the occupant IEQ satisfaction survey, the Basic Level recommends using the CBE surveys (CBE 2008) or the Building Use Studies (BUS) surveys (UBT 2008) that have benchmarking scores for office buildings. The benchmark data sets for instrumented measures are adapted from other recognized standards, handbooks, and the U.S. government documents, including the U.S. EPA ENERGY STAR ratings (EPA 2010a) and the 2007 ASHRAE Handbook HVAC Applications, Chapter 35-Energy Use and Management (ASHRAE 2007d) for energy use; the U.S. Department of Energy (DOE) Federal Energy Management Program (FEMP) Federal Water Use Indices (FEMP 2009), the Verein Deutscher Ingenieure (VDI, The Association of German Engineers) 3807 Part 3 (VDI 2000) , and the Chartered Institution of Building Services Engineers (CIBSE) Guide G, Public Health Engineering (CIBSE 2004) for water use; the ASHRAE Standard 55-2004 (ASHRAE 2004) and the EN 15251: 2007 (CEN 2007) for thermal comfort; the ASHRAE 62.1-2007 (ASHRAE 2007b) for indoor air quality, the IESNA Lighting Handbook (IES 2000) and the EN 12464-1:2002 (CEN 2002) for lighting; and the 2007 ASHRAE Handbook HVAC Applications, Chapter 47-Sound and Vibration Control (ASHRAE 2007f), the ANSI/ASA S12.2-2008 (ASA 2008), the ANSI/ASA S12.60-2010/Part 1 (ASA 2010) and the EN 15251: 2007 (CEN 2007) for acoustics.

When the evaluation using the Level 1 metrics indicates either excessive energy or water use or IEQ performance out of the comfort range, further evaluations using Level 2 and 3 are recommended since the Basic Level only provides an indication whereas the Level 2 and 3 are diagnostic and investigative, respectively.

2.2.1.2. Level 2: Intermediate

The Intermediate Level 2 protocol is intended to provide an enhanced level of evaluation of a building's performance. Since this Intermediate Level is expected to be applied to a small portion of the building stock where more detailed evaluation is desirable such as sustainable or high performance building, it is presented separately for each performance category. Data required for the Intermediate Level include:

- Descriptive Information: Specific building performance-related building/system characteristics;
- Subjective Measures: 'Right-now' thermal comfort occupant survey and diagnostic lighting satisfaction occupant survey; and
- Instrumented Measurements: Monthly or weekly whole-building/major system energy use; annual and monthly water use for total building, landscape and wastewater; data logging of selected IEQ parameters, including: temperature, humidity, mean radiant temperature, air speed, and CO_2 level; and spot measurements of full grid illuminance, luminance, background noise and reverberation time.

For an occupant 'right-now' thermal comfort survey, the following two databases are recommended for benchmarks: the ASHRAE RP-884 database (de Dear 1998) and the Smart Controls and Thermal Comfort (SCATs) database (Nicol and McCartney 2001) that were developed based on the survey results in 160 and 26 buildings, respectively. For the diagnostic lighting satisfaction occupant survey, there is no established benchmark information. Except for the Energy Use and Water Use section, the benchmark data sets for instrumented measures are adapted from the same standards and handbooks as the Basic Level 1, including the ASHRAE Standard 55-2004 (ASHRAE 2004) and the EN 15251: 2007 for thermal comfort (CEN 2007); the ASHRAE 62.1-2007 (ASHRAE 2007b) for indoor air quality; the IESNA Lighting

Handbook (IES 2000) for lighting; and the 2007 ASHRAE Handbook HVAC Applications, Chapter 47-Sound and Vibration Control (ASHRAE 2007f), the ANSI/ASA S12.2-2008 (ASA 2008), the ANSI/ASA S12.60-2010/Part 1 (ASA 2010) and the EN 15251: 2007 (CEN 2007) for acoustics. At the Intermediate Level, the ASHRAE PMP recommends several benchmarking database, including the electric end-use database for California commercial building (Itron 2006) and the VDI 3807 Part 4 data (VDI 2008). The resultant energy and water use metrics are expected to be used primarily as self-reference benchmarks for energy and water performance improvement. Targets can be set relative to this self-reference energy use benchmarks established for the whole-building and for the major end-use.

2.2.1.3. Level 3: Advanced

The Advanced Level 3 protocol is intended to provide a very comprehensive evaluation of a building's performance for critical situations or research purposes. Since this Advanced Level is costly, it is expected to be applied to a very small portion of the building stock. Each performance category is presented separately. The required data for the Advanced Level include:

- Descriptive Information: Detailed building performance-related building/system characteristics;
- Subjective Measures: Specialized local comfort occupant survey for asymmetrical or transient thermal environment; and
- Instrumented Measurements: Daily and hourly whole-building/major system energy use; annual and monthly water use for total building and major end-uses (i.e., landscape, HVAC/process, wastewater, gray water and hot water); data logging of selected thermal comfort parameters with a more detailed spatial resolution (i.e., temperature gradients, radiation asymmetry, and air speed distribution); data logging of CO_2, $PM_{2.5}$, and TVOCs levels; detailed illuminance and luminance measurements using HDR photography; and measurements of speech privacy, speech communication and sound and vibration isolation for acoustic evaluations.

At the Advanced Level, the resultant energy and water use metrics are expected to be used as more advanced self-reference benchmarks. To set the self-reference benchmarks for energy use, the following two approaches are suggested to be used: whole-building calibrated simulation or inverse building and systems models. The benchmark data sets for IEQ instrumented measures are adapted from the same standards and handbooks as the Level 1 and 2.

For thermal comfort, the ASHRAE RP-884 database (de Dear 1998) and the SCATs database (Nicol and McCartney 2001) also provide the main benchmarks.

2.2.2. *Instrumentation and Cost Requirements for Field Testing the ASHRAE PMP*

The instrumentation and cost requirements to field test the ASHRAE PMP were reviewed and identified for each performance metric of each level of the protocols. The performance metrics reviewed can be categorized into three groups: descriptive information, subjective measures and instrumented measures. Table 2 presents instrumentation as well as cost requirements of the subjective and instrumented measures of the ASHRAE PMP.

2.2.2.1. Level 1: Basic

The first required performance metrics of the Basic Level are the basic building and system characteristics related to building energy, water and IEQ performance. A review of facility and HVAC system documentation, an operator interview and a site assessment are recommended to collect the basic descriptive information of the building and system. For the IEQ performance characteristics, a review of complaint logs is also recommended if available. For the Basic Level instrumented measures, monthly energy and water utility bills are required to calculate annual energy use index (EUI), energy cost index (ECI), water use index (WUI) and water cost index (WCI) of the building. The U.S. EPA ENERGY STAR Portfolio Manager (EPA 2010b), a web-based energy and water management tool, is recommended for a comparison with the EUI, ECI, WUI and WCI of the candidate building for the Basic Level. To test the Basic Level IEQ protocols, a CBE or BUS occupant IEQ survey is required in addition to spot measurement instruments, including: hand-held temperature, humidity, air speed, lighting (illuminance) and sound level meters.

2.2.2.2. Level 2: Intermediate

The first required performance metrics of the Intermediate Level are the specific building and system characteristics related to building energy, water and IEQ performance. The same instrumentation as the Basic Level is recommended for these measurements, including a documentation review, an operator interview and a site assessment.

For the Intermediate Level instrumented measures, an energy monitoring system for whole-building and major end-use systems is required. For the water use, if the building has a

Table 2: Instrumentation and Cost Requirements for Field Testing of the ASHRAE PMP: Subjective and Instrumented Measures (ASHRAE 2010a)

		Energy	Water	Thermal Comfort	IAQ	Lighting	Acoustics
LEVEL 1	Performance Metric			Occupant IEQ Survey Results			
		EUI, ECI	WUI, WCI	Ta (F), RH (%), Radiation (Tg (F), MRT (F), OT (F)), Va (fpm)	OA flow (cfm), Ta (F), RH (%), CO (ppm) if needed	Illuminance level (lux, fc)	A-weighted SPL (Leq in dBA)
	Instrumentation Requirements	EPA Energy Star Rating System: Portfolio Manager & Target Finder		CBE or BUS Survey			
		Energy Utility Bills (Electricity and Natural Gas)	Water Utility Bills (Building and Landscape)	Hand-Held Temp./RH/Air Velocity Meter	1) EPA National Ambient Air Quality Standards data 2) Hand-Held Temp./RH/Air Velocity Meter	Light Meter	1) Type 1 Sound Level Meter 2) Portable Acoustic Calibrator
	Cost	$1,000 - $2,000	$1,000 - $2,000	$1,000 (Occupant IEQ Survey)			
				$1,600 - $3,400	$3,000 - $4,500	$1,000 - $3,350	$2,000 - $3,000
LEVEL 2	Performance Metric	Monthly/Weekly Energy and Demand for Whole-Building and Major Systems	Annual/Monthly Water Use for Total site, Landscaping, and Waste Water	1) Right-Now Comfort Survey Results 2) Data-Logging of Ta (F), RH (%), Radiation (Tg (F), MRT (F), OT (F)), Va (fpm)	OA flow (cfm), Data-Logging of CO_2 (ppm), OA Quality if needed	1) Diagnostic Lighting Satisfaction Survey Results 2) Full-Grid Illuminance Measurements 3) Discomfort Glare	1) Back Ground Noise (Leq in dBA) in Octave Bands 2) Reverberation Time (T_{60})
	Instrumentation Requirements	Energy (Electricity and Thermal) Monitoring System with Data Logger	Water Utility Bills (Building and Landscape)	1) Right-Now Thermal Comfort Survey 2) Temp./RH/Air Velocity Sensors with a Data Logger	Air Velocity Meter, CO_2 Sensor with a Data Logger	1) Diagnostic Lighting Satisfaction Survey 2) Light Meters or Photometric Sensors with a Data Logger	1) Type 1 Sound Level Meter with a Parallel Octave Band Filters 2) Portable Acoustic Calibrator 3) Noise Source (Loudspeakers)
	Cost	$3,000 - $11,000	$2,500 - $3,500	$25,000 - $40,000	$10,000 - $17,000	$3,450 - $10,200	$9,000 - $12,000
LEVEL 3	Performance Metric	Daily/Hourly Energy and Demand for Whole-Building and Major Systems	Annual/Monthly Water Use for Total site, Landscaping and Special End Uses (e.g. wastewater, gray water, hot water use)	1) Specialized Local Comfort Survey for Asymmetrical or Transient Thermal Environment 2) Data-Logging of Temperature Gradients and Radiation Asymmetry	Data-Logging of CO_2 (ppm), PM2.5 (mg/m^3), and TVOCs (ppm)	High-Resolution Measurement of Illuminance and Luminance using HDR Photography	1) Speech Privacy (AI, PI) and Speech Communication (SII, STI) 2) Sound and Vibration Isolation (NIC, IIC)
	Instrumentation Requirements	Energy (Electricity and Thermal) Monitoring System with Data Logger	Water Meter with Data Logger	1) Specialized Local Comfort Survey 2) Temp./RH/Air Velocity Sensors with a Data Logger	CO_2, PM2.5, and TVOCs Sensors with a Data Logger	1) HDR Cameras 2) Photosphere Software	1) Type 1 Sound Level Meter with a Parallel One-Third Octave Band Filters 2) Portable Acoustic Calibrator 3) Noise Source (Loudspeakers)
	Cost	$3,000 - $60,000	$2,500 - $3,500	$10,000 - $20,000	$37,500 - $47,500	$1,200 - $6,400	$15,000 - $20,000

separate landscape meter, monthly building and landscape water use can satisfy the instrumentation requirements of the Intermediate Level water use protocols. To test the Intermediate Level IEQ protocols, temperature, humidity, air speed, CO_2, and photometric sensors are required with a data logger for continuous and detailed measurements of several required IEQ parameters. For the acoustics, a sound pressure level meter equipped with a parallel octave band filters and a noise source (such as loudspeakers) are required to evaluate the background noise and reverberation time. Thermal comfort and lighting protocols also require subjective measurements: a right-now thermal sensation/comfort occupant survey and a diagnostic lighting satisfaction occupant survey. Both survey forms are provided in the Appendix of the ASHRAE PMP.

2.2.2.3. Level 3: Advanced

The first required performance metrics of the Advanced Level are the detailed building and system characteristics related to building energy, water and IEQ performance. In the Advanced Level, the same instrumentation as the Basic and Intermediate Level is recommended, including a documentation review, an operator interview and a site assessment.

For the Advanced Level instrumented measures, an energy monitoring system that can measure hourly or sub-hourly energy data for whole-building and major end-use systems is required. For the water use protocols, separate water meters are required for special end-use types (i.e., HVAC/process, wastewater, gray water, and hot water). To test the Advanced Level IEQ protocols, temperature, humidity, air speed, CO_2, $PM_{2.5}$, and TVOCs sensors are required with a data logger for more detailed and continuous measurements of thermal and IAQ environments. For the lighting, a HDR camera and software that can create a HDR image such as Photosphere (Anyhere 2010) are required. For the acoustics, a sound pressure level meter equipped with a parallel one-third octave band filters and a noise source such as loudspeakers are required to evaluate the speech privacy, speech communication and sound and vibration isolation. Thermal comfort protocols also require subjective measurements: a specialized local comfort occupant survey for asymmetrical or transient thermal environment. The survey form is provided in the Appendix of the ASHRAE PMP.

2.2.3. *Comparisons of the ASHRAE PMP with the Existing Procedures on Building Performance Measurements*

There have been numerous documents that address building performance measurements (ASA 2008 and 2010; ASHRAE 2002, 2004, 2007a, 2007b, 2007c and 2010; CEN 2002, 2007 and 2008a; CIBSE 2006a, 2006b and 2008; DOE 2002b; EVO 2009; FEMP 2008; IES 2000; ISO 1998, 2002 and 2005; VDI 2000; NEEB 2006), yet inconsistencies still exist between the different approaches. Table 3 summarizes the characteristics of these different publications. In general, most of these documents cover only a single aspect of building performance, which makes them narrow in scope. Of the documents surveyed, none covered a building's overall performance measurements, including: energy use, water use, thermal comfort, indoor air quality, lighting and acoustics. Therefore, it appears the ASHRAE PMP represent the first comprehensive, multi-level protocols that cover a building's overall performance. As shown in Table 3, many of the previous protocols provide measurement methods for selected measures and benchmarks for a comparison. However, few covered instrumentation and cost information.

2.2.4. *Summary of the ASHRAE PMP Literature Review*

The review and comparisons of the ASHRAE/CIBSE/USGBC Performance Measurement Protocols for Commercial Buildings with the existing building performance measurement procedures reveal that the ASHRAE PMP is the first integrated protocol on building performance measurement, including energy use, water use and IEQ. However, some of the performance measurement methods, metrics and instrumentation in the first version of the ASHRAE PMP are not clearly defined, and there are several issues missing from the protocols, including equipment calibration, measurement protocols, sampling methods and issues regarding measurement length and data frequency intervals. In addition, some metrics of certain performance categories overlap each other. Thus, for the current version of the ASHRAE PMP to become more than a combination of each performance category in one document, it needs to be tested in a real building and ratings from the three levels compared.

Table 3: Comparison of Building Performance Measurement Procedures

Building Performance Measurement Publications		Energy	Water	Thermal Comfort	IAQ	Lighting	Acoustics	Methods	Instrumentation	Benchmarks	Cost
No.	**Name**	**Performance Category**									
1	ASHRAE/CIBSE/USGBC PMP (ASHRAE 2010)	√	√	√	√	√	√	√	√	√	√
2	ASHRAE Standard 105-2007 (ASHRAE 2007a)	√						√			
3	ASHRAE Guideline 14-2002 (ASHRAE 2002)	√	√					√	√		√
4	IPMVP Volume I:2009 (EVO 2009)	√	√					√	√		√
5	IPMVP Volume II:2002 (DOE 2002b)			√	√	√		√	√		√
6	EN 15603:2008 (CEN 2008a)	√						√			
7	CIBSE TM22:2006 (CIBSE 2006a)	√						√		√	
8	CIBSE TM39:2006 (CIBSE 2006b)	√						√	√		√
9	CIBSE TM46:2008 (CIBSE 2008)	√								√	
10	VDI 3807 Part3: 2000 (VDI 2000)		√							√	
11	FEMP Guidance to Federal Agencies for Determining Baseline Water Usage (FEMP 2008)		√					√			
12	ANSI/ASHRAE Standard 55-2004 (ASHRAE 2004)			√				√		√	
13	ISO 7726:1998 (ISO 1998)			√				√	√		
14	ISO 7730:2005 (ISO 2005)			√				√		√	
15	EN 15251:2007 (CEN 2007)			√	√	√	√	√		√	
16	ANSI/ASHRAE Standard 62.1-2007 (ASHRAE 2007b)				√			√		√	
17	EN 12464-1: 2002 (CEN 2002)					√		√		√	
18	ISO/CIE 8995-1:2002 (ISO 2002)					√		√		√	
19	IESNA Lighting Handbook, 9th ed. (IES 2000)					√		√	√	√	
20	ASHRAE HVAC-Induced Room Noise Measurement Procedure (ASHRAE 2007c)						√	√	√		
21	NEBB Sound and Vibration Measurement Procedural Standards, 2nd ed. (NEBB 2006)						√	√	√		
22	ANSI/ASA S12.2-2008 (ASA 2008)						√	√		√	
23	ANSI/ASA S12.60-2002 (ASA 2002)						√	√	√	√	
Percent of Total		**35%**	**22%**	**26%**	**17%**	**26%**	**26%**	**91%**	**43%**	**57%**	**22%**

2.3. Building Performance Labeling Programs for Existing Commercial Buildings

In recent years, there have been several efforts to label a building's performance and compare the performance of one building with other similar building, including the U.S. EPA ENERGY STAR (EPA 2010a), the ASHRAE Building Energy Labeling (ABEL) (ASHRAE 2010b), and the European Union (EU) Energy Performance of Buildings Directive (EPBD) (European Commission 2010). These labeling programs focus on a measured energy performance of the building rather than other performance categories such as water use and IEQ performance.

2.3.1. *U.S. EPA ENERGY STAR*

The U.S. EPA ENERGY STAR labeling program rates a buildings' energy performance on a scale of 1–100 against a peer group of facilities, with adjustments for climate, facility size, hours of operation, and the number of occupants. To obtain an ENERGY STAR Label, the users are required to enter 12 consecutive months of energy use data for all fuel types used in the building into the ENERGY STAR Portfolio Manager (EPA 2010b). Then the Portfolio Manager converts the annual site energy consumption of the building into the total equivalent source energy use using the national average source-site ratios. The peer group database for a comparison is derived from the U.S. DOE Energy Information Administration's (EIA) national survey known as Commercial Building Energy Consumption Survey (CBECS) (EIA 2003). Top-rated buildings above 75 qualify for the ENERGY STAR Label. The buildings that demonstrate improvements in reducing their energy use at 10%, 20%, 30% may qualify to be an ENERGY STAR Leader. Although the qualification for the ENERGY STAR Label or Leader designation is decided based on the operational energy performance of the building, it also requires a simple verification of a building's IEQ performance (i.e., thermal comfort, IAQ, and lighting) against industry standards.

2.3.2. *ASHRAE Building Energy Labeling (ABEL)*

The ASHRAE ABEL program (ASHRAE 2010f) is a new building energy labeling program. There are seven performance categories in the ABEL program: net-zero energy (A+), high performance (A), very good (A-), good (B), fair (C), poor (D), and unsatisfactory (F), which allows greater differentiation for net-zero or high performance buildings compared with the ENERGY STAR rating system. The ABEL program uses the operational ratings of the building to label the existing buildings' performance. The operational rating is the ratio of an annual normalized source Energy Use Index (EUI) of the building to the median energy use of the corresponding building type. To calculate a source EUI of the building normalized with climate, occupancy or building function, the ABEL program requires using the ENERGY STAR Portfolio Manager (EPA 2010b). For the median energy use data, it requires using the ENERGY STAR Target Finder (EPA 2010c) program. Although the performance category of the ABEL program is decided using the energy performance of the building, the ABEL requires a building IEQ assessment that includes both an occupant survey and spot measurements of selected thermal, IAQ, and lighting parameters. In addition to the operational ratings, the ABEL program will include the asset ratings (i.e., designed rating) of the building using the results of a building energy model for both new and existing buildings in the near future.

2.3.3. *EU Energy Performance of Buildings Directive (EPBD) Energy Performance Certificate*

Article 7 of EU Directive 2002/91/EC (2003) requires an Energy Performance Certificate for all buildings when constructed, sold or rented. There are two different types of the certificates for commercial buildings: Display Energy Certificates (DEC) based on operational ratings and Energy Performance Certificate (EPC) based on asset ratings. The DECs are required for all public buildings and institutions with a floor area over 1,000 m^2. The certificate typically includes an energy efficiency category that ranges from A (Best) to G (Worst). This classification is based on the Energy Performance (EP) indicator that can be determined according to the EN 15217:2007 (CEN 2008b). The EP can represent primary energy, CO_2 emissions, net delivered energy, or cost. The boundary of each energy efficiency category is also determined according to the EN 15217:2007 using two reference values: an Energy Performance Regulation Reference[12] or a Building Stock Reference[13].

[12] An Energy Performance Regulation Reference corresponds to the value that is typically required by energy performance regulations for new buildings (CEN 2008b).

[13] A Building Stock Reference corresponds to the median energy performance value of the national or regional building stock (CEN 2008b).

2.3.4. *Summary of Building Performance Labeling Programs*

The review of building performance labeling programs for the existing commercial buildings reveals that current building performance labeling programs focus on a single attribute of a building performance, energy use, rather than on an overall building performance. Thus there is a need for a new comprehensive, figure-of-merit labeling system or methodology that covers all aspects of a building's overall performance.

2.4. Summary of Literature Review

This literature review presented an overview of previous studies on building performance measurements for each performance category (i.e., energy use, water use, thermal comfort, indoor air quality, lighting, and acoustics), a review of the ASHRAE/CIBSE/USGBC Performance Measurement Protocols (PMP) for Commercial Buildings, including comparisons with other existing procedures of building performance measurement, and a review of current building performance labeling programs. Research into building IEQ performance measurements started in the early 20th century. Professional societies were launched about the same time for the respective fields of study (i.e., thermal comfort, IAQ, lighting, and acoustics). In the early 1970s, a major shift took place after the first energy crisis. To reduce the energy cost, several M&V and building energy monitoring protocols and procedures were developed. At the same time, many thermal comfort field studies were carried out to validate the universally applicable, constant, comfort temperature based on Fanger's PMV and PPD indices, partly due to an energy savings potential of the Adaptive Model. Unfortunately, the energy crisis reduced outside air intake, which may have contributed to sick building syndrome (SBS) and building-related illness (BRI), and as a result, numerous IAQ assessment field studies were performed to better understand the phenomena. The major findings from the literature review on previous building performance studies include:

- Energy: The existing procedures mainly focus on energy performance only although many energy retrofit projects affect the IEQ performance of the building related to thermal comfort, IAQ, lighting, and acoustics. There is lack of reliable benchmarking data that includes detailed energy monitoring data (i.e., hourly or sub-hourly energy use of whole-building and major end-uses with the coincident weather data).

- Water: Some efforts to establish a standardized procedure for quantifying the amount of water used in buildings or major water-consuming equipment were made as a part of energy management programs and water conservation practices. However, there are few discussions about standardized water data collection and analysis procedures.
- Thermal Comfort: Basic measurement protocols and metrics (i.e., air temperature, humidity, mean radiant temperature, air speed, clothing, and activity) of today's thermal comfort standards were established in the 1970s, and such measurements have been widely used by thermal comfort researchers. However, there is a lack of validated questionnaire modules that can access a building's thermal comfort performance from the perspective of the occupants beyond comfort votes.
- IAQ: There are a number of performance metrics in IAQ research due to the wide variety of indoor air compounds although CO_2 and CO are widely used as basic indicators. Some efforts were made to develop a standardized IEQ investigation procedure, including the U.S. EPA protocol in 1994. However, its practicability and cost-effectiveness needs further study since the protocol was specially designed for the high accuracy requirements of the U.S. EPA's ORIA BASE study. In addition, the measurement of indoor air speed and flow was not addressed.
- Lighting: The basic measurement metrics (i.e., illuminance, luminance and luminance ratio, and discomfort glare) to evaluate lighting performance in buildings were well established and have been widely investigated in many studies since the 1900s. However, there remains a lack of standardized field measurement procedures to quickly access a building's lighting performance over all hours of the day, across different seasons of the year.
- Acoustics: The basic measurement protocols and metrics (i.e., A-weighted sound pressure level, NC, RC, BNC, RC Mark II, and reverberation time), instrumentation, and calibration requirements to evaluate acoustical performance in buildings are well established and have been widely investigated in many studies since the early 1900s. However, most methods focus on quantitative measurements of sound levels and do not include an occupant's subjective assessment of their acoustical environment.

Although a number of studies on building performance measurements have been conducted and numerous efforts have been made to develop a standardized building performance measurements procedures for the respective fields of study (i.e., energy use, water use, thermal comfort, IAQ, lighting, and acoustics), there remains a need for an integrated protocol for building performance measurement, which would include energy use, water use, thermal comfort, IAQ, lighting, and acoustics. Thus as the first integrated protocol on building performance measurement, the ASHRAE PMP is expected to be used as a tool to identify building performance-related problems and to verify green building practices.

However, some of the performance measurement methods, metrics and instrumentation in the first version of the ASHRAE PMP are not clearly defined, and there are several issues missing from the protocols, including: equipment calibration, measurement protocols, sampling methods and issues regarding measurement length and data frequency intervals. In addition, some metrics of certain performance categories overlap each other. Thus for the current version of the ASHRAE PMP to become more than a combination of each performance category in one document, it needs to be tested in a real building and ratings from the three levels compared. In addition, current building performance labeling programs focus on a single attribute of a building performance, energy use, rather than on an overall building performance. Thus, there is a need for a new comprehensive, figure-of-merit labeling system or methodology that covers all aspects of a building's overall performance.

CHAPTER III
SIGNIFICANCE OF THE STUDY

3.1. Significance of the Study

A proposed new or modified approach derived from the case study will contribute to enhancing the validity, reliability, and practicality of the ASHRAE PMP for its best possible implementation in practice. In addition, recommendations developed for a figure-of-merit for rating a building's overall performance based on the ASHRAE PMP are expected to allow users to rate a building's overall performance in a figure-of-merit, which will also contribute to the verification of green building technologies and practices from all aspects of building performance, including energy, water, and IEQ.

3.2. Limitations of the Study

There are some limitations in the proposed research. The ASHRAE PMP will be tested using a case study of one office building in College Station, TX. Therefore, this case-study building may not represent all aspects of all office buildings in USA. Likewise, the field test that will be developed and the evaluations of the protocols will be limited to the characteristics of the case-study building. Other buildings with different HVAC systems and other building characteristics in different climates may lead to different conclusions. In addition, the recommendations developed for a figure-of-merit for rating a building's overall performance is limited to energy use, water use and IEQ performance of the building. Sustainability, carbon and other emission impacts will not be directly considered.

CHAPTER IV
METHODOLOGY*

This chapter describes the methodology used in this study. This study was performed in three phases: Phase I: Field test of the ASHRAE PMP; Phase II: Proposed new or modified approaches to improve the ASHRAE PMP; and Phase III: Recommendations for a new figure-of-merit for rating a building's overall performance based on the ASHRAE PMP. The following Sections 4.1 to 4.3 provide detailed description of the methodologies and approaches used to address each phase.

4.1. Phase I: Field Test of the ASHRAE PMP

Based on a review of the ASHRAE PMP and previous studies on building performance measurements as well as market research on measurement instruments, a field test was developed and applied to data taken from the case-study office building. Table 4 presents the protocols that were field tested under this study. For the Basic and Intermediate Levels, all six performance areas were covered. For the Advanced Level, water and acoustics protocols were not tested.

Table 4: Tested Protocols

Area/Protocol	Basic (Level 1)	Intermediate (Level 2)	Advanced (Level 3)
Energy	Yes	Yes	Yes
Water	Yes	Yes	No
Thermal Comfort	Yes	Yes	Yes
IAQ	Yes	Yes	Partially
Lighting	Yes	No (Modified)	Yes
Acoustics	Yes	No (Modified)	No

* Part of this chapter is reprinted with permission from "Field-Test of the New ASHRAE/CIBSE/USGBC Performance Measurement Protocols for Commercial Buildings: Basic Level." By Kim and Haberl, 2012a. *ASHRAE Transactions* 118(1):135-142, Copyright 2012 by ASHRAE; and from "Field-Test of the New ASHRAE/CIBSE/USGBC Performance Measurement Protocols: Intermediate and Advanced Level Indoor Environmental Quality Protocols" By Kim and Haberl, 2012b. *ASHRAE Transactions* 118(2), Copyright 2012 by ASHRAE.

4.1.1. *Case-Study Building Description*

The seven-story, case-study building is an office building in College Station, Texas. The building was constructed in 1992 and currently serves as one of the Texas A&M University facilities occupied by about 323 employees. The conditioned floor area of the building is 123,960 ft^2. The windows are non-operable, double-pane, tinted glazing with a window-to-wall ratio of approximately 40%. The space use includes: offices, meeting rooms, and a gym. The gym has shower facilities with a total of six shower stalls. Figures 1 to 5 show photos of the case-study building and the building's thermal plant. Figures 6 and 7 show a typical private and open office of the building.

The building is served by 17 single duct variable air volume (SDVAV) air handling units (AHUs) with variable frequency drives (VFDs) and two 100% outside air AHUs that provide the SDVAV units with conditioned outside air. There are 230 series fan powered VAV terminal boxes with hot water reheat coils. The stand-alone thermal plant of the building has two 280-ton (3.36 MMBtu/h) centrifugal chillers and two 1.68 MMBtu/h hot water boilers with an input capacity of 2.10 MMBtu/h. The cooling loads of the case-study building are normally met by running one chiller. Chillers are sequenced to run equal amounts of time each year. Service water heating is provided by a 300 gallon natural gas fired water heater with a rated heat input capacity of 0.80 MMBtu/h.

The building has two separate water meters (i.e., the main building meter and a landscape meter) installed by the College Station Utilities. Figure 8 shows the building and some of the landscape covered by the meters. Currently, there are approximately 2.0 acres of landscape, including 1.76 acres (76,850 ft^2) of irrigated turf and 0.23 acres (10,000 ft^2) of irrigated landscape beds around the building. About 0.1 acres (4,500 ft^2) of irrigated turf were added during the winter of 2009-2010.

Figure 1: Front View of the Case-Study Building (West Façade)

Figure 2: Back View of the Case-Study Building (East Façade)

Figure 3: Right View of the Case-Study Building (South Façade)

Figure 4: Left View of the Case-Study Building (North Façade)

Figure 5: Thermal Plant of the Case-Study Building

Figure 6: Interior View of Typical Private Office Space of the Case-Study Building

Figure 7: Interior View of Typical Open Office Space of the Case-Study Building

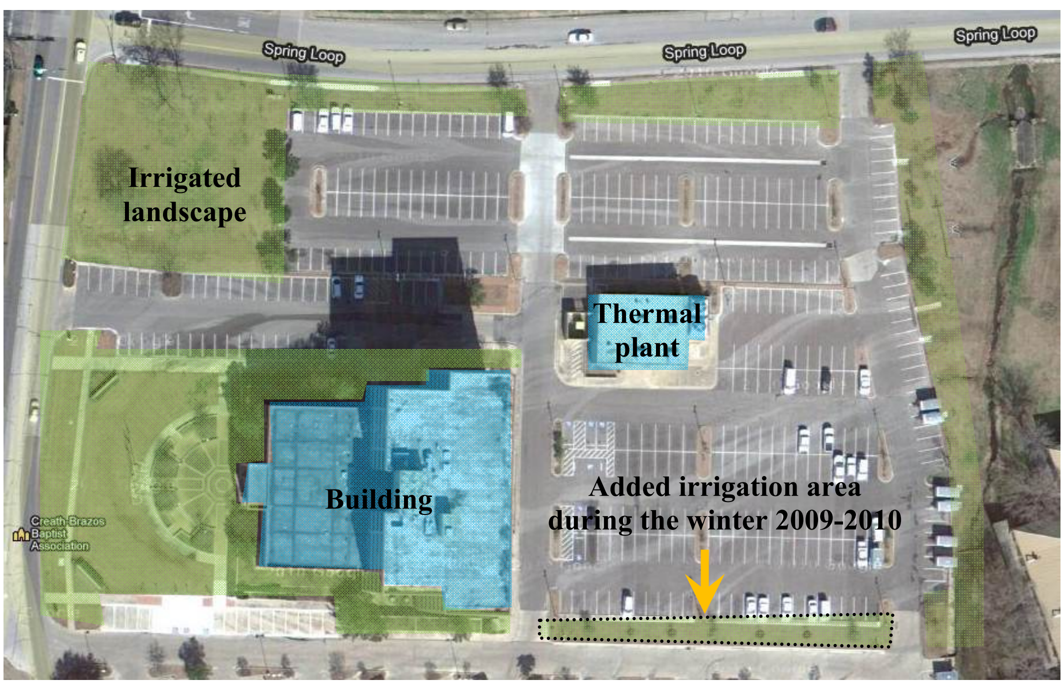

Figure 8: Case-Study Building and the Irrigated Landscape Areas

4.1.2. ***Energy Use***

4.1.2.1. Basic Level

The performance metrics required at the Basic Level energy protocol are an annual whole-building energy use index (EUI) and an energy cost index (ECI) with basic energy-related building/system characteristics. The case-study building uses two forms of energy: electricity and natural gas. Monthly electric utility bills for the case-study building were collected from September 2006 to November 2011, and monthly natural gas utility bills were collected from February 2009 to November 2011[14]. For the billing periods between September 2006 and January 2009, the original natural gas utility bills were not available[15]. However, consumption and cost data for natural gas was available from a database without specific billing dates. Once the data were collected, the EUIs and ECIs of the building were calculated and compared with the appropriate benchmarks.

4.1.2.2. Intermediate and Advanced Level

The performance metrics required at the Intermediate Level energy protocol are monthly or weekly whole-building/major system energy use and demand with specific energy-related building/system characteristics. At the Advanced Level, the required metrics are daily and hourly whole-building/major system energy uses and demands with detailed energy-related building/system characteristics.

The measurements of electricity use for the case-study building used sub-hourly (15 minute interval) data collected from a previously installed data logger in the thermal plant of the building (Kim and Haberl 2009) as well as monthly utility bills. For the building's monthly natural gas consumption, the monthly utility data, which was previously collected at the Basic Level, was used. All data were then analyzed and compared with the appropriate benchmarks.

Table 5 lists the measurement parameters and instrumentation of the 22 sensors installed in the thermal plant of the case-study building for electric, thermal, and on-site weather monitoring. The Synergistic data logger collected data from 19 sensors in 15 minute intervals since October 1998. In 2006, three additional channels to capture the electricity used by the Motor Control Centers (MCC) were added. In this study, the data collected from May 2008 to

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[14] This study limited the analysis period to November 2011 due to a change of occupancy in a case-study building in December 2011.
[15] Before February 2009, the case-study building was part of overall natural gas transportation invoice, which covered about 60 buildings.

Table 5: Energy Monitoring System Measurement Parameters and Instrumentation (Kim and Haberl 2009)

	Channel Type[1]	Parameter	Instrumentation	Start	Last Replacement	Last Verification	Unit
Electric	CT0	Chilled Water Pumps (power, A1B1/A1B1)	1. ETL Testing Lab. 100A 4LS Type Current Transducers 2. Ohio Semitronics Watthour Transducer (WL-3968)	10/2/98	–	4/29/10	kWh
	CT1	Chilled Water Pumps (power, C1B1/C1B1)	1. ETL Testing Lab. 100A 4LS Type Current Transducers 2. Ohio Semitronics Watthour Transducer (WL-3968)	10/2/98	–	4/29/10	kWh
	CT2	Motor Control Centers (power, A1N1)	1. ETL Testing Lab. 600A 4LS Type Current Transducers 2. Ohio Semitronics Watthour Transducer (WL-3968)	2/9/06	–	4/29/10	kWh
	CT3	Motor Control Centers (power, B1N1)	1. ETL Testing Lab. 600A 4LS Type Current Transducers 2. Ohio Semitronics Watthour Transducer (WL-3968)	2/9/06	–	4/29/10	kWh
	CT4	Motor Control Centers (power C1N1)	1. ETL Testing Lab. 600A 4LS Type Current Transducers 2. Ohio Semitronics Watthour Transducer (WL-3968)	2/9/06	–	4/29/10	kWh
	D0	Whole-Building Electricity	1. ETL Testing Lab. 3000A 4LS Type Current Transducers 2. Ohio Semitronics Watthour Transducer (WL-3968)	10/2/98	–	4/29/10	kWh
	D1	Office Building Electricity	1. ETL Testing Lab. 3000A 4LS Type Current Transducers 2. Ohio Semitronics Watthour Transducer (WL-3968)	10/2/98	–	–	kWh
	D2	Chiller 1 & 2 Electricity	1. ETL Testing Lab. 600A 4LS Type Current Transducers 2. Ohio Semitronics Watthour Transducer (WL-3968)	10/2/98	–	4/29/10	kWh
Thermal	A0	Chiller 1 Water Flow	Emerson DMT-25 Annubar Flow Meter with Kele DT13 Output Transducer	10/2/98	–	7/4/06 - 7/10/06	GPM
	A1	Chiller 1 Supply Water Temperature	Minco 1000 Ohm RTD Sensor (S623 PF100Y24T)	10/2/98	4/29/10	4/29/10	F
	A2	Chiller 1 Return Water Temperature	Minco 1000 Ohm RTD Sensor (S623 PF100Y24T)	10/2/98	2/9/10	2/9/10	F
	A3	Condenser 1 Water Flow	Emerson DMT-25 Annubar Flow Meter with Kele DT13 Output Transducer	10/2/98	–	7/4/06 - 7/10/06	GPM
	A4	Condenser 1 Supply Water Temperature	Minco 1000 Ohm RTD Sensor (S623 PF100Y24T)	10/2/98	2/9/10	2/9/10	F
	A5	Condenser 1 Return Water Temperature	Minco 1000 Ohm RTD Sensor (S623 PF100Y24T)	10/2/98	2/9/10	2/9/10	F
	A6	Chiller 2 Water Flow	Emerson DMT-25 Annubar Flow Meter with Kele DT13 Output Transducer	10/2/98	–	7/4/06 - 7/10/06	GPM
	A7	Chiller 2 Supply Water Temperature	Minco 1000 Ohm RTD Sensor (S623 PF100Y24T)	10/2/98	2/9/10	2/9/10	F
	A8	Chiller 2 Return Water Temperature	Minco 1000 Ohm RTD Sensor (S623 PF100Y24T)	10/2/98	2/9/10	2/9/10	F
	A9	Condenser 2 Water Flow	Emerson DMT-25 Annubar Flow Meter with Kele DT13 Output Transducer	10/2/98	–	7/4/06 - 7/10/06	GPM
	A10	Condenser 2 Supply Water Temperature	Minco 1000 Ohm RTD Sensor (S623 PF100Y24T)	10/2/98	2/9/10	2/9/10	F
	A11	Condenser 2 Return Water Temperature	Minco 1000 Ohm RTD Sensor (S623 PF100Y24T)	10/2/98	2/9/10	2/9/10	F
Weather	A12	Outdoor Temperature	Vaisala Temp. & RH Transmitter HMD 60Y	10/2/98	11/19/09	11/19/09	F
	A13	Outdoor RH		10/2/98	11/19/09	11/19/09	%

NOTES:

1) CT=Power channel; D=Digital channel; A=Analog channel

November 2011 was used[16]. Figure 9 shows the electric monitoring diagram of the case-study building. Figures 10 to 17 show photos of data acquisition system and instrumentation for electric, thermal, and weather monitoring.

Readings from current transducers were verified on March 2010 using a hand-held Fluke 39 power meter. The Resistance Temperature Detector (RTD) temperature sensors for chilled water and condenser water supply and return temperature were replaced in February 2010. The temperature readings of each channel were verified using a calibrated, hand-held Fluke 52 K/J thermometer with K-type thermocouples. The old Vaisala HMD60Y temperature and humidity transmitter for outdoor temperature and humidity at the site was replaced in November 2009. Before the installation, the electric signals from the channels for outdoor temperature and humidity to the logger were verified using an ALTEK Model 245 20mA Signal Analyzer. After the installation, the outdoor temperature and humidity readings were verified using a calibrated, portable Vaisala HMI 41 humidity and temperature indicator with HMP 42 probe.

For a weekly inspection of the collected energy use data, the data are plotted with the National Oceanic and Atmospheric Administration (NOAA) National Climatic Data Center (NCDC) weather data (NCDC 2012) which is collected at the College Station Easterwood Airport and with the Solar Test Bench (STB) data (ESL 2012) which is collected on the roof of the Texas A&M Langford Architecture Center. These weekly inspection plots were designed to help in finding damaged or malfunctioning sensors. If an abnormal usage pattern is detected, the analysis of this abnormal pattern with the coincident weather data may explain the situation. If this doesn't give an enough answer, an inspection of the corresponding sensor or data logger may be required. The outdoor temperature and humidity readings at the site can be directly verified by comparing with the NOAA and STB weather data.

[16] The data had not been collected between January 2007 and April 2008.

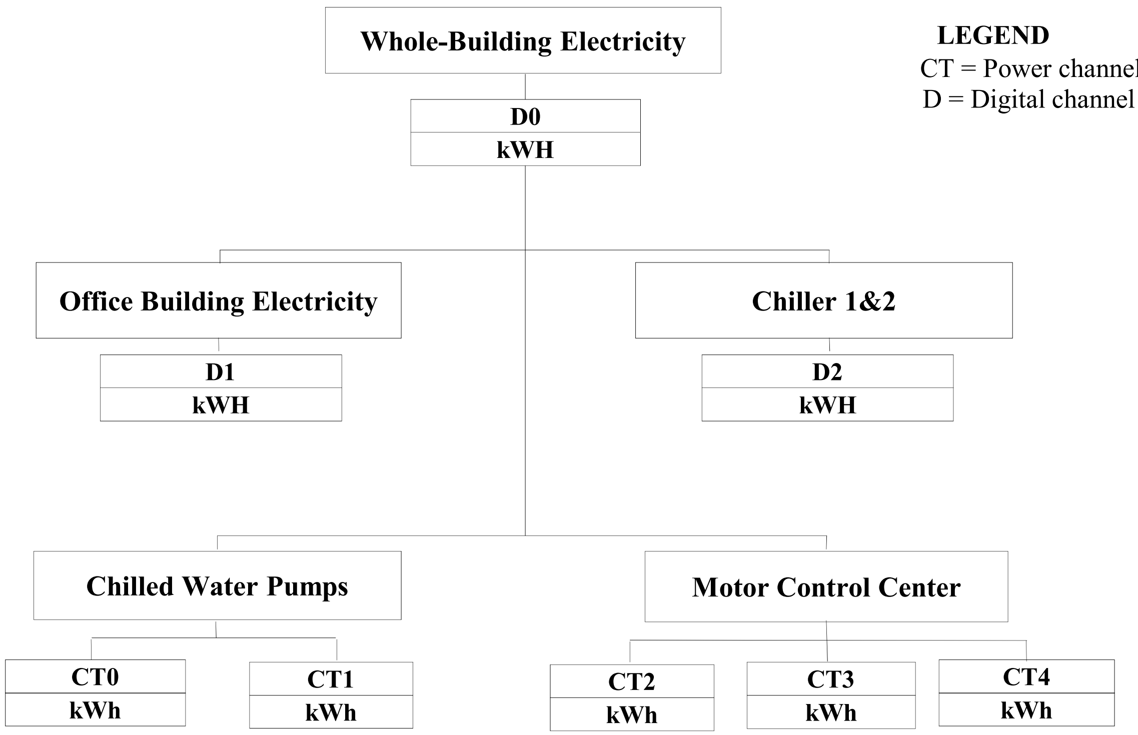

Figure 9: Electric Monitoring Diagram for the Case-Study Building (Kim and Haberl 2009)

Figure 10: Data Acquisition System and Electric Monitoring Instrumentation

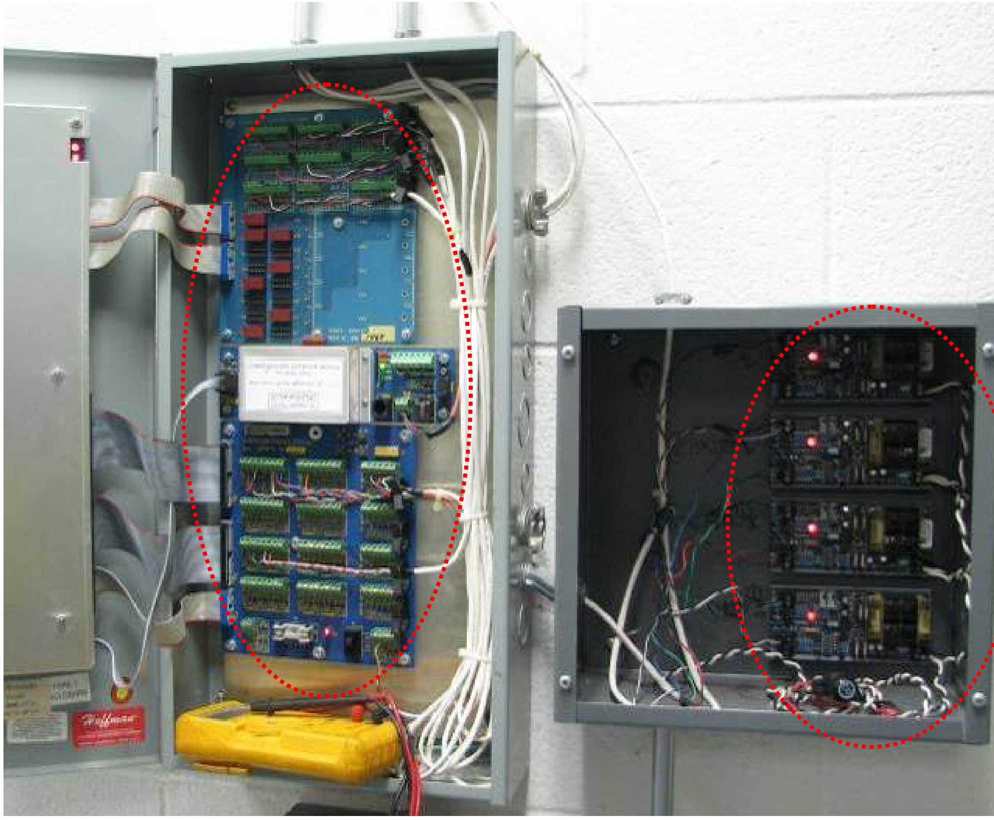

Figure 11: Synergistic Data Logger (Left) and Kele DT13 Output Transducer for Chiller and Condenser Water Flow Meters (Right)

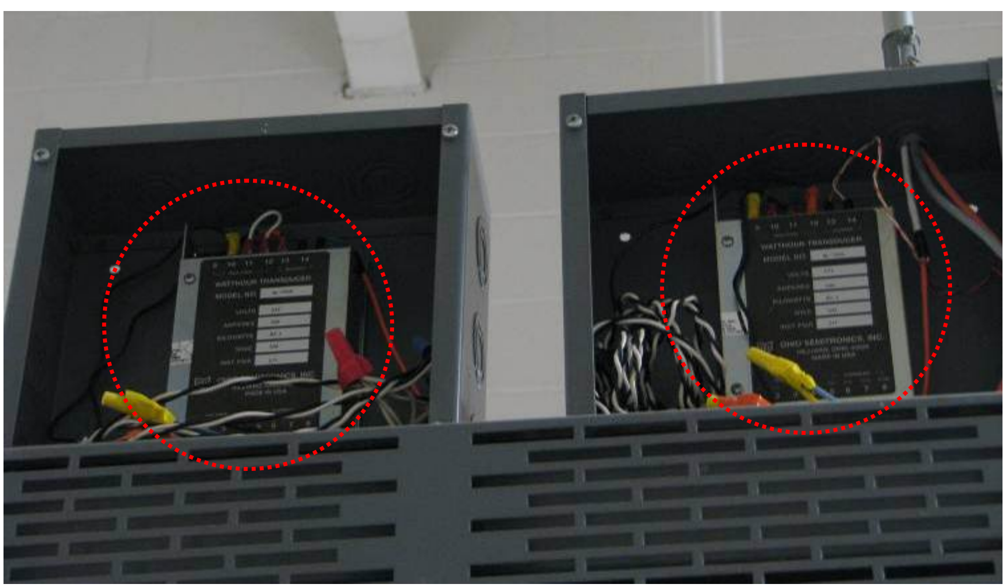

Figure 12: Watt-Hour transducers for Main Office Building Electricity Use (Left) and Chiller Electricity Use (Right)

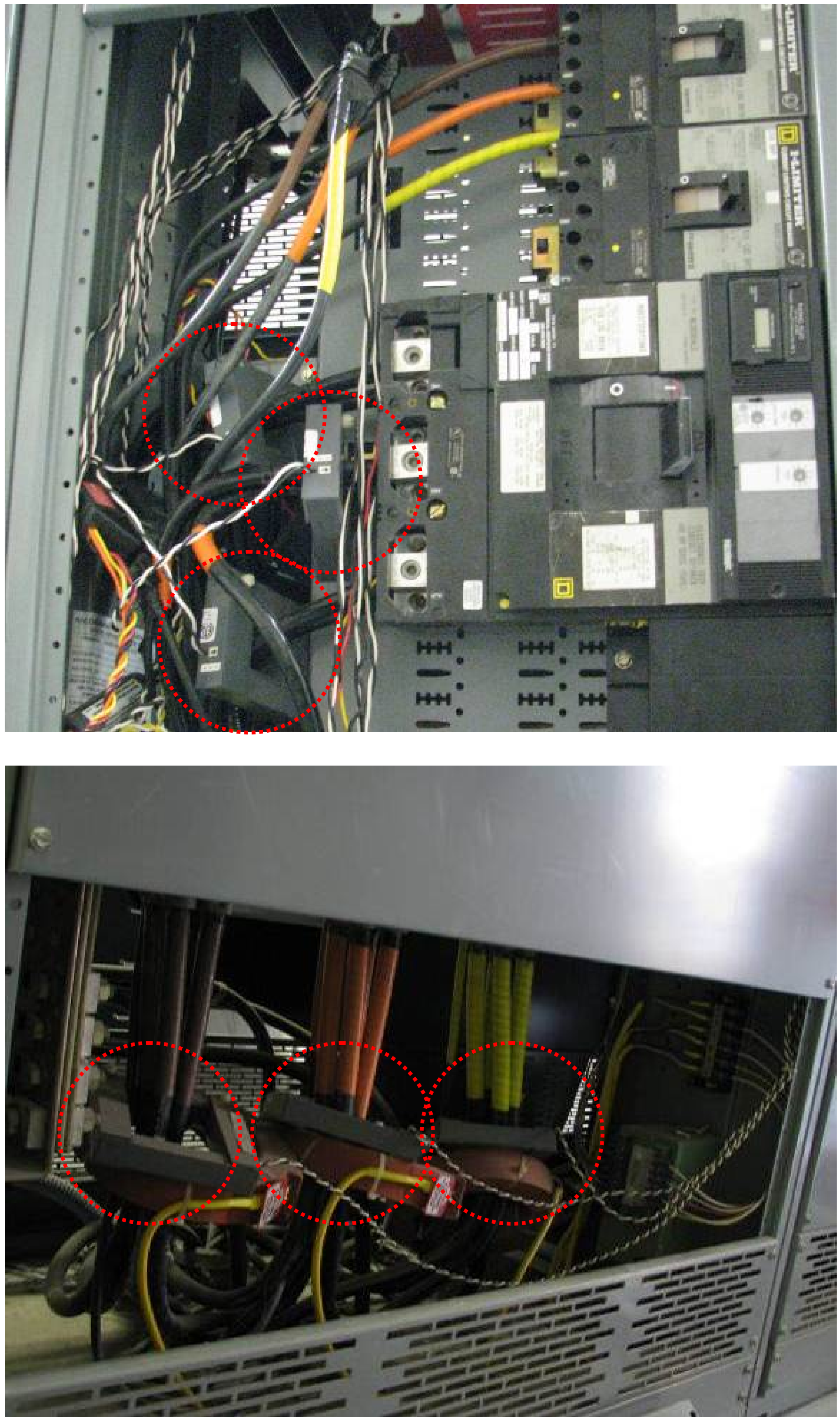

Figure 13: Current Transducers for Chiller Electricity Use (Upper) and Whole-Building Electricity Use (Lower)

Figure 14: RTD Sensors for Chilled Water Supply (Upper) and Return (Lower) Temperatures

Figure 15: RTD Sensors for Condenser Water Temperatures

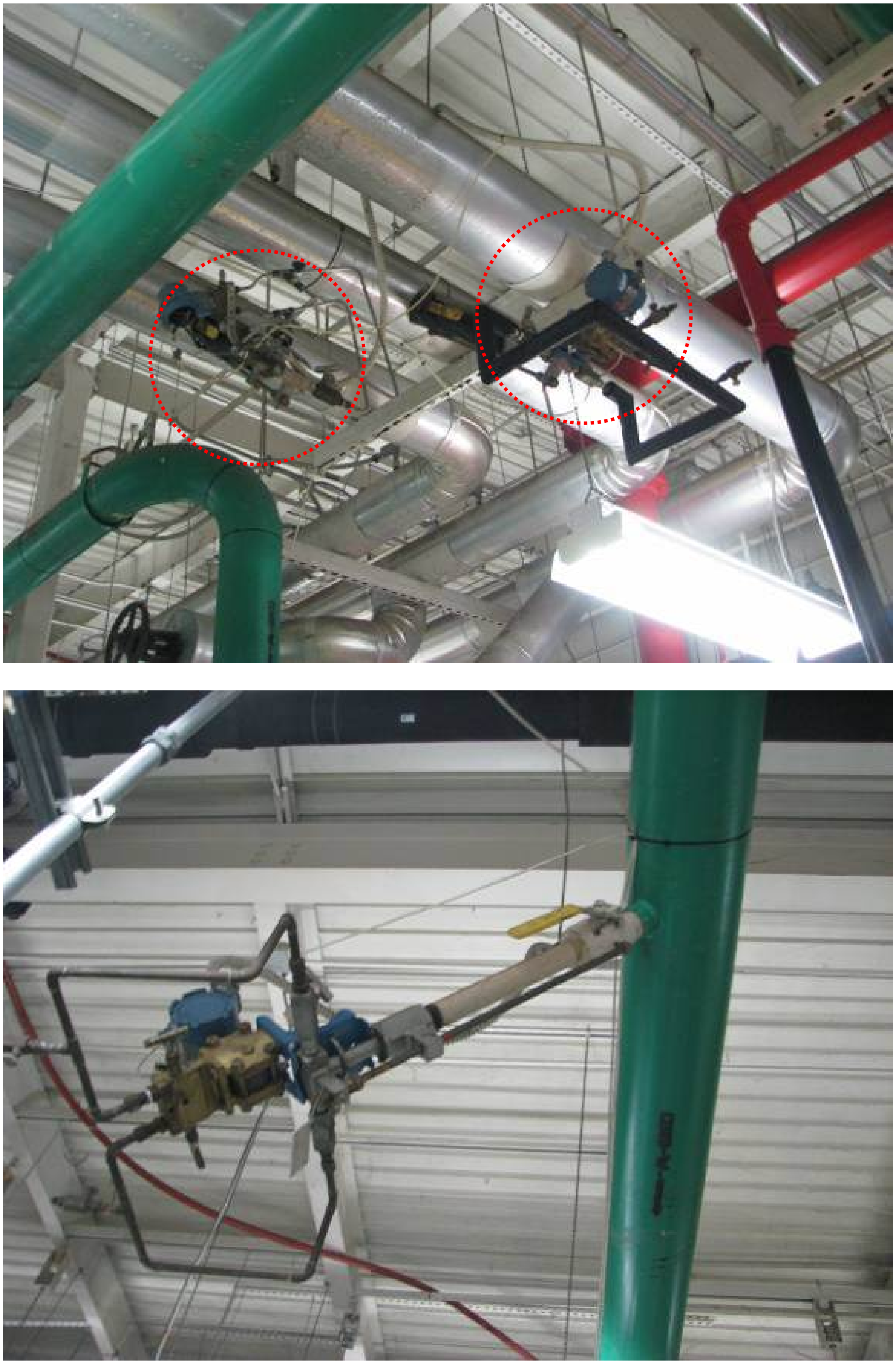

Figure 16: Flow Meters for Chilled Water (Upper) and Condenser Water (Lower)

Figure 17: Outdoor Temperature and Humidity Transmitter Installed on the North Façade of the Thermal Plant with a Radiation Shield and Bug Screen

4.1.3. *Water Use*[17]

4.1.3.1. Basic Level

The performance metrics required at the Basic Level water protocol are an annual total site water use index (WUI) and a water cost index (WCI) with basic information about water-related building/system and landscaping characteristics. Measurements of water use of the building used monthly utility bills from the two separate water meters (main building and landscape) installed by the College Station Utilities. Monthly water utility bills for the case-study building were collected from September 2006 to November 2011, but the analysis was performed for the data collected between January 2008 and November 2011 due to reliability issues in 2007 data[18]. Once the data was collected, the WUIs and WCIs of the building were calculated and compared with the appropriate benchmarks for Level I.

4.1.3.2. Intermediate Level

The performance metrics required at the Intermediate Level water protocol are the annual and monthly water uses for the total building, landscape and wastewater use with information about specific water-related building/system and landscaping characteristics. Measurements of the water use of the building used the monthly utility data collected at the Basic Level. The collected data were then analyzed and compared with the appropriate benchmarks for Level II.

4.1.4. *IEQ (Thermal Comfort, IAQ, Lighting and Acoustics)*

4.1.4.1. Basic Level

The common IEQ performance metrics required at the Basic Level are the results of the occupant IEQ satisfaction survey and spot measurements of several IEQ parameters with information about the Basic Level IEQ-related building/system characteristics. First, to measure the subjective IEQ performance of the building, which includes occupants' satisfaction and self-reported productivity, paper-based IEQ assessment questionnaire surveys were conducted using the survey tool developed by the Center for the Built Environment (CBE) at the University of

[17] The Advanced Level water protocol was not tested in this study.
[18] The monthly landscape water use billed for July 2007 is 2 kgal/mo, which is extremely lower than the consumption of other years in July: 362 kgal/mo in 2008, 425 kgal/mo in 2009, 237 kgal/mo in 2010, and 337 kgal/mo in 2011. Conversations with the facility personnel could not reveal the reasons of this extremely low landscape water use in July 2007, which would be the peak irrigation season of the case-study building's landscape.

California, Berkeley (CBE 2008). To observe changes in the building's IEQ performance that may be seasonal, the survey was conducted twice, once in May 2010 and again in February 2011.

The CBE survey itself was designed to take an occupant 10 to 15 minutes to complete. The survey questions consist of an evaluation of seven indoor environmental quality topics, including: office layout, office furnishings, thermal comfort, air quality, lighting, acoustics, and cleaning/maintenance, with a background survey (i.e., gender, age, etc.). For each IEQ topic area, the occupant's satisfaction was evaluated using a 7-point satisfaction scale (3: very satisfied, 0: neutral, -3: very dissatisfied) followed by branching questions[19] to identify the sources of discomfort, as shown in Figure 18. Figure 19 shows the 7-point CBE self-reported productivity scale (3: enhances, 0: neutral, -3: interferes) used in this study. A complete questionnaire survey form as well as contact letters used in this study are presented in the Appendix A.

A total of 250 questionnaires were distributed randomly to the occupants of the case-study building. The survey ran for two weeks to allow the participants to fill it in at their convenience. As a result, 101 and 85 questionnaires were collected for summer and winter periods, respectively, which correspond to a 40% and 34% of response rate[20]. Two surveys collected in the summer were excluded from the analysis because of large amounts of missing data. The survey results were then statistically analyzed and compared with the CBE benchmarking scores for office buildings that consist of 39,498 responses. To compare the results between summer and winter, an independent-samples t-test as well as a paired-samples t-test (i.e., dependent samples t-test) were completed[21]. The tested null hypothesis for independent samples t-test was that the mean satisfaction and productivity scores of the two groups (i.e., summer versus winter) are the same, which essentially states that there are no seasonal influences on the occupants' subjective IEQ assessments of a building. The paired samples t-test was performed using 23 pairs of data. For this test, the null hypothesis was that the mean difference of paired satisfaction and productivity scores between summer and winter is zero, which basically states no seasonal changes in the individual responses.

In addition to subjective measurements, spot measurements of several IEQ parameters were conducted, including: air and globe temperatures, humidity, air speed, outdoor air (OA)

[19] The branching questions followed only when the respondents were dissatisfied with their IEQ performance.
[20] Generally, a 40% response rate is considered enough to evaluate the occupant's IEQ satisfaction (ASHRAE 2010a).
[21] An independent-samples t-test was selected in this analysis since the surveys were conducted using random sampling.

2. How satisfied are you with the temperature in your workspace?

Very Satisfied

3	2	1	0	-1	-2	-3

Very Dissatisfied

<u>If you voted on the satisfied side (3, 2, 1, & 0), please go to the next question 3. If you voted on the dissatisfied side (-1, -2, -3), please answer the following questions.</u>

2-1. You have said that you are dissatisfied with the temperature in your workspace. Which of the following contribute to your dissatisfaction?

In warm/hot weather, the temperature in my workspace is: (Check all that apply)

- ☐ Often too hot
- ☐ Often too cold

In cool/cold weather, the temperature in my workspace is: (Check all that apply)

- ☐ Often too hot
- ☐ Often too cold

2-2. When is this most often a problem? (Check all that apply)

- ☐ Morning (before 11am)
- ☐ Mid-day (11am – 2 pm)
- ☐ Afternoon (2 pm – 5pm)
- ☐ Evening (after 5 pm)
- ☐ Weekends/holidays
- ☐ Monday mornings
- ☐ No particular time
- ☐ Other: ______________________

2-3. How would you best describe the source of this discomfort? (Check all that apply)

- ☐ Humidity too high (damp)
- ☐ Humidity too low (dry)
- ☐ Air movement too high
- ☐ Air movement too low
- ☐ Incoming sun
- ☐ Heat from office equipment
- ☐ Drafts from windows
- ☐ Drafts from vents
- ☐ My area is hotter/colder than other areas
- ☐ Thermostat is inaccessible
- ☐ Thermostat is adjusted by other people
- ☐ Clothing policy is not flexible
- ☐ Hot/cold surrounding surfaces (floor, ceiling, walls or windows)
- ☐ Heating/cooling system does not respond quickly enough to the thermostat
- ☐ Other: ______________________________

Figure 18:7-Point Satisfaction Scale (3: very satisfied, 0: neutral, -3: very dissatisfied) and the Branching Questions for Thermal Comfort

3. Overall, does your thermal comfort in your workspace enhance or interfere with your ability to get your job done?

Enhances

3	2	1	0	-1	-2	-3

Interferes

Figure 19: 7-Point Self-Reported Productivity Scale (3: enhances, 0: neutral, -3: interferes)

flow rates, CO_2, horizontal illuminance level on the work plane, vertical illuminance level on the computer monitor, and A-weighted sound pressure levels. The measurements were performed in June of 2010 for 17 offices. The 17 offices were selected based on the results of the first IEQ satisfaction survey: ten offices represent where occupants were dissatisfied with their IEQ environments (i.e., thermal comfort, IAQ, lighting, or acoustics), and seven offices where occupants were satisfied. The outdoor air (OA) flow rates were measured at intakes of two 100% OA AHUs. Table 6 lists the selected IEQ-related parameters and instrumentation used for the

IEQ spot measurements with the specifications. Figure 20 through Figure 26 show photos of instruments used in the spot measurements. The IEQ spot measurement survey form developed in this study is presented in the Appendix A. The spot measurement results were then analyzed and compared with the CBE survey for the same room and the appropriate benchmarks.

To accomplish uniformity, a specific measurement protocol was developed and used. The protocols used for measurements in office spaces are as follows:

Step 1) Ask for permission for measurement.

Step 2) Temperature, humidity and globe temperature measurements

2-1. Select a measurement location near to the occupant's workstation.

<u>Special Note:</u> *If the room is occupied by multiple occupants, the temperature/RH measurements should be taken in the center of the room or in locations where the most extreme values of temperature/RH parameters are likely to occur such as near windows, diffuser outlets, corners, etc., but not less than 39 in. (1.0 m) inward from the center of the largest window.*

2-2. Set the meters for temperature/RH/globe temperature measurements.

2-3. Locate the probes at 24 in. (0.6 m) for seated occupants and 43 in. (1.1 m) for standing occupants and allow the instruments to be in position for approx. 10-15 minutes (i.e., sensor stabilization period).

2-4. Avoid direct sunlight onto the instruments.

2-5. During the sensor stabilization period, proceed to the next steps.

Step 3) CO_2 level measurements

3-1. Select a measurement location near to the occupant's workstation.

<u>Special Note:</u> *If the room is occupied by multiple occupants, the CO_2 level measurement should be taken at or near the workstation located at the corner or most inside the room.*

3-2. Set the meter for CO_2 level measurements.

3-3. Locate the sensor at 43 in. (1.1 m, head height when seated) and allow time for the reading to stabilize (approx. 5 min).

3-4. During the sensor stabilization period, proceed to the next steps.

Step 4) IEQ survey form (Appendix A)

4-1. Record the room number, date, time, and sky condition at the time of measurement.

4-2. Sketch a simple floor plan of the space, including the location and approx. size of the windows, doors, furniture, luminaires, and the occupant's normal location.

4-3. Record the ceiling/task lamp types.

4-4. Conduct clothing Observations using the methods prescribed in the ASHRAE Standard 55-2004 and Standard 55-2010 CLO Table B1, B2, and B3.

Special Note: *If there are no persons in the measurement space, leave the clothing observations blank.*
If there are between 1 and 4 persons in the measurement space, observe all clo values.
If there are between 5 and 9 persons in the measurement space, observe at least 5 clo values. (i.e., a random sampling)
If there are between 10 and 29 persons in the measurement space, observe at least 10 clo values. (i.e., a random sampling)
If there are over 30 persons in the measurement space, observe at least 20 clo values. (i.e., a random sampling)

On random sampling, the proportion of males to females in measurement space has to be considered.

4-5. Record the occupancy of the room at the time of the measurement and the occupant's main activity in the space.

Special Note: *If there are more than two groups using the space, record occupant's activity separately.*

4-6. Take one or more photographs of the space (if allowed). Make sure to capture the relevant features of the space, and then annotate or label the features in photo.

Step 5) Illuminance level measurements

5-1. Check whether all lighting systems are in use and inquire about the normal use characteristics.

5-2. Set the meter for illuminance level measurement. Make sure the meter reading with the cap over the sensor is zero.

Special Note: *Remove the cap and select the appropriate measurement range and unit (lux or fc) if the meter has these options.*

5-3. Locate the sensor at an angle that coincides with the angle of the tasks being performed in the space.

Special Note: *In a typical office space, horizontal illuminance level shall be taken on the work plane, and vertical illuminance level shall be taken on the computer monitor facing the occupant.*

5-4. Avoid shadows on the sensor except the shadows from workers' normal working position. Stand far enough away from the sensor to not affect the reading.

Special Note: *In some cases, this may require being below the horizontal measurement surface using the HOLD button feature.*

5-5. Record the readings and note the daylight conditions to the work plane at the time of lighting measurement.

Special Note: *If the work plane is exposed to direct sunlight, it is advisable to measure over a range of daylight conditions when possible.*

Change the measurement range to find the best range for the application as needed.

Step 6) Check the temperature/RH/CO_2 level readings and decide whether the equilibrium is attained (Yes or No)[22].

6-1. If yes, record the displayed readings of temperature, humidity, globe temperature and CO_2 level.

6-2. If no, wait for another 5 minutes, and go to 7.

6-3. If needed, repeat the process at different measurement points.

[22] Cautions should be taken during the measurements of temperature, RH, and CO_2 level since the presence of surveyors could dramatically change the readings of temperature, RH, and CO_2 level.

Step 7) Sound pressure level measurements

7-1. Make note of all sound-producing equipment (i.e., computers, radios, etc.) that turn on at the time of noise measurement.

Special Note: *If an intruding noise from outdoor sources is of concern, testing should be scheduled during times when these sounds are at a maximum.*

If windows are designed to be opened for ventilation, measurements should be performed with and without the windows open.

7-2. Set the meter for sound pressure level measurements.

Special Note: *Select the appropriate measurement scale (A frequency) and response time (fast or slow).*

Select the measurement mode (Leq, equivalent continuous noise level, for time-averaged sound pressure level) and integration time (1 minute) if the meter has these options.

7-3. Locate the microphone near the seated position of the occupants.

Special Note: *If there is a noise source, point the microphone toward the noise source.*

7-4. Hold the meter away from the body or mount it on a tripod.

7-5. Record the time-average A-weighted (Leq) sound pressure level.

7-6. If needed, repeat the process at different measurement points.

Step 8) Air speed measurements

8-1. Set the instrument for the air speed measurement.

Special Note: *Select the appropriate time constant (20 seconds) if the instrument has the option.*

8-2. Locate the sensor at 43 in. (1.1 m, head height when seated).

Special Note: *If the probe is directional, align the probe with the direction of the main air flow of the room, if it exists (i.e., diffuser, open window, etc.). Air speed measurement is highly dependent on where the air comes from. Readings can vary depending on whether a diffuser is on or off.*

8-3. Record the readings every 20 seconds for at least three minutes and average it.

Special Note: Use the STORE and AVERAGE functions if the meter has the option.

8-4. If you are not sure the direction of the main air flow of the room, repeat the processes with aligning the probe in an opposite direction.

Table 6: IEQ Spot Measurement Parameters and Instrumentation

Parameter	Unit	Instrumentation	Sensor Type	Accuracy	Range	Cost
Air temperature	F	Vaisala HMI 41 indicator & HMP 42 probe	PT 100 IEC 751 class B	±0.4°F at 68°F; ±0.7°F (from -4 to 140°F)	−40 to 212°F	$1,470
	F	Fluke 52 K/J thermometer	K-type thermocouple	±2.0°F or 0.38%	−40 to 500°F	$420
Relative humidity	%	Vaisala HMI 41 indicator & HMP 42 probe	Capacity polymer sensor	±2.0% RH (from 0 to 90% RH)	0 to 100% RH	$1,470
Globe temperature	F	Fluke 52 K/J thermometer with a 38 mm diameter table tennis ball painted gray	K-type thermocouple	±2.0°F or 0.38% (from 32 to 500°F)	−40 to 500°F	$420
Air velocity	fpm	TSI 8360 Velocicalc Plus	Hot-film anemometer	3 fpm or 3% of reading	30 to 9,999 ft/min	$1,230 (TSI 9545[2])
CO_2	ppm	Telaire 7001	Single beam absorption infrared sensor	±50 ppm or ±5% reading	0 to 5,000 PPM	$465
Horizontal and vertical illuminance	fc	Extech HD450 heavy duty data logging light meter	Silicon photo-diode with spectral response filter	± 5% reading + 10 digits (from 0 to 400 fc)	0 to 40,000 fc	$325
LAeq[1]	Leq (dB(A))	Extech 407780 integrating sound level meter	Electret condesner microphone	±1.5 dB	30 to 130 dB	$999

NOTES:
1) A-weighted equivalent sound pressure level.
2) TSI 8360 was discontinued as of January 2008, and TSI 9545 is a functional equivalent model of TSI 8360.

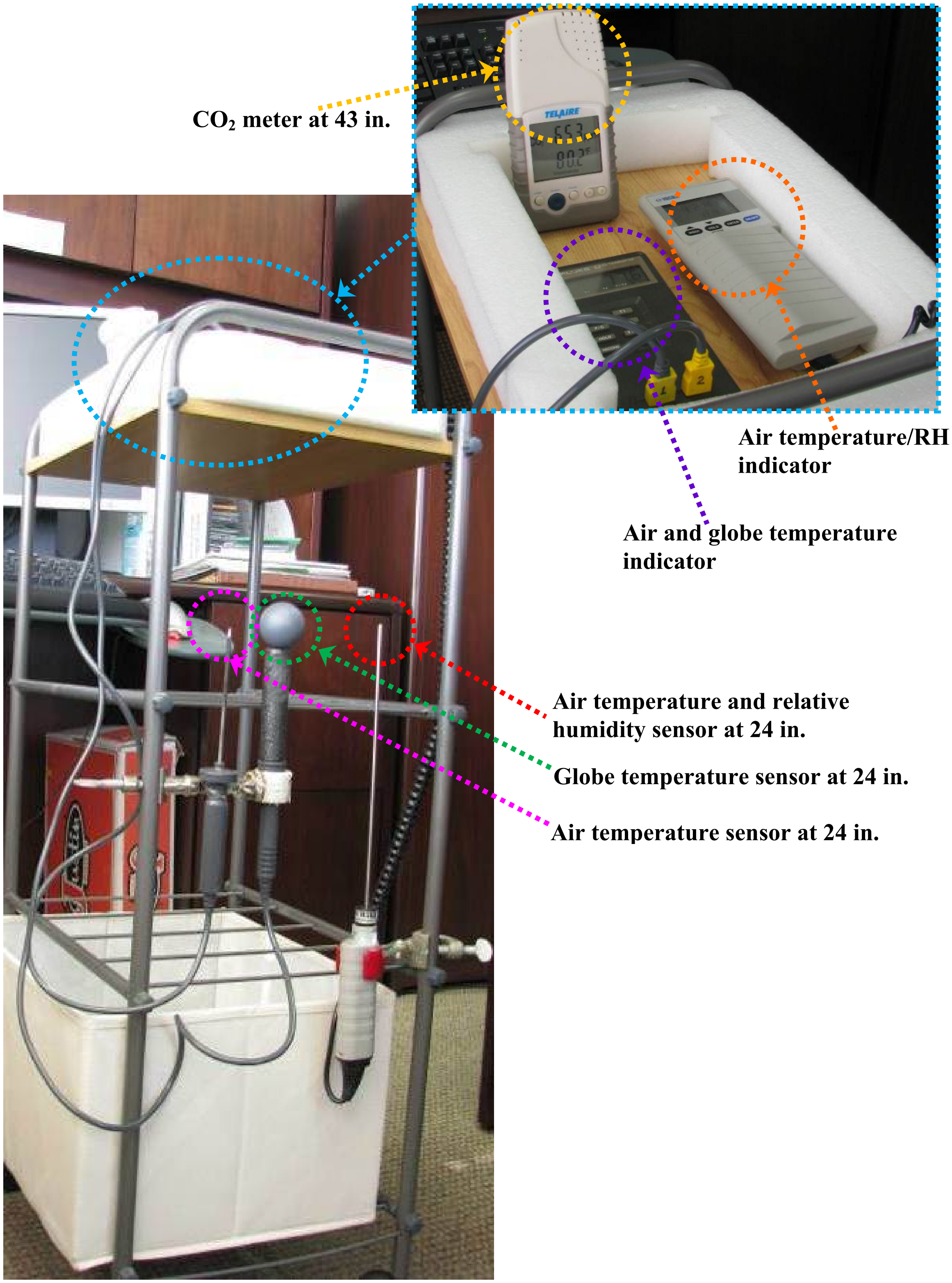

Figure 20: Mobile Cart Used for IEQ Spot Measurements

Figure 21: Vaisala HMI41 Indicator and HMP42 Humidity and Temperature Probe for Air Temperature and Relative Humidity Measurements

Figure 22: Fluke 52 K-Type Thermocouples for Air and Globe Temperature Measurements

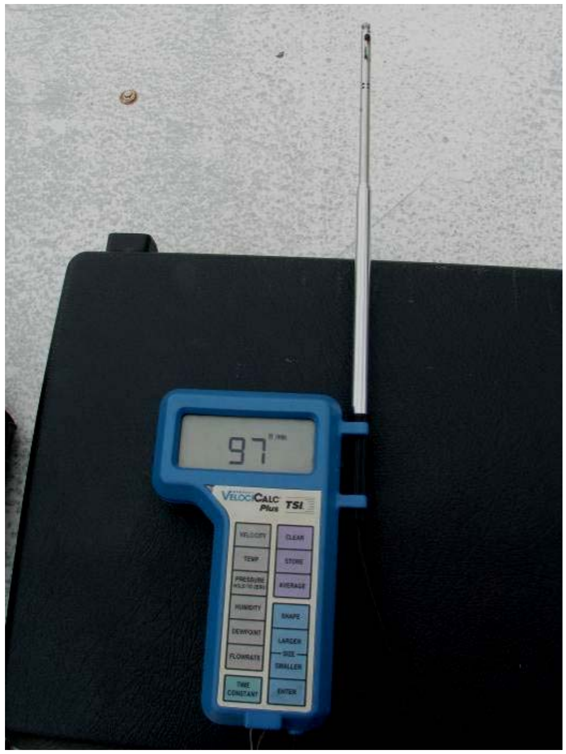

Figure 23: TSI 8360 Velocicalc Plus for Air Speed and OA flow Rate Measurements

Figure 24: Telaire 7001 for CO_2 Measurements

Figure 25: Extech 407780 Integrating Sound Level Meter for A-Weighted Sound Pressure Level Measurements

Figure 26: Extech HD450 Heavy Duty Data Logging Light Meter for Horizontal and Vertical Illuminance Level Measurements

4.1.4.2. Intermediate and Advanced Level

For the Intermediate and Advanced Level IEQ protocols, one field test that covered both levels was developed and applied to the case-study building since both levels require similar data collection efforts of several IEQ parameters. The performance metrics required at the Intermediate Level IEQ protocol are data logging of selected IEQ parameters, including: temperature, humidity, mean radiant temperature, air speed, and CO_2; and spot measurements of full grid illuminance, luminance, background noise and reverberation time with specific IEQ-related building/system characteristics as well as 'right-now' thermal comfort occupant survey and diagnostic lighting satisfaction occupant survey. At the Advanced Level, the required metrics are data logging of selected thermal comfort parameters with a more detailed spatial resolution (i.e., temperature gradients, radiation asymmetry, and air speed distribution); data logging of CO_2, $PM_{2.5}$, and TVOCs levels; detailed illuminance and luminance measurements using high dynamic range (HDR) photography; and measurements of speech privacy, speech communication and sound and vibration isolation for acoustic evaluations with detailed IEQ-related building/system characteristics as well as specialized local comfort occupant survey for asymmetrical or transient thermal environment.

Table 7 presents the performance metrics that were selected and modified in this field study, which include Intermediate and Advanced Level IEQ protocols. The measures selected and the approaches that were modified were made based on the results of the Basic Level field test while also considering significance and practicality of the measures. For example, a diagnostic lighting satisfaction survey was not considered in this study since the case-study building's lighting performance was consistently well above the average benchmarking scores based on the Basic Level field test results. A spot measurement of full-grid illuminance and luminance was not performed partly due to the practical applicability of these measures (i.e., low availability and high cost requirements). On the other hand, to improve a limitation of spot measurement observed from the Basic Level field test[23], continuous measurements of horizontal and vertical illuminance as well as A-weighted and C-weighted sound pressure levels were performed in this study.

To accomplish the selected measurements, a comprehensive instrumentation cart was developed to collect continuous, time-series data from selected IEQ-related parameters while

[23] IEQ spot measurements have one major limitation: it is hard to catch dynamic responses of IEQ with spot measurements.

Table 7: IEQ Performance Metrics Required by the ASHRAE PMP Intermediate and Advanced Levels

<table>
<tr><th colspan="2">Type of Measures</th><th>Area[1]</th><th>Required Performance Metrics</th><th>Tested</th></tr>
<tr><td rowspan="7">Intermediate</td><td>Descriptive</td><td>ALL</td><td>Specific IEQ-related building/system characteristics</td><td>Yes</td></tr>
<tr><td rowspan="2">Subjective</td><td>TC</td><td>'Right-now' thermal comfort survey</td><td>Yes</td></tr>
<tr><td>L</td><td>Diagnostic lighting satisfaction survey</td><td>No</td></tr>
<tr><td rowspan="4">Instrumented[2]</td><td>TC</td><td>(C) Temp., humidity, MRT, and air speed</td><td>Yes</td></tr>
<tr><td>IAQ</td><td>(C) CO_2 concentration</td><td>Yes</td></tr>
<tr><td>L</td><td>(S) Full grid illuminance and luminance</td><td>No (Modified)</td></tr>
<tr><td>A</td><td>(S) Background noise and reverberation time.</td><td>No (Modified)</td></tr>
<tr><td rowspan="6">Advanced</td><td>Descriptive</td><td>ALL</td><td>Detailed IEQ-related building/system characteristics</td><td>Yes</td></tr>
<tr><td>Subjective</td><td>TC</td><td>Local comfort survey for asymmetrical or transient environment</td><td>No</td></tr>
<tr><td rowspan="4">Instrumented[2]</td><td>TC</td><td>(C) Temp., humidity, MRT, and air speed w/ detailed spatial resolution</td><td>Yes</td></tr>
<tr><td>IAQ</td><td>(C) CO_2, $PM_{2.5}$, and TVOCs</td><td>Partially</td></tr>
<tr><td>L</td><td>(S) High dynamic range (HDR) photography</td><td>Yes</td></tr>
<tr><td>A</td><td>(S) Speech privacy, speech communication, and sound/vibration isolation</td><td>No</td></tr>
</table>

NOTES:
1) TC: Thermal Comfort, IAQ: Indoor Air Quality, L: Lighting, A: Acoustics
2) (C): Continuous measurement, (S): Spot measurement

recording the occupancy using an occupancy sensor[24], including: four air temperatures, four globe temperatures, humidity, air speed, CO_2, total volatile organic compounds (TVOCs)[25],

[24] The occupancy was measured using a dual-technology occupancy sensor that employs both passive infrared and ultrasonic technologies.
[25] The TVOCs were measured using an instrument that produces a voltage signal that increases as the TVOCs level increases. This instrument was selected to quantify the relative amount of TVOCs in the measurement space by detecting most solvent-based VOCs, including acetone, benzene, diacetone alcohol, formaldehyde, methylene chloride, methyl ethyl ketone, perchloroethylene, toluene, and trichloroethylene.

horizontal and vertical illuminance, as well as A-weighted and C-weighted sound pressure levels (SPL), as shown in Table 8 and Figures 27 through 32. To construct the cart, previous studies were reviewed to identify the instruments that had been used to measure the corresponding metrics. The survey of currently available equipment on the market, included sensor type, accuracy, resolution, response time, and power consumption, along with calibration and cost information to determine the appropriate sensors. A summary table of market research on the available instruments is presented in the Appendix B. Appendix C includes detailed calibration procedures for the sensors used to develop a comprehensive instrumentation cart in this study.

Using the portable instrumentation cart, continuous IEQ measurements were conducted in eleven office spaces of a case-study building from July to September 2011. The eleven offices were selected based on the results of the Basic Level IEQ assessment survey. Four offices were chosen where occupants were dissatisfied with their IEQ environments (i.e., thermal comfort, IAQ, lighting, or acoustics) and seven additional offices were chosen where occupants were satisfied. The measurements were made over a one week period in each office with a scan interval of 10 second and three different data logging intervals (1 minute, 5 minute, and 15 minute). The cart was placed as close to the occupant as possible while ensuring enough space for occupants to minimize disturbances (Figure 33).

Detailed illuminance and luminance measurements were also performed using a Canon S5 IS digital camera and Photosphere software (Anyhere 2010). A series of photos were taken by varying the aperture size (i.e., f-stops) as well as shutter speeds with a Canon S5 IS. The eight to ten photos were then combined into one HDR image using the Photosphere. The created HDR image was also displayed in false color luminance map using the same software.

In addition to the instrumental measurements, an occupant 'right-now' survey of thermal sensation, comfort, acceptability, preference, clothing and activity was simultaneously conducted. The 'right-now' survey form used in this study is presented in the Appendix A. The occupants were asked to repeat the survey twice a day over the measurement period. Once the data were collected, the performance metrics described in the ASHRAE PMP were calculated and compared with the appropriate benchmarks.

Table 8: IEQ Continuous Measurement Parameters and Instrumentation Specifications

Parameter	Unit	Meas. Height (in.)	Instrumentation	Sensor Type	Accuracy	Range	Cost
Air temperature	F	4, 24, 43, 66	Omega GG-T-28-SLE	T-type thermocouple	±0.9°F or 0.4% reading (above 32°F)	0 to 662°F	\$0.43/ ft
Globe temperature	F	4, 24, 43, 66	Omega GG-T-28-SLE inside a 38 mm diameter table tennis ball painted gray	T-type thermocouple	±0.9°F or 0.4% reading (above 32°F)	0 to 662°F	\$0.43/ ft
Relative humidity	%	43	Vaisala HMP45A Humidity and Temperature Probe	Capacitive polymer sensor	±2.0% RH (0 to 90% RH)	0 to 100% RH	\$595
Air speed	fpm	43	TSI Model 8455 Air Velocity Transducer	Hot-film anemometer	±2.0% reading	25 to 1,000 fpm	\$775
CO_2	ppm	39	Telaire 7001	Single beam absorption infrared sensor	±50 ppm or ±5% reading	0 to 5,000 ppm	\$465
TVOCs [3]	mV	39	Eco Sensors VOC Gas Sensor Model C-21	Heated metal oxide semiconductor (HMOS)	Not specified	0 to 140 ppm (0 to 1,300 mV)	\$326
Horizontal illuminance	fc	30	Licor LI-210 Photometric Sensor	Silicon photovoltaic detector	± 5.0% reading	0 to 10,000 fc	\$480
Vertical illuminance	fc	43	Licor LI-210 Photometric Sensor	Silicon photovoltaic detector	± 5.0% reading	0 to 10,000 fc	\$480
LAeq [4]	Leq (dB(A))	47	Extech 407780 Integrating Sound Level Meter	Electret condenser microphone	±1.5 dB	30 to 130 dB	\$999
LCeq [5]	Leq (dB(C))	47	TES 1350 Sound Level Meter	Electret condenser microphone	±1.5 dB	35 to 90 dB	\$216

NOTES:

1) At the height of workplane

2) At the height of seated occupant's ear

3) The TVOCs were measured using an instrument that produces a voltage signal that increases as the VOCs level increases. This instrument was selected to quantify the relative amount of VOCs in the measurement space by detecting most solvent based VOCs, including acetone, benzene, diacetone alcohol, formaldehyde, methylene chloride, methyl ethyl ketone, perchloroethylene, toluene, and trichloroethylene.

4) A-weighted equivalent sound pressure level (dBA)

5) C-weighted equivalent sound pressure level (dBC)

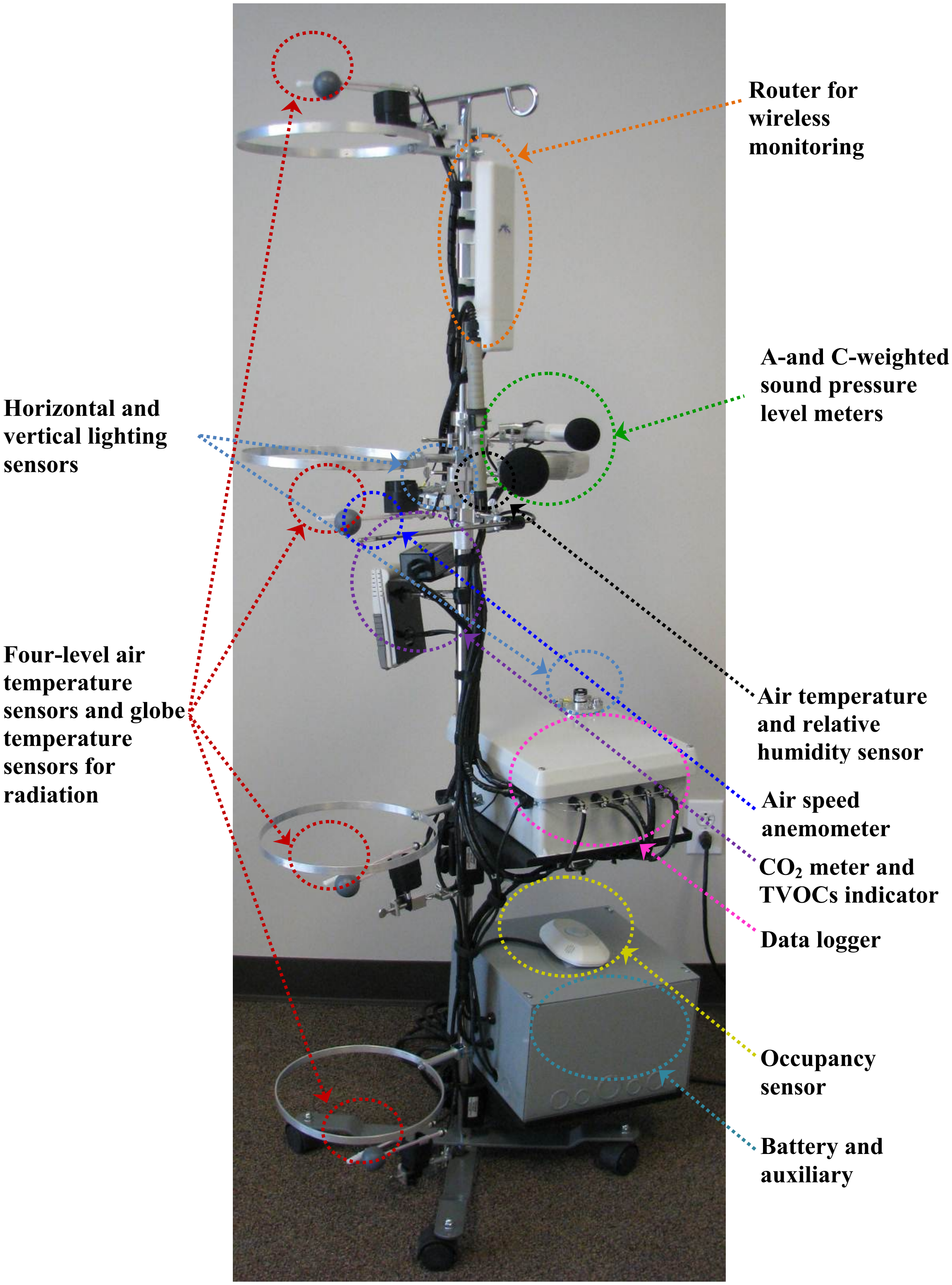

Figure 27: Comprehensive IEQ Continuous Monitoring Cart

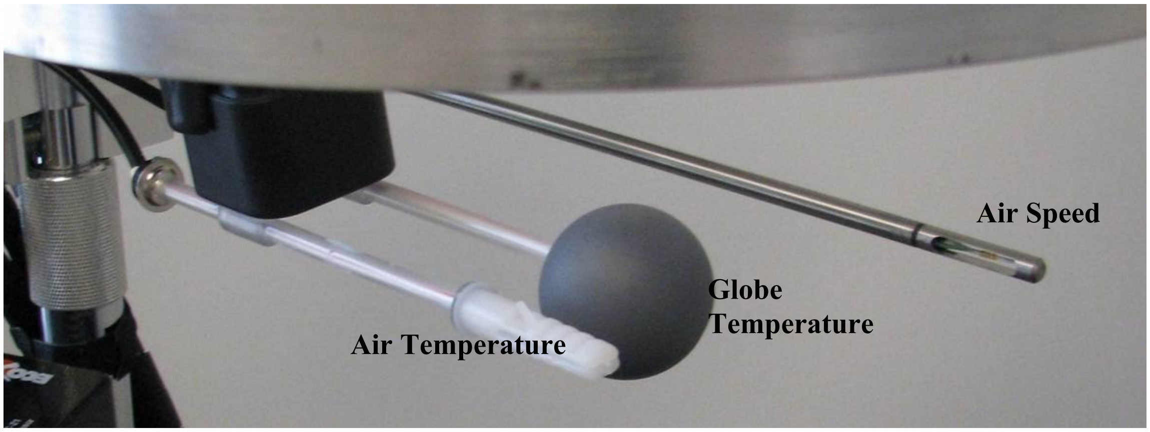

Figure 28: T-Type Thermocouples for Air Temperature with Radiation Shield and Globe Temperature with a Gray Table Tennis Ball; and Hot film Anemometer (Directional, 240° Wide Sector) for Air Speed

Figure 29: Capacitive Polymer Relative Humidity Sensor

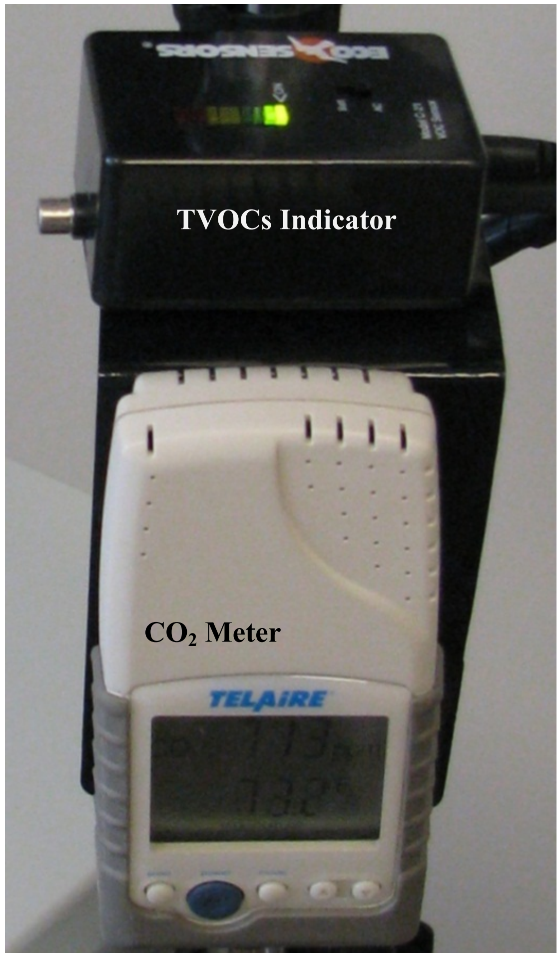

Figure 30: Infrared CO_2 Meter and Heated Metal Oxide Semiconductor (HMOS) TVOCs Indicator

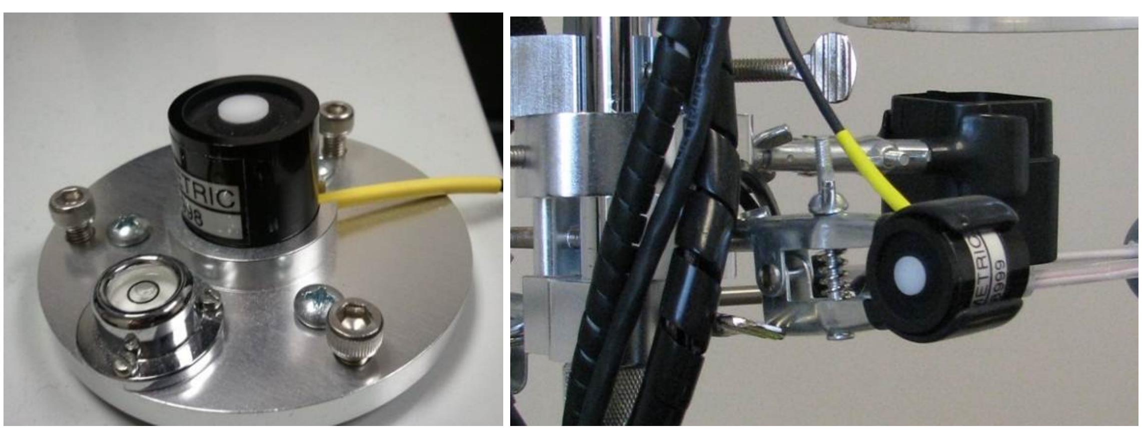

Figure 31: Silicon Photovoltaic Detectors for Horizontal (Left) and Vertical (Right) Illuminance Levels

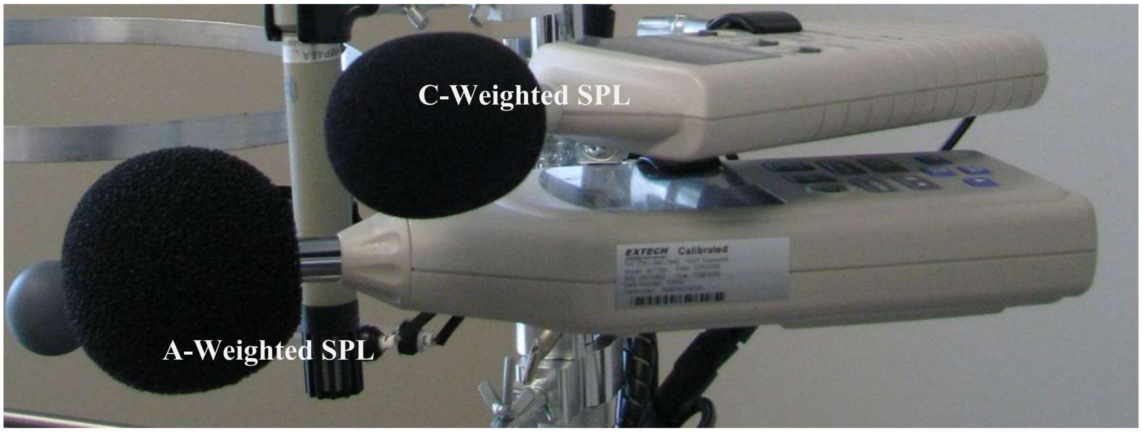

Figure 32: Electret Condenser Microphones for A-Weighted and C-Weighted Sound Pressure Levels

Figure 33: Example Photos Showing the Location of IEQ Continuous Monitoring Cart Placed in Typical Private Office Spaces of the Case-Study Building

4.2. Phase II: Proposed New or Modified Approaches to Improve the ASHRAE PMP

4.2.1. *Evaluation of the ASHRAE PMP*

4.2.1.1. Summary of Findings and Recommendations

The problems and issues with implementing the ASHRAE PMP in a case-study building were noted throughout the entire research process. As a result, a total of forty issues were identified, including thirteen for energy use, five for water use, and twenty-two for IEQ protocols. The identified problems and issues related to a current version of the ASHRAE PMP were listed, and for each issue, recommendations were developed to improve the ASHRAE PMP.

4.2.1.2. Applicability Evaluations

The applicability of the three levels of measurement in the ASHRAE PMP was examined using the results from a literature analysis of the ASHRAE PMP as well as the field test results from the case-study building. A literature analysis includes a comparison of the procedures and approaches in the ASHRAE PMP with other existing protocols. Evaluation criteria were developed in three domains: validity, reliability and practicality, which were built upon the framework originally suggested by the Malmqvist and Glaumann (2006)[26].

The following questions were addressed to evaluate the validity, reliability and practicality of each level of the protocols that were field tested under this study, based on a scale from 1 (very bad) to 5 (very good) (Malmqvist 2008).

- Validity

1) *Content Validity*: To what extent do the metrics measure the intended aspect of performance?
2) *Criterion Validity*: Do comparable external benchmarks exist?

- Reliability

1) *Accuracy:* To what extent do the procedures (methods) yield accurate results?
2) *Repeatability:* To what extent do the procedures (methods) yield repeatable results?

[26] Malmqvist and Glaumann (2006) suggested theoretical and practical criteria to evaluate the environmental performance indicators, including validity, reliability, and accuracy for theoretical criteria; and cost, competence demands, intelligibility, and influence for practical criteria. Since these evaluation criteria were intended to be used for assessing the applicability of the indicators to be used for environmental management systems (EMS), some modifications were made 1) to exclude non-applicable requirements and 2) to expand its scope to evaluate overall approaches in the ASHRAE PMP(i.e., metrics, measurement methods, and benchmarking methods).

- Practicality

1) *<u>Cost:</u>* How costly is it to perform the intended measurements?
2) *<u>Ease-of-Measurement:</u>* How easy is it to accomplish the intended measurements?

Although this procedure is based on a subjective evaluation, this is expected to clarify the problems and issues associated with the current version of the ASHRAE PMP as well as to allow a systematic comparison of the current methods against the proposed new or modified approaches.

4.2.2. *New or Modified Approaches to Improve the ASHRAE PMP*

For the selected twelve issues, new or modified approaches to improve the applicability of the ASHRAE PMP in terms of validity, reliability, and practicality were proposed based on the evaluation results of the ASHRAE PMP, including two modified and three new approaches for energy use; one new approach for water use; and six new approaches for IEQ protocols. The twelve issues were selected based on its relative importance compared to other issues noted in this study (i.e., high priority); and the needs for evidence-based recommendations. The proposed approaches were then evaluated against the existing methods by addressing the same evaluation criteria in Section 4.2.1.2, including validity, reliability, and practicality.

4.3. Phase III: Recommendations for a New Figure-of-Merit for Rating a Building's Overall Performance based on the ASHRAE PMP

Recommendations were developed for a new figure-of-merit for rating a building's overall performance based on the application of the ASHRAE PMP procedures. These include: a single figure-of-merit representation based on above-average percentage scores or percentile rank of scores that are separately calculated for six performance areas (i.e., energy use, water use, thermal comfort, IAQ, lighting, and acoustics); and ideas for a future figure-of-merit rating system such as Predicted Percentage of Hours Dissatisfied (PPHD %) for IEQ instrumented measurements and a cost-based rating system. The strengths and limitations of the proposed recommendations were discussed.

CHAPTER V

RESULTS OF FIELD TEST OF THE ASHRAE PMP[*]

This chapter presents the results of Phase I: Field test of the ASHRAE PMP. The following Sections 5.1 to 5.3 provide the field test results of the ASHRAE PMP for each performance area of each level of the protocols, including: energy use, water use, and IEQ (i.e., thermal comfort, IAQ, lighting, and acoustics), respectively. For each performance area of each level, the performance metrics required in the ASHRAE PMP were calculated and then compared with the appropriate benchmarks, followed by observations from the field test.

5.1. Energy Use

5.1.1. *Level I: Basic Level*

5.1.1.1. *Performance Metrics*

In the ASHRAE PMP, the energy performance metrics required at the Basic Level are an annual whole-building energy use index (EUI) and an energy cost index (ECI).

a) EUI and ECI Calculation Results

Figures 34 and 35 show the annual moving average whole-building total EUI (kBtu/ft^2·yr) and ECI (\$/ft^2·yr) of the case-study building calculated using the two procedures suggested in the ASHRAE PMP: ASHRAE Standard 105-2007 (ASHRAE 2007a) and the ENERGY STAR Portfolio Manager (EPA 2010b). In addition to these procedures, EUIs and ECIs were calculated without any adjustments and plotted in the figures as shown[27]. The line graphs (right axis) show these three different EUIs (Figure 34) and ECIs (Figure 35) calculated using different adjustment methods. The bar charts (left axis) show the annual moving average

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[*] Part of this chapter is reprinted with permission from "Field-Test of the New ASHRAE/CIBSE/USGBC Performance Measurement Protocols for Commercial Buildings: Basic Level." By Kim and Haberl, 2012a. *ASHRAE Transactions* 118(1):135-142, Copyright 2012 by ASHRAE; and from "Field-Test of the New ASHRAE/CIBSE/USGBC Performance Measurement Protocols: Intermediate and Advanced Level Indoor Environmental Quality Protocols" By Kim and Haberl, 2012b. *ASHRAE Transactions* 118(2), Copyright 2012 by ASHRAE.

[27] In this calculation, the monthly consumption of electricity and natural gas was simply added to compute the annual totals without any adjustments to the billing period since the annual total EUIs and ECIs could not be calculated over the entire analysis period using the two methods suggested in the ASHRAE PMP because of a lack of natural gas billing dates between September 2006 and January 2009. Before February 2009, the case-study building was part of overall natural gas transportation invoice for the Texas A&M Campus, which covered about 60 buildings.

whole-building total energy use (MMBtu/yr) and energy cost (thousands$/yr) before applying normalization by the gross floor area of the building.

The EUI of the case-study building varied between 80.9 and 88.9 kBtu/ft^2·yr during the analysis period. However, since the Basic Level does not require normalizing energy data for weather, it is hard to confirm whether the increase or decrease was affected by changing weather conditions, building occupancy, or other operation and maintenance (O&M) issues. On the other hand, the ECIs of the case-study building increased during the analysis period by about 31% from \$1.70 to \$2.23/ft^2·yr because of the increased electricity rates from \$0.050 to \$0.076/kWh (i.e., 52% increase) for an energy charge and from \$9.5 to \$10.4/kW (i.e., 9% increase) for a demand charge (Figure 36).

b) Comparison of The Two EUI Calculation Procedures

The different EUIs calculated using the two procedures suggested in the ASHRAE PMP for a period from January 2010 to November 2011 showed a percentage error[28] between -0.39% and 0.69%. This was caused by the different adjustment methods used by the two procedures. In one method, the ENERGY STAR Portfolio Manager adjusted the consumption to fit the calendar month, while in the other method, the ASHRAE Standard 105-2007 selects the analysis period based on the billing period of the energy type with the largest total used to minimize errors associated with the adjustments.

When the procedure without any adjustments is compared to the procedure with adjustments, the percentage error varied from -0.83% to 0.80%. This means when the billing dates are not available, the unadjusted annual total EUIs and ECIs can be considered as an acceptable alternative to the EUIs and ECIs calculated using the two procedures in the ASHRAE PMP: ASHRAE Standard 105 or ENERGY STAR Portfolio Manager.

The calculation procedures using the ASHRAE Standard 105-2007 and the ENERGY STAR Portfolio Manager are as follows:

- *ASHRAE Standard 105*:

1) Enter the monthly consumption and costs of electricity and natural gas and the corresponding billing period in a summary table.
2) Convert electricity (kWh) and natural gas (MCF) to the same units (MCF) using the conversion factors from the ASHRAE PMP: 3.412 kBtu/kWh and 1,030 kBtu/kcf.

[28] To calculate the percentage error (PE), the following equation is used. PE= 100 × (EUI_1 – EUI_2)/EUI_1, in which: EUI_1 = EUI calculated using the procedure 1; and EUI_2 = EUI calculated using the procedure 2.

3) Calculate the monthly, daily average electricity and natural gas consumption and costs by dividing the monthly consumption and costs by the number of billing days.
4) Calculate the annual total electricity consumption and costs by adjusting the last month's consumption and costs of the 12 consecutive months to cover the 365 days. Add or subtract the appropriate values using the monthly daily average electricity consumption and cost for the last month of the analysis period.
5) Calculate the annual total natural gas consumption and costs by adjusting natural gas billing period to cover the same 365 consecutive days of electricity billing period. Add or subtract the appropriate values using the monthly, daily average natural gas consumption and cost for the first and last months of the analysis period.
6) Sum up the calculated annual total electricity and natural gas consumption and divide it by the gross floor area of the case-study building to calculate annual whole-building EUI (kBtu/$ft^2 \cdot yr$).
7) Sum up the calculated annual total electricity and natural gas costs and divide it by the gross floor area of the case-study building to calculate annual whole-building ECI ($/$ft^2 \cdot yr$).

- *ENERGY STAR Portfolio Manager (https://www.energystar.gov/istar/pmpam/) :*

1) Add a property for the case-study building
2) Enter the basic information of the case-study building in the Section of Space Use.
3) Enter the monthly consumption and costs of electricity (kWh and $US) and natural gas (MCF and $US) with the corresponding billing period in the Section of Energy Meters.
4) Select the last month of the analysis period to see the corresponding annual whole-building site and source EUI (kBtu/$ft^2 \cdot yr$).
5) For the annual whole-building ECI, create a custom view that includes "Annual Energy Cost ($US)" and "Total Energy Cost per Sq. Ft. ($/$ft^2 \cdot yr$)" and select it in the Section of Facility Performance. Select the last month of the analysis period to see the corresponding annual whole-building ECI ($/$ft^2 \cdot yr$).

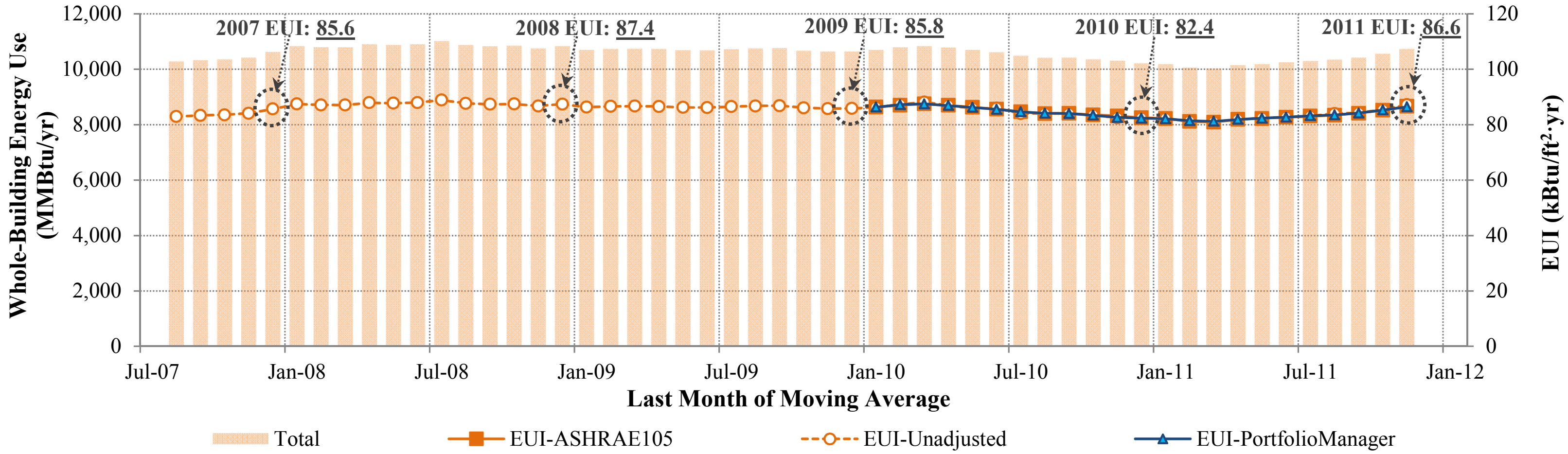

Figure 34: Annual Moving Average Whole-Building Energy Use (Left Axis) and EUIs (Right Axis) of the Case-Study Building

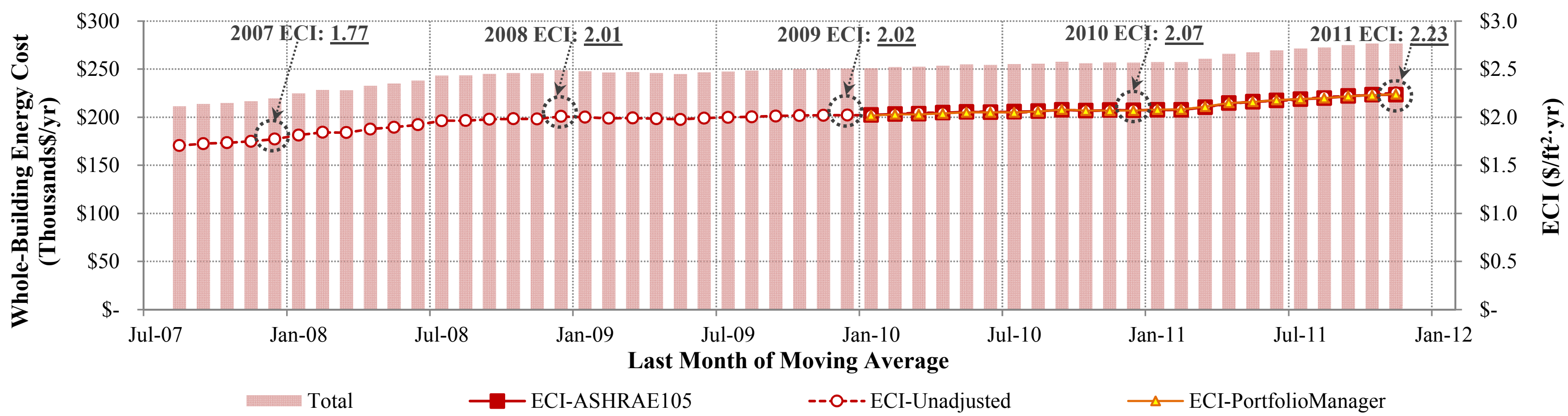

Figure 35: Annual Moving Average Whole-Building Energy Cost (Left Axis) and ECIs (Right Axis) of the Case-Study Building

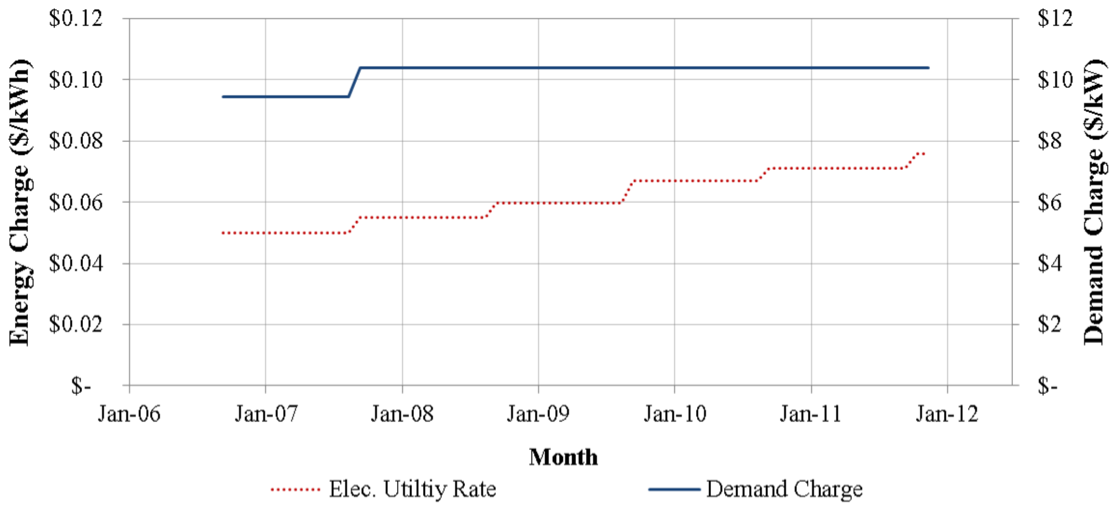

Figure 36: College Station Utilities' Medium Commercial (15-300 kW) Energy (Left Axis) and Demand (Right Axis) Charge for the Analysis Period

5.1.1.2. Performance Evaluation/Benchmarking

The evaluation of energy performance metrics was performed by comparing the calculated EUIs to two sources of benchmarking data: the 2007 ASHRAE Handbook HVAC Applications, Chapter 35-Energy Use and Management (ASHRAE 2007b) and the U.S. EPA ENERGY STAR ratings (EPA 2010b), as shown in Figures 37 and 38. A comparison of the annual total site EUI of the case-study building with the 2003 Commercial Sector EUI percentiles for administrative/professional office buildings published in the 2007 ASHRAE Handbook HVAC Applications[29] shows that the energy performance of the case-study building had been fluctuating slightly since 2007: 85.6 kBtu/ft^2·yr (69.0th percentile against the 2003 CBECS benchmarks) in 2007, 87.4 kBtu/ft^2·yr (70.5th percentile) in 2008, 85.8 kBtu/ft^2·yr (69.2th percentile) in 2009, 82.4 kBtu/ft^2·yr (66.5th percentile) in 2010, and 86.6 kBtu/ft^2·yr (69.8th percentile) in 2011. Thus against the ASHRAE recommended benchmarks, the case-study building's energy performance is worse than average during the analysis period. Compared to the ENERGY STAR performance rating for office, bank/financial institution, and courthouse type buildings, the energy efficiency ratio of the case-study building, which is the actual source EUI divided by the predicted source EUI, had been improving slightly from 50 in 2009 to 52 for

[29] The percentiles were calculated using the Department of Energy (DOE) Energy Information Administration (EIA) 2003 Commercial Building Energy Consumption Survey (CBECS) database (EIA 2003). A higher number indicates a worse performance.

both 2010 and 2011[30]. The case-study building's energy performance is about average against the peer group defined in the ENERGY STAR Portfolio Manager.

Unfortunately, as shown, different benchmarking sources yielded different results. While the building's energy performance was below average with the ASHRAE benchmarks based on site EUI, the ENERGY STAR benchmarking data, which is based on source EUI and emphasizes electricity use, yielded an average performance[31]. This difference may also be partly caused by adjustments performed when calculating energy performance ratings in the ENERGY STAR Portfolio Manager to normalize the predicted source EUI for weather and key operating characteristics, including the number of employees and computers, the weekly operating hours, and the gross square foot.

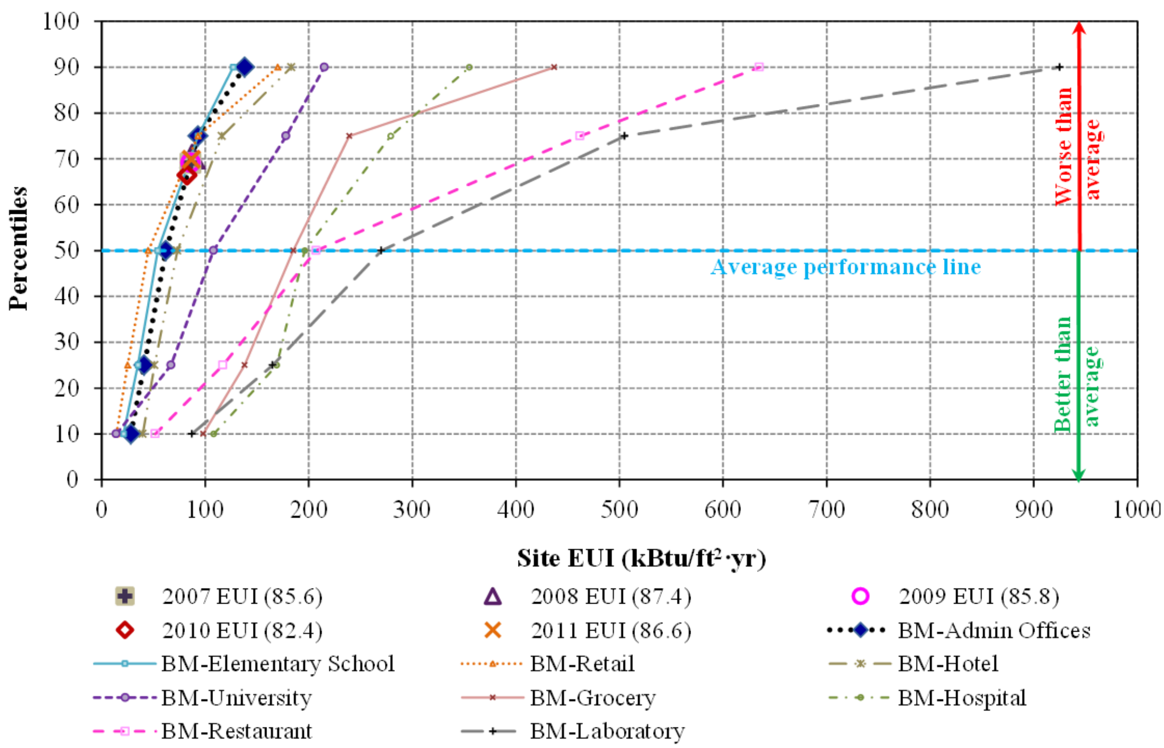

Figure 37: Annual Whole-Building Total Site EUI of the Case-Study Building Compared to the ASHRAE Benchmarks for Administrative/Professional Office Buildings and Other Eight Representative Building Types based on the U.S. DOE EIA CBECS Database.

[30] The ENERGY STAR performance rating is based on 1-100 scale. A rating of 50 indicates average performance, and a higher number indicates a better performance.
[31] To convert site to source energy, different conversion factors are used for electricity and natural gas. In ENERGY STAR performance ratings, the source energy multipliers of 3.34 for electricity and 1.047 for natural gas are applied to site energy use (EPA 2010b).

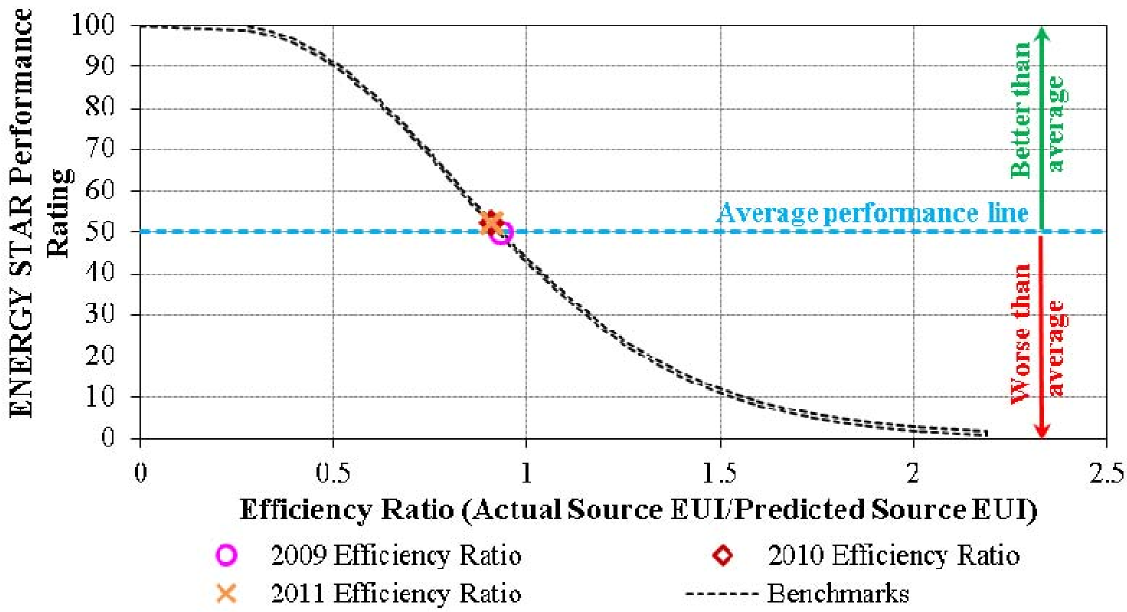

Figure 38: Efficiency Ratio (Actual Source EUI Divided by Predicted Source EUI) of the Case-Study Building Compared to the ENERGY STAR Portfolio Manager Benchmarks for Office, Bank/Financial Institution, and Courthouse Type of Buildings

5.1.1.3. Observations

Observations from the field test of the ASHRAE PMP Basic Level energy protocol are as follows[32]:

- The ASHRAE PMP Basic Level energy protocol recommends users to benchmark the calculated energy performance metrics (i.e., EUI) against as many sources as applicable. The perceived performance of the case-study building is highly dependent on which benchmark the user utilizes. However, different benchmarking sources yield very different results: i.e., worse than average performance against the ASHRAE benchmarks versus average performance against the ENERGY STAR Portfolio Manager benchmarks.
- The required metrics for the ASHRAE PMP Basic Level energy protocol are the annual whole-building energy use index (kBtu/ft^2·yr) and energy cost index (\$/ft^2·yr). However, the energy cost index is calculated using the unit costs of electricity and natural gas which are not fixed costs over time. Therefore, there may be differences in cost indices that are larger than the differences in usage. In this study, the calculated energy use indices of the case-study

[32] A shorter observation listed in this section is repeated as an issue in Section 5.1.4.

building have fluctuated during the analysis period, and during the same period, the energy cost indices have continuously increased because of the increased electricity rates.

- The energy performance metrics required at the ASHRAE PMP Basic Level are indices at the whole-building level, which are the sum of all energy used in the building. Unfortunately, when the building consumes different energy from two or more sources**,** the metrics calculated separately for each energy source may provide additional insights compared to the combined metrics at the whole-building level without any extra data collection efforts since the data were previously collected separately for each energy source.
- A comparison of the two different EUIs calculation procedures suggested in the ASHRAE PMP revealed no significant differences in the calculated EUIs with a percentage error between -0.39% and 0.69%. In addition, upon further investigation, it was determined that the small differences were caused by different adjustment methods. In one method, the ENERGY STAR Portfolio Manager adjusted the consumption to fit the calendar month, while in the other method, the ASHRAE Standard 105-2007 selects the analysis period based on the billing period of the energy type with the largest total used to minimize errors associated with the adjustments. Overall, between the two procedures, no significant difference was confirmed in this study.

5.1.2. *Level II: Intermediate Level*

5.1.2.1. *Performance Metrics*

The energy performance metrics required at the Intermediate Level are monthly energy use and demand as well as a major end-use assessment.

a) Monthly Energy Use and Demand

Figure 39 shows the monthly electricity and natural gas energy use metrics of the case-study building normalized and displayed as a daily average basis from September 2006 to November 2011 for electricity and from February 2009 to November 2011 for natural gas. During this period, the monthly electricity use varied between 5,739 and 8,706 kWh/day, with the increase in usage following the expected seasonal curve (i.e., the lowest consumption in winter with increasing consumption in spring and the highest consumption in summer with decreasing consumption in the fall). A further examination focused on the base load and the weather-dependent electricity use. The base-load electricity use (i.e., the lowest value in the 12-month period) was stable during this period: between 5,739 and 5,931 kWh/day[33]. In contrast, during this same period, the annual average weather-dependent electricity use, which is the consumption calculated by subtracting the base-load electricity use from the monthly total electricity use, had been fluctuating: 1,320 kWh/day in 2007; 1,420 kWh/day in 2008, 1,435 kWh/day in 2009; and 1,244 kWh/day in 2010. Thus the case-study building consumes electricity primarily for the base load, which accounts for around 80% of total consumption.

The monthly natural gas use varied between 0.6 and 12.0 MCF/day[34]. During this period, between September 2009 and November 2010, the natural gas consumption was unusually low, which indicates some operational changes in systems during this period. However, conversations with the facility personnel could not reveal the reasons of this consistently low natural gas consumption levels during this period.

Figure 40 presents the monthly peak electric demand of the case-study building from September 2006 to November 2011. During the analysis period, the peak demand of the case-study building varied between 389 and 715 kW. Abnormally high peaks were observed three

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[33] The base-load electricity use was not calculated for 2006 and 2011 since one full year of data was not available.

[34] It was suspected that the billed natural gas use data of 0.0 MCF/day for November 2010 was estimated rather than actually measured. Thus, in this analysis, the billed data for November 2010 was adjusted to match the consumption of the previous month, which is 0.9 MCF/day for October 2010. The data for December 2010 was also adjusted by subtracting 0.9 MCF/day from the initially billed data of 6.5 MCF/day.

times: 636 kW in October 2006, 696 kW in March 2007, and 715 kW in June 2009. The reasons of these high peaks were not revealed at the Intermediate Level analysis using only monthly utility bills. However, the end-use analysis using sub-hourly electricity data at the Advanced Level could disclose the events causing these abnormally high peaks[35]. Except for these three months, the monthly peak demand of the case-study building was below 600 kW.

Figure 41 shows the monthly electrical load factor (ELF)[36] with the occupant load factor (OLF) of the case-study building. The OLF of the case-study building is calculated as 33% by dividing 55 (weekly occupied hours of the case-study building[37]) by 168 (i.e., the total hours in the week). The calculated ELF varied between 39% and 68%, which is higher than the OLF during an entire analysis period, which indicates an energy savings potential by decreasing the consumption during unoccupied hours. Several dips were observed in the calculated ELF, and most of them were found in non-cooling months that have lower electricity use. Again, the events causing the dips were unable to be confirmed at the Intermediate Level analysis, but could be revealed at the Advanced Level in Section 5.1.3.

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[35] The reasons of these abnormally high peaks are discussed in Section 5.1.3 Level III: Advanced Level.
[36] The ELF is calculated using the formula in Section 4 of the ASHRAE PMP: ELF (monthly) = (electric use (kWh) for the month) / (electric demand for the month (kW) × number of days in the month × 24 h/day).
[37] The case-study building is normally occupied from 7:00 a.m. to 6:00 p.m.

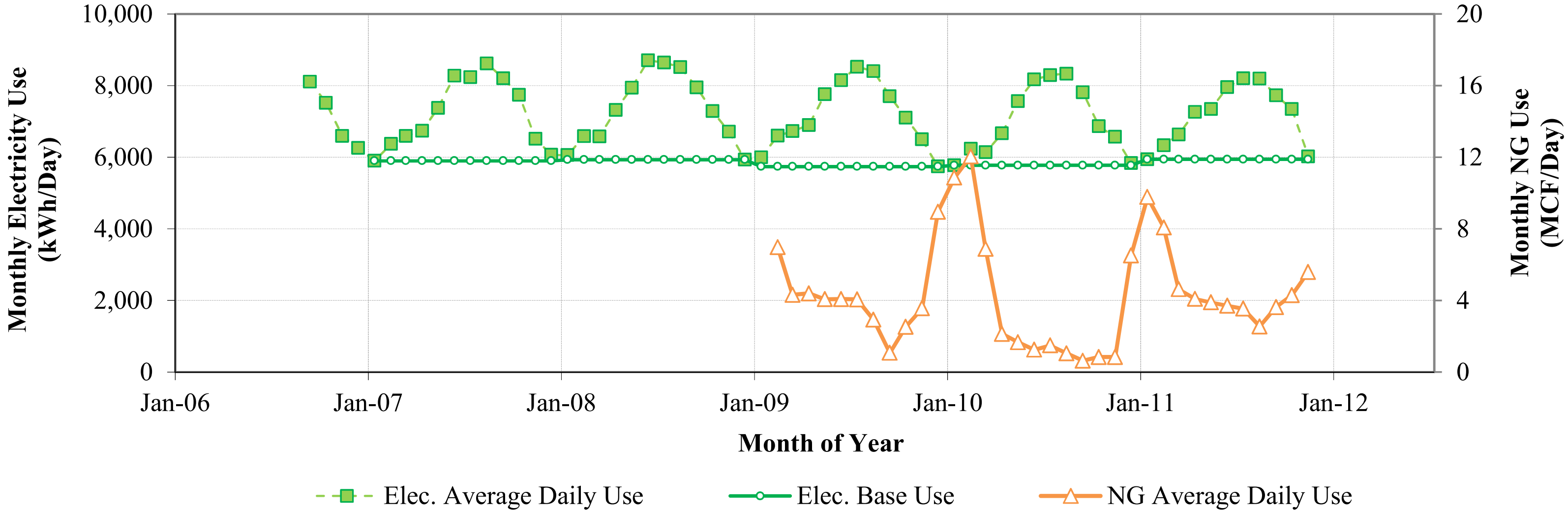


Figure 39: Monthly Electricity (Left Axis) and Natural Gas (Right Axis) Use Profile for the Case-Study Building

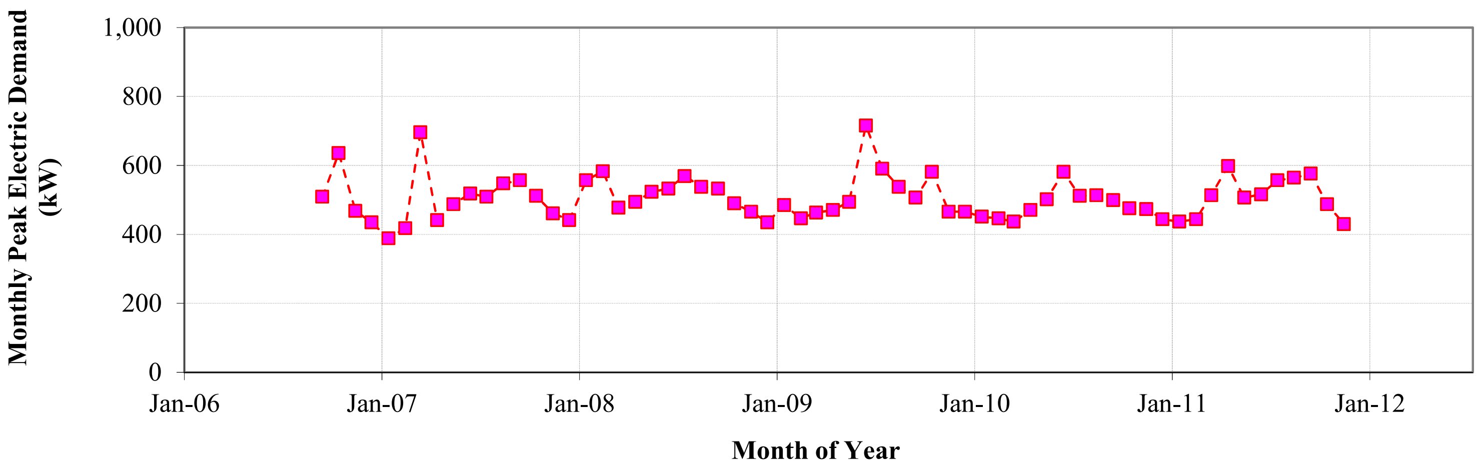


Figure 40: Monthly Peak Electric Demand for the Case-Study Building

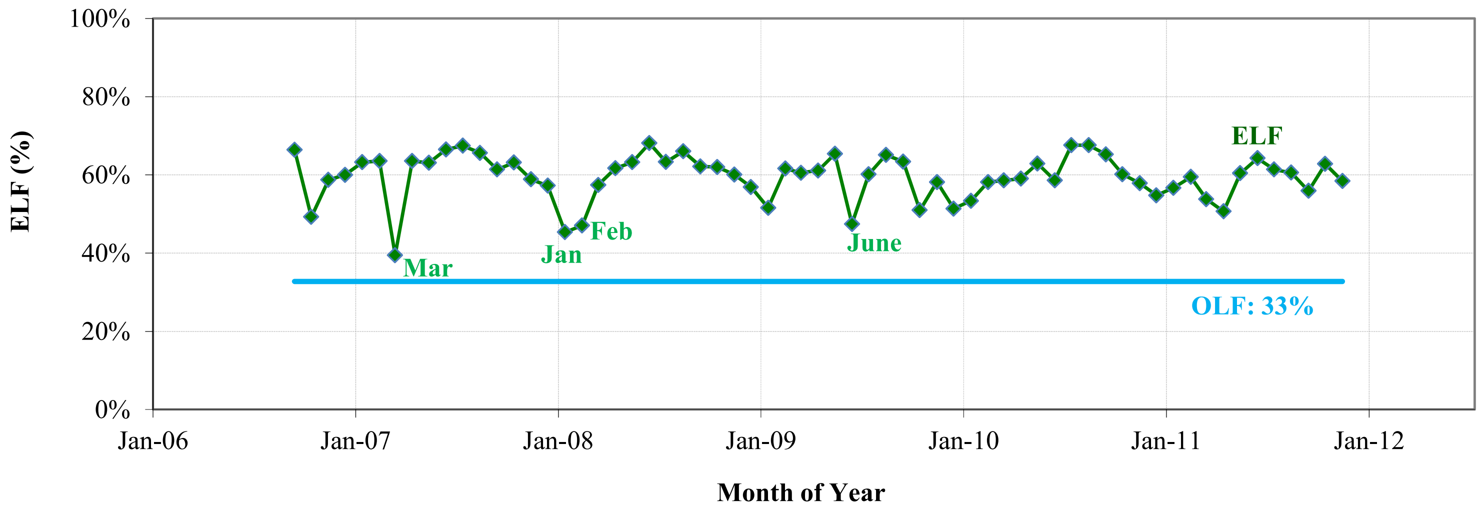


Figure 41: Monthly Electrical Load Factor for the Case-Study Building

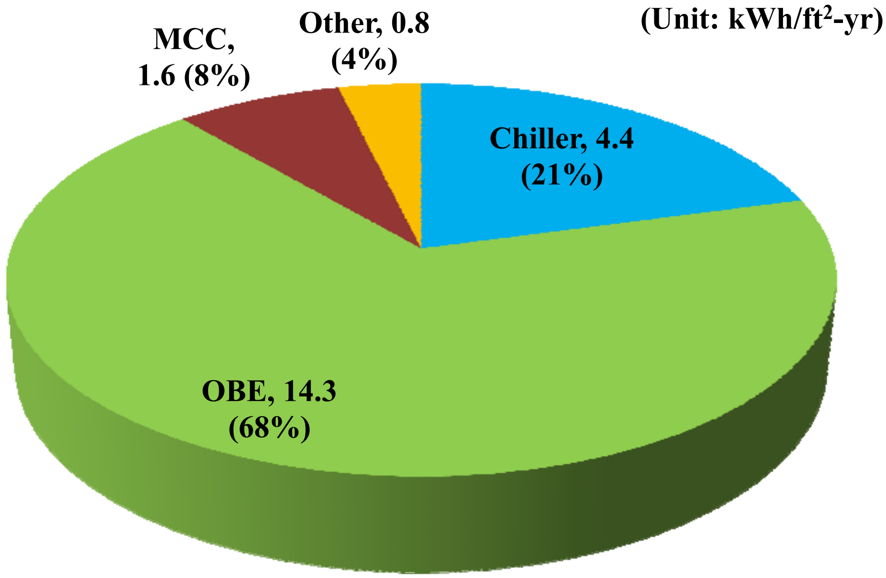
b) End-Use Assessment

The end-use assessment of the case-study building's electricity use was performed using the collected sub-hourly electricity use data for the whole building and major end-uses. Section 4.1.2.1 provides an electric monitoring diagram of the case-study building (Figure 9) and details on the instruments as well as measurement parameters. Using the collected sub-hourly data, the annual electricity use of the building was calculated for the following end-uses: office building electricity (OBE, including fans, lighting and equipment), chiller electricity, motor control center electricity (MCC, including chilled water pumps, condenser water pumps, hot water pumps, cooling tower fans, and boiler auxiliaries), and other[38].

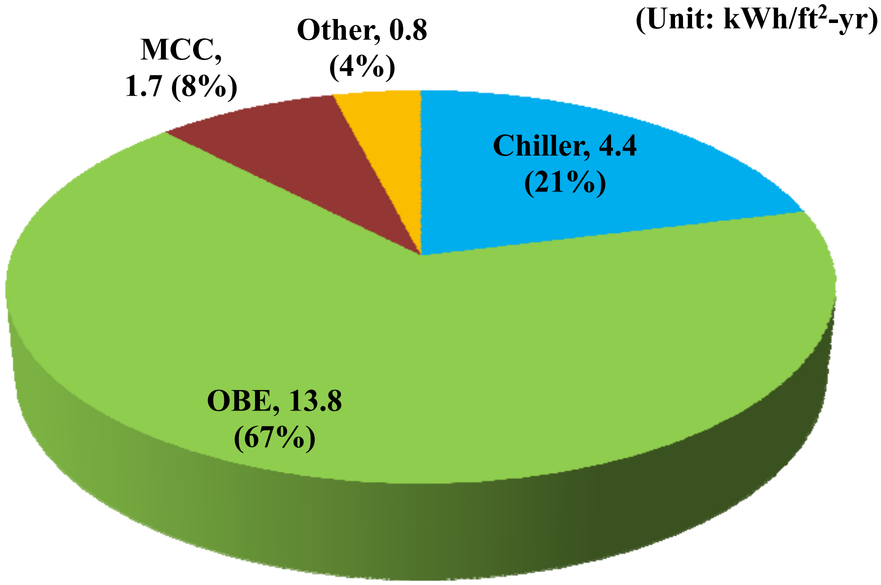
Figure 42 presents the calculated energy use intensity ($kWh/ft^2 \cdot yr$) by each end-use for (a) 2009 (January to December) and (b) 2010 (January to December). The OBE was the largest end-use category of electricity consumption: 68% in 2009 and 67% in 2010. The chillers[39] were the second largest electricity-consuming item: 21% in both 2009 and 2010. The MCC and other consumption account for about 8% and 4%, respectively for both 2009 and 2010. This result indicates that the case-study building is an internal-load dominated building that consumes most of its energy associated with large internal heat gains from lighting, equipment and occupants. Thus the measures of improving efficiency of lighting and equipment would have the highest impact in improving the energy efficiency of the building.

[38] Other consumption was determined by subtracting the sum of all end-uses from whole-building electricity (WBE) consumption.

[39] The electricity use of the chiller No.2 was synthesized by adding the residuals that were calculated by subtracting the modeled Other electricity use from the measured Other electricity use, to the measured chiller electricity use when the chiller NO.2 was run. The modeled Other electricity use was calculated using the temperature dependent regression model of Other electricity use when the chiller No.1 was run. Details are presented in Appendix D, including the basis of this data synthesis.



(a) 2009 (January to December)



(b) 2010 (January to December)

Figure 42: Measured Electricity End-Use Consumption of the Case-Study Building: (a) 2009 and (b) 2010

5.1.2.2. Performance Evaluation/Benchmarking

The evaluation of energy performance at the Intermediate Level requires self-reference comparisons using a whole-building inverse energy use model that allows a year-to-year comparison normalized for the selected independent variables such as weather or occupancy. Using the ASHRAE Inverse Modeling Toolkit (IMT) (Kissock et al. 2004), the whole-building electricity, demand, and natural gas models were developed with a single independent variable (i.e., outdoor temperature) for the years between 2007 and 2011[40]. Performance changes were then calculated against the baseline year. Since the current version of the ASHRAE PMP does not provide any advice about how to ensure a fair level of confidence in the calculated model as well as performance changes (i.e., savings[41]), the Whole-Building Performance Path of the ASHRAE Guideline 14-2002 (ASHRAE 2002) was referenced in the entire calculation procedure, although the compliance with the ASHRAE Guideline 14-2002 is not required in the current version of the ASHRAE PMP.

a) Whole-Building Electricity Use

The whole-building electricity (WBE) use models were developed for the years between 2007 and 2011 using the ASHRAE IMT, and the performance changes were calculated against the baseline year 2007.

- Calculation of outdoor temperature indices for WBE use model

The ASHRAE PMP does not provide any advice how to select a relevant outdoor temperature index for different types of energy use. Thus, to determine the most significant outdoor temperature index for the WBE use model, this study tested the monthly average temperatures computed in two ways: either (a) by averaging daily minimum and maximum outdoor dry-bulb temperatures (T_{minmax})[42], or (b) by averaging hourly outdoor dry-bulb temperatures (T_{hourly})[43] for each billing period.

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[40] For the 2011 inverse model, December data was eliminated due to a change of occupancy in a case-study building in December 2011.

[41] In this dissertation, the word "savings" is used to denote the changes in energy or water use performance against the baseline year. Negative savings means increased energy or water use against the baseline year.

[42] T_{minmax} is the average monthly value calculated using the daily minimum and maximum outdoor dry-bulb temperatures measured by the National Oceanic and Atmospheric Administration (NOAA) National Weather Service (NWS) using the Automated Surface Observation Station (ASOS) at the College Station Easterwood Airport. These data were obtained through the NOAA National Climatic Data Center (NCDC) weather database (NCDC 2012).

[43] T_{hourly} is the average monthly value calculated using the hourly outdoor dry-bulb temperatures measured by the NOAA NWS using the ASOS at the College Station Easterwood Airport. These data were also obtained through the NOAA NCDC weather database (NCDC 2012).

To construct average daily temperature database to be used for temperature dependent regression models using utility bills, Kissock (2007) compared these two temperature indices using over 50,000 daily temperature records in the National Oceanic and Atmospheric Administration (NOAA) National Climatic Data Center (NCDC) database. He found an average deviation of 1.5 F between these two indices. However, he concluded that the bias is not statistically significant, so the use of either temperature index should not impact on the calculated energy use models. However, the impact of the use of T_{minmax} and T_{hourly} on the calculated savings was not examined.

Figure 43 presents the distribution of the monthly average temperatures calculated using these two methods with residuals. On average, the monthly average of daily minimum and maximum temperatures, T_{minmax}, was 0.6 F higher than the monthly average hourly temperature, T_{hourly}. Larger deviations were observed in the summer when the temperatures were above 80 F[44]. The observed deviation between the two indices is mainly due to a different method used to determine the two indices, although both indices were calculated based on the data measured by the National Oceanic and Atmospheric Administration (NOAA) National Weather Service (NWS) using the same system: Automated Surface Observation Station (ASOS) at the College Station Easterwood Airport (NCDC 2012).

First, T_{minmax} was calculated using the daily minimum and maximum outdoor dry bulb temperatures. The daily minimum and maximum temperatures are the lowest and highest temperatures for the corresponding calendar day reported in the midnight. On the other hand, T_{hourly} was calculated using the hourly temperatures that are the running 5 minute average temperatures at the hourly report time (NOAA 1998). Therefore, there may be a discrepancy between the daily minimum and maximum temperatures versus the minimum and maximum hourly temperatures. Figure 44 presents the daily minimum and maximum outdoor dry-bulb temperatures as well as the hourly temperatures for the winter (i.e., January and February 2010) and the summer (i.e., July and August, 2010). In winter, occasionally, there was a difference between the daily minimum temperatures versus the minimum hourly temperatures, while no noticeable difference was observed between the daily maximum temperatures versus the maximum hourly temperatures. Meanwhile, in summer, the situation is reversed; occasionally, there was a difference between the daily maximum temperatures versus the maximum hourly temperature, while no difference was observed between the two minimum indices.

[44] The absolute maximum deviation was 1.7 F.

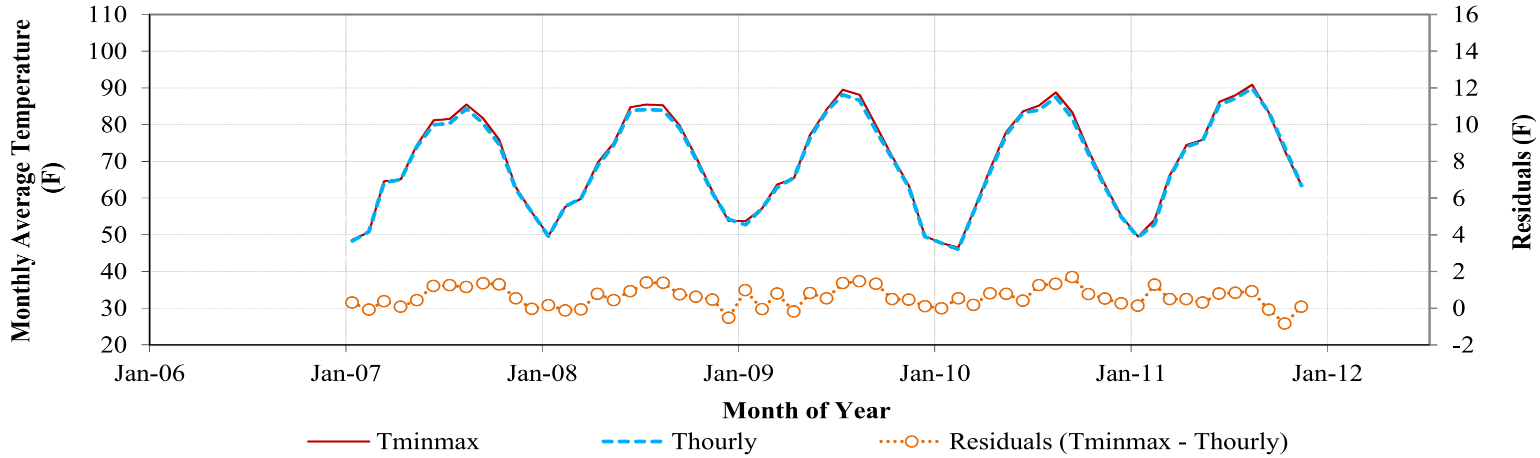
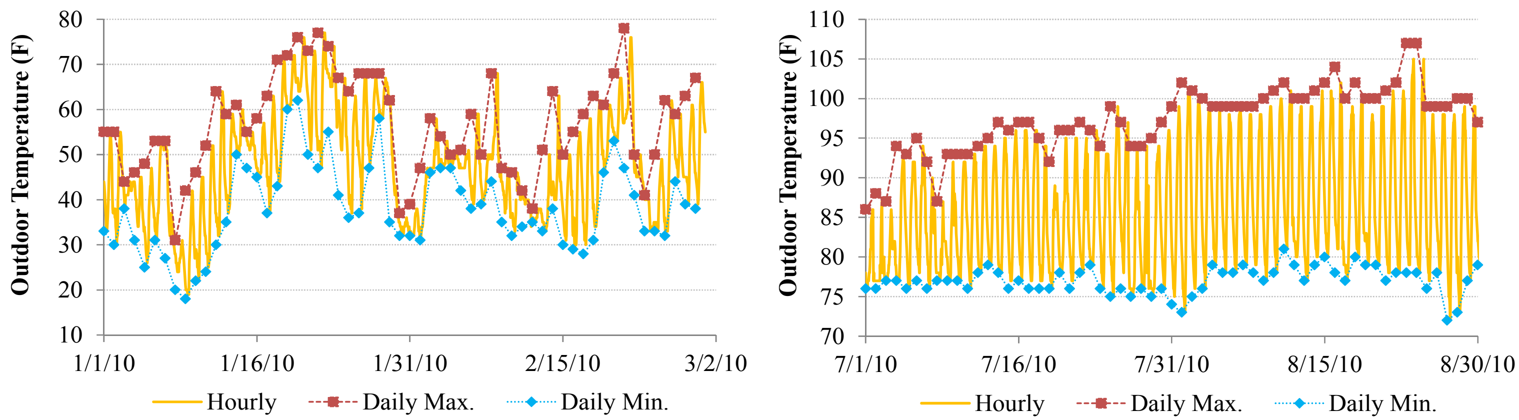


Figure 43: Distribution of Monthly Average of Daily Minimum and Maximum Temperatures (T_{minmax}) and Monthly Average of Hourly Temperatures (T_{hourly}) (Left Axis) with Residuals (Right Axis) for the Years from 2007 to 2011

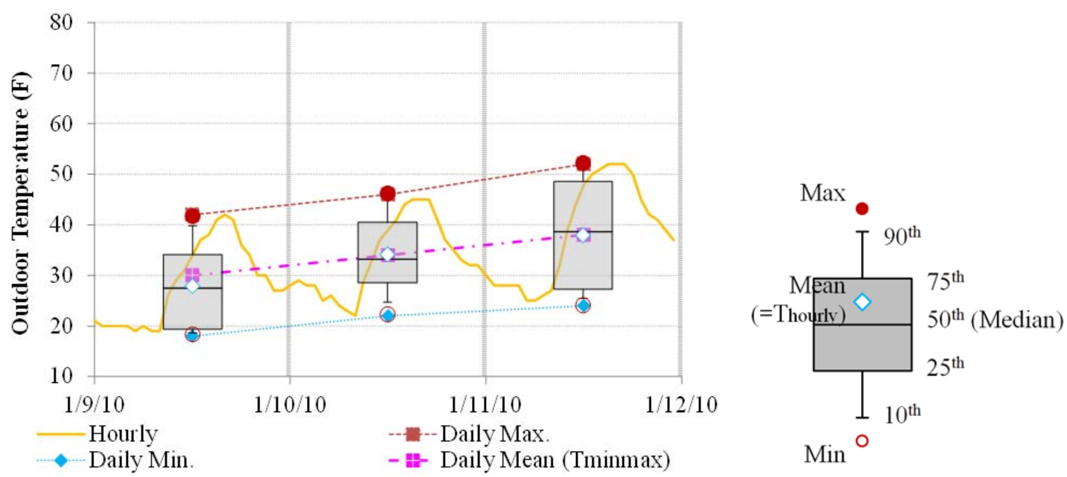


(a) Winter (January to February 2010)

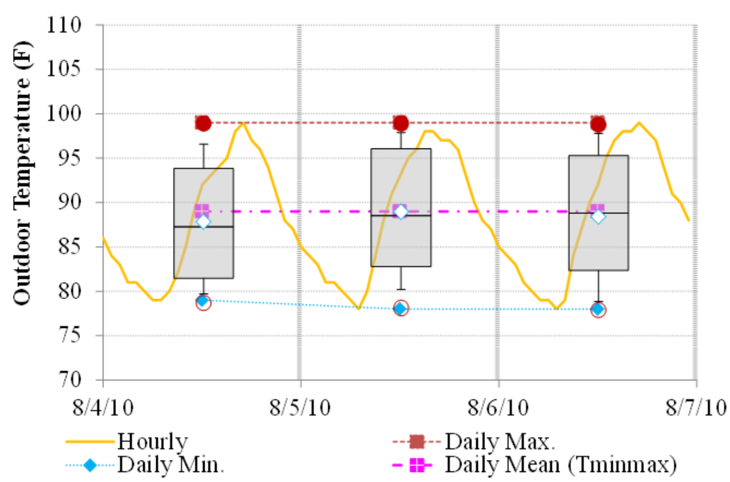
(b) Summer (July to August 2010)

Figure 44: Hourly Temperatures with the Daily Minimum and Maximum Temperatures: (a) Winter (Left) and (b) Summer (Right) (Note different scales on Y-axis between the figures.)

Even when no deviations were noted between the daily minimum and maximum temperatures versus the minimum and maximum hourly temperatures, there may be a difference between the two calculated indices: T_{minmax} versus T_{hourly}. This is because that T_{minmax} is an arithmetic mean of the two values (i.e., daily minimum and maximum temperatures), while T_{hourly} is an average of 24 hourly readings that forms a skewed sinusoidal, diurnal curve. Figure 45 presents T_{minmax} and T_{hourly} calculated for the selected three days that have the same (or very similar, at most 1.0 F difference) daily minimum and maximum temperatures as the minimum and maximum hourly temperatures. For the selected three days, deviations found between T_{minmax} and $_{Thourly}$ are: −0.3 to 1.6 F in winter and −0.1 and 1.0 F in summer.



(a) Winter (January 9 to 11, 2010)



(b) Summer (August 4 to 7, 2010)

Figure 45: T_{minmax} and T_{hourly} Calculated for the Selected Three Days: (a) Winter (Upper) and (b) Summer (Lower)

- WBE use inverse model

To select the most appropriate form of the regression model for the monthly WBE use data, four basic models, including 1, 2, 3, and 4-parameter models, were constructed. Figure 46 shows monthly whole-building electricity use normalized on a daily average basis against the two monthly average temperature indices (i.e., T_{minmax} and T_{hourly} for each billing period) along with all four models calculated using the 2007 data. To eliminate net bias error due to billing period variation, each of the twelve data points was weighted by the number of days in the corresponding billing period, which is one of the compliance requirements of the ASHRAE Guideline 14-2002[45]. The model coefficients and statistical indicators of the four models are listed in Table 9.

Of the four models, both the 3-paramter (3-P) and 4-parameter (4-P) models appeared to yield the best-fit with the highest coefficient of determination (R^2) of 0.98[46] against both T_{minmax} and T_{hourly} as well as the lowest coefficient of variation of the root mean square error (CV-RMSE)[47] of 1.6% against T_{minmax} and 1.7% against T_{hourly}. The 4-P model was found to have a very similar fit to the 3-P model with its near-flat cooling slope for temperatures below the change point[48] (i.e., 8.7 kWh/day/F against T_{minmax} and 12.0 kWh/day/F against T_{hourly}). Thus, the 3-P cooling change-point model was selected for the final model of the monthly WBE use and presented in Figure 47 for the years from 2007 to 2011.

The models were well determined with high R^2 between 0.95 and 0.98 as well as low CV-RMSE between 1.6% and 2.5%, as shown in Table 10. The weather-independent, base-load

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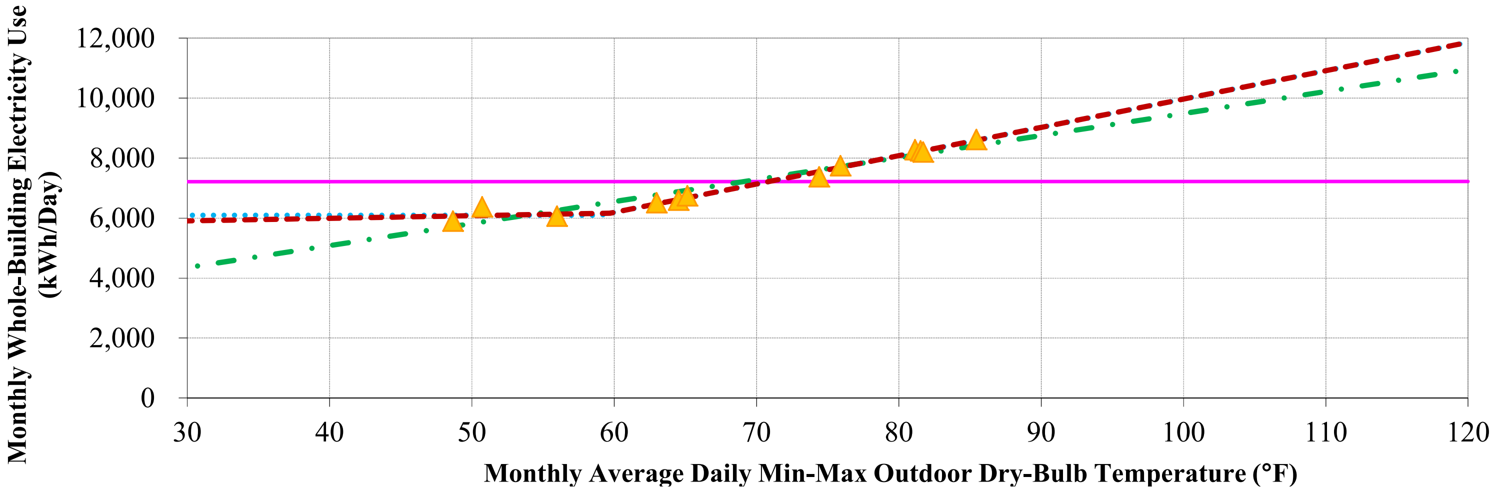
[45] Section 6.1.3.3 of the ASHRAE Guideline 14-2002 says "By using the average daily consumption (monthly consumption divided by reading period days), the regression procedure must use a weighted regression technique."

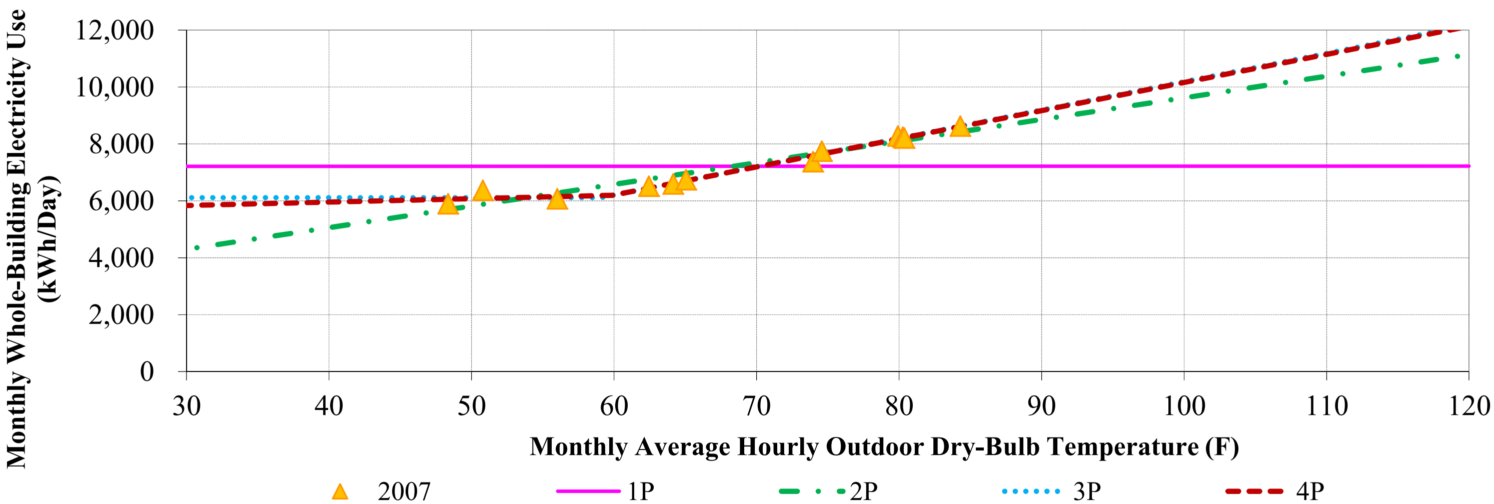
[46] The R^2 is used to quantify goodness-of-fit of the model. R^2 equal to 1.0 means a perfect fit, and R^2 above 0.8 indicates that the fit is good (ASHRAE 2010a). To calculate the R^2, the following equation is used. $R^2 = 1 - [\Sigma(y_i - \hat{y}_i)^2 / \Sigma(y_i - \bar{y})^2]$, in which: y_i = measured monthly or daily energy use or demand (kWh/day, kW, or MCF/day); $\hat{y}_i$ = regression model's predicted monthly or daily energy use or demand (kWh/day, kW, or MCF/day); and $\bar{y}$ = arithmetic mean of measured monthly or daily energy use or demand (kWh/day, kW, or MCF/day).

[47] The CV-RMSE is used to quantify how data are scattered around the model. The Whole-Building Prescriptive Path in Section 5.3.2.1 of the ASHRAE Guideline 14 (ASHRAE 2002) allows the baseline model to have a maximum CV-RMSE between 20% and 30% depending on the number of months of post-retrofit data available for computing savings. To calculate the CV-RMSE, the following equation is used. $\text{CV-RMSE} = 100 \times [\Sigma(y_i - \hat{y}_i)^2/(n - p)]^{1/2} / \bar{y}$, in which: y_i = measured monthly or daily energy use or demand (kWh/day, kW, or MCF/day); $\hat{y}_i$ = regression model's predicted monthly or daily energy use or demand (kWh/day, kW, or MCF/day); n = number of observations; p = number of parameters in the regression model; and $\bar{y}$ = arithmetic mean of measured monthly or daily energy use or demand (kWh/day, kW, or MCF/day).

[48] The change-point temperature (Tcp) is the temperature above which cooling begins.



(a) Monthly Average of Daily Minimum and Maximum Outdoor Temperatures (T_{minmax}) for the Billing Period



(b) Monthly Average of Hourly Outdoor Temperatures (T_{hourly}) for the Billing Period

Figure 46: Monthly WBE Use versus Monthly Outdoor Temperatures, Including 1, 2, 3, 4-P Models for 2007

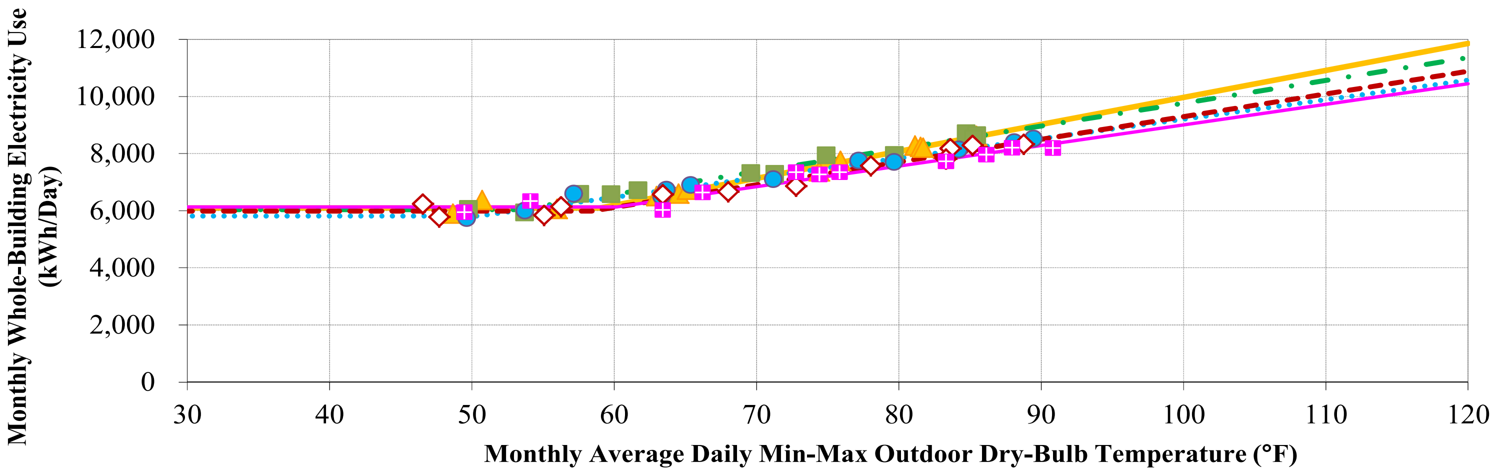
Table 9: Model Coefficients and Statistical Indicators for Monthly 1, 2, 3, 4-P WBE Use Models for 2007

(a) Monthly Average of Daily Minimum and maximum Outdoor Temperatures (T_{minmax}) for the Billing Period

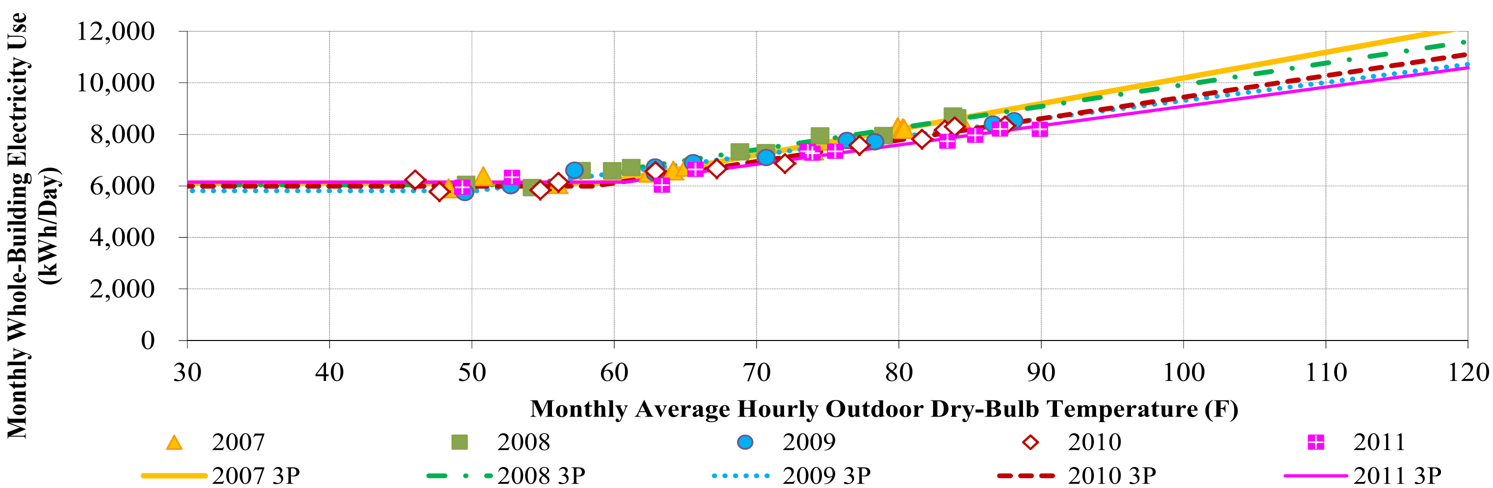
Coefficient	Description	1P (N=12)	2P (N=12)	3P (N=12)	4P (N=12)
Ycp	Base load (kWh/day)	-	-	6,097	6,166
Ymean	Mean load (kWh/day)	7,212	-	-	-
Yintercept	Y-intercept load (kWh/day)	-	2,151	-	-
CS_1	Cooling slope for temperature below Tcp (kWh/day/ΔF)	-	73.4	0.0	8.7
CS_2	Cooling slope for temperature above Tcp (kWh/day/ΔF)	-		94.3	94.3
Tcp	Change point temperature (F)	-	-	59.0	59.7
R^2	Squared correlation coefficients	-	0.94	0.98	0.98
CV-RMSE	Coefficient of variation of the root mean square error (%)	-	3.2%	1.6%	1.6%
CV-STD	Coefficient of Variation of the Standard Deviation (%)	13.4%	-	-	-

(b) Monthly Average of Hourly Outdoor Temperatures (T_{hourly}) for the Billing Period

Coefficient	Description	1P (N=12)	2P (N=12)	3P (N=12)	4P (N=12)
Ycp	Base load (kWh/day)	-	-	6,109	6,197
Ymean	Mean load (kWh/day)	7,212	-	-	-
Yintercept	Y-intercept load (kWh/day)	-	2,021	-	-
CS_1	Cooling slope for temperature below Tcp (kWh/day/ΔF)	-	76.0	0.0	12.0
CS_2	Cooling slope for temperature above Tcp (kWh/day/ΔF)	-		99.8	98.8
Tcp	Change point temperature (F)	-	-	59.1	59.9
R^2	Squared correlation coefficients	-	0.93	0.98	0.98
CV-RMSE	Coefficient of variation of the root mean square error (%)	-	3.3%	1.7%	1.7%
CV-STD	Coefficient of Variation of the Standard Deviation (%)	13.4%	-	-	-



(a) Monthly Average of Daily Minimum and Maximum Outdoor Temperatures (T_{minmax}) for the Billing Period



(b) Monthly Average of Hourly Outdoor Temperatures (T_{hourly}) for the Billing Period

Figure 47: Monthly WBE Use versus Monthly Outdoor Temperatures, Including 3-P Cooling Change-Point Models for the Years from 2007 to 2011

Table 10: Model Coefficients and Statistical Indicators for Monthly WBE Use Models

(a) Monthly Average of Daily Minimum and Maximum Outdoor Temperatures (T_{minmax}) for the Billing Period

Coefficient	Description	2007 (N=12)	2008 (N=12)	2009 (N=12)	2010 (N=12)	2011 (N=11)[1]
Ycp	Base load (kWh/day)	6,097	6,037	5,814	5,983	6,131
CS	Cooling slope (kWh/day/ΔF)	94.3	79.8	68.4	79.5	72.1
Tcp	Change point temperature (F)	59.0	53.3	50.4	58.4	60.2
R^2	Squared correlation coefficients	0.98	0.98	0.98	0.97	0.95
CV-RMSE	Coefficient of variation of the root mean square error (%)	1.6%	1.8%	1.8%	2.4%	2.5%

(b) Monthly Average of Hourly Outdoor Temperatures (T_{hourly}) for the Billing Period

Coefficient	Description	2007 (N=12)	2008 (N=12)	2009 (N=12)	2010 (N=12)	2011 (N=11)[1]
Ycp	Base load (kWh/day)	6,109	6,043	5,814	5,991	6,142
CS	Cooling slope (kWh/day/ΔF)	99.8	83.9	70.3	83.2	74.8
Tcp	Change point temperature (F)	59.1	53.7	50.3	58.5	60.7
R^2	Squared correlation coefficients	0.98	0.98	0.98	0.97	0.96
CV-RMSE	Coefficient of variation of the root mean square error (%)	1.7%	1.7%	1.7%	2.3%	2.3%

NOTES:

1) December data was eliminated due to a change of occupancy in a case-study building in December 2011.

electricity use (Ycp) varied between 5,814 and 6,142 kWh/day per year, with the highest consumption in 2011 and the lowest consumption in 2009. The temperature-dependent cooling energy consumption (i.e., cooling slope, CS (kWh/day/F)) varied between 68.4 and 99.8 kWh/day/F, and the change-point temperature (i.e., the temperature above which cooling begins, Tcp) was calculated to be between 50.3 and 60.7 F per year. The 2007 model was estimated to have the highest slope with a change-point temperature similar to 2010 and 2011 models, which means the case-study building used more electricity for cooling with an increase in outdoor air temperature in 2007 compared to 2010 and 2011. The lowest slope was estimated in 2009 but with the lowest change-point temperature.

Almost identical results were obtained using two different monthly average temperature indices (i.e., T_{minmax} and T_{hourly}) except the cooling slopes. The models with T_{hourly} had slightly higher cooling slopes than the models with T_{minmax}. This is because the computed monthly average hourly temperatures, T_{hourly}, were consistently lower than the monthly average of daily minimum and maximum temperatures, T_{minmax}, at the temperatures above 80 F.

- Calculation of performance changes in WBE use

To track the changes in energy performance of the building over several years, the weather-normalized savings[49] were calculated for 2008 to 2011 against the baseline year 2007 by subtracting the billed, actual consumption from the predicted consumption using the 2007 IMT 3-P cooling models, which is the standard method in the International Performance Measurement and Verification Protocol (IPMVP) (EVO 2009; DOE 2002b) and the ASHRAE Guideline 14-2002 (ASHRAE 2002). Another approach that has been typically used to determine savings is the method based on the Normalized Annual Consumption (NAC). The NAC method determines the savings by subtracting the predicted consumption for the "normal" weather year using the corresponding post year model from the predicted consumption for the same "normal" weather year using the baseline model. Engan (2007) examined the differences in the results between these two methods with the use of both regression models (i.e., IPMVP Option C) and the calibrated simulations (i.e., IPMVP Option D). The results showed that the NAC method resulted in less variability in the calculated energy savings than the IPMVP method.

One of the important criteria for the selection of a temperature-dependent baseline model is the base year's weather conditions. Wang (1998) pointed out that the use of a baseline model

[49] In this dissertation, the word "savings" is used to denote the changes in energy or water use performance against the baseline year. Negative savings means increased energy or water use against the baseline year.

with a limited temperature range to predict energy use of a year with extreme weather conditions would increase prediction errors associated with the savings determination. Thus, the percentage differences of the annual minimum and maximum temperature values of each year from 2008 to 2011 against the annual minimum and maximum temperature values of the selected base year 2007 were calculated. The calculated percentage differences were found to be between 95.7% and 102.2% (T_{minmax}) and between 95.1% to 102.5% (T_{hourly}) for the minimum values; and between 100% and 106.3% (T_{minmax}) and between 99.8% to 106.7% (T_{hourly}) for the maximum values, which complied with the ASHRAE Guideline 14-2002: 90% of the minimum and 110% of the maximum values of the independent variables used in the baseline model.

Figure 48 and Table 11 show the results using the models with T_{minmax} as well as T_{hourly}. The uncertainties associated with the calculated savings were also determined at the two levels of confidence: 68% and 95%, and the uncertainties with a 95% level of confidence are listed in the table[50]. The uncertainties at the 68% level of confidence were calculated to determine whether they met the requirements specified in the Whole-Building Performance Path of the ASHRAE Guideline 14-2002 (ASHRAE 2002). It was found that the calculated uncertainties at the 68% level of confidence to be lower than the maximum level of uncertainty required in this guideline, which is 50% of annual reported savings at 68% confidence.

Another metric that needs to be checked to determine the compliance with the Whole-Building Performance Path of the ASHRAE Guideline 14-2002 is a net determination bias[51]. The ASHRAE Guideline 14 requires a net determination bias to be less than 0.005% per Section 5.2.10. In this study, the computed net determination biases of the baseline models were 0.033% for the T_{minmax} model and 0.050% for the T_{hourly} model, which were higher than the acceptable level required in the ASHRAE Guideline 14-2002. This indicates a high level of uncertainty in the baseline models based on the 3-P cooling change-point models with a single independent variable (i.e., outdoor temperature). Thus a new baseline model needs to be developed to comply

[50] The uncertainties in savings were calculated based on the revised ASHRAE Guideline 14-2012 working draft, Measurement of Energy and Demand Savings (ASHRAE 2012).
[51] The net determination bias (NDB) is used to test the algorithm (i.e., baseline model) for savings determination by comparing an energy use determined by the baseline model against the actual baseline energy usage rather than to estimate the model's prediction errors. To calculate the NDB, the following equation is used. $NDB = 100 \times [\Sigma(y_i - \hat{y}_i)/ \Sigma y_i]$, in which: y_i = measured monthly or daily energy use or demand (kWh/day, kW, or MCF/day); and $\hat{y}_i$ = regression model's predicted monthly or daily energy use or demand (kWh/day, kW, or MCF/day).

with the ASHRAE Guideline 14-2002[52].

In spite of the issue with high net determination biases of the baseline models, the savings were calculated[53]. Overall, the savings calculated from the two different models were found to be similar. In 2008, a negative electricity savings was calculated with very high uncertainties: −50 ± 41 MWh/yr at the 95% confidence level using the T_{minmax} model (1.9% ± 1.6%) and −44 ± 44 MWh/yr at the 95% confidence level using the T_{hourly} model (1.7% ± 1.7%). Since 2009, the energy performance of the building has continuously improved, but high levels of uncertainties present: 1.6% ± 1.6% (T_{minmax} model) and 1.8% ± 1.7% (T_{hourly} model) in 2009; 3.7% ± 1.6% (T_{minmax} model) and 3.8% ± 1.7% (T_{hourly} model) in 2010; and 5.1% ± 1.6% (i.e., T_{minmax} model) and 5.9% ± 1.7% (T_{hourly} model) in 2011. At the 95% confidence level, it would be difficult to justify a decrease or an increase of whole-building electricity use in 2008 and 2009 against the baseline year of 2007. In 2010 and 2011, at the 95% confidence level, a small improvement in whole-building electricity use performance was observed. However, the reasons for this small improvement remain unknown at the Intermediate Level[54]. More detailed end-use analysis to reveal the reasons can be found in Section 5.1.3 Level III: Advanced Level.

A seasonal trend was observed in the monthly savings line: lower (or negative) savings in February, and increasing savings in August and September. The lower savings observed in February may indicate an under-prediction of the base-load consumption using the base year 2007 model due to holidays in December and January. At the annual-level calculation, a lower savings in February due to under-predicted base-load consumption by the model may be offset by an over-predicted savings in December and January, but the accuracy of such a model is limited. Thus, a modified approach is proposed in Section 6.2.1.2, which fixes the issue with the under-predicted base-load consumption of 3-P model due to holidays as well as the issue with high net determination biases of the baseline models.

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[52] Using outdoor temperature and the number of holidays as independent variables, a combination 3-P multi-variable regression (3-P MVR) cooling model was proposed with the net determination biases less than 0.005%. Details are presented in Section 6.2.1.2.
[53] The compliance with the ASHRAE Guideline 14-2002 is not required in the current version of the ASHRAE PMP.
[54] Conversations with the facility personnel revealed that there were no noticeable changes in occupancy of the building.

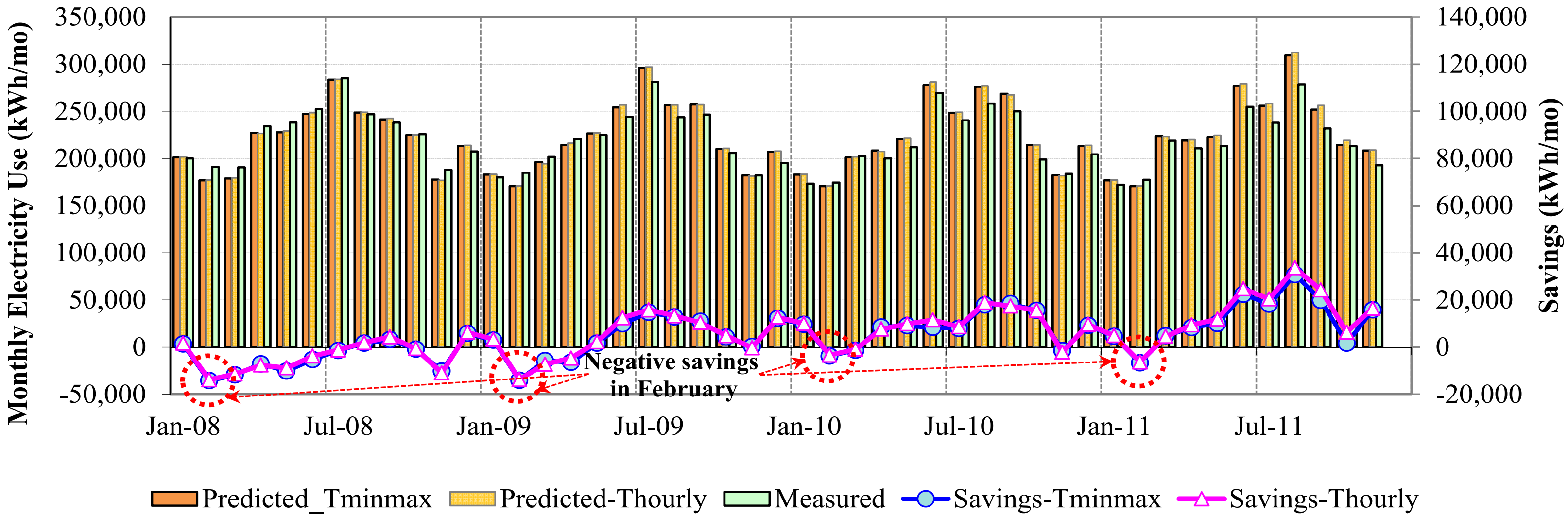

Figure 48: Monthly WBE Savings Against the Baseline Year 2007 Using the Monthly 3-P Model for the Years from 2008 to 2011 (T_{minmax} = Monthly Average of Daily Minimum and Maximum Outdoor Temperatures for the Billing Period; and T_{hourly} = Monthly Average of Hourly Outdoor Temperatures for the Billing Period)

Table 11: Annual Summary of WBE Savings Against the Baseline Year 2007 Using the Monthly 3-P Model

	Total Billed (MWh/period)	(a) Tminmax Model			(b) Thourly Model		
		Total Predicted (MWh/period)	Savings[1] (MWh/period)	Savings[1] (%)	Total Predicted (kWh/period)	Savings[1] (MWh/period)	Savings[1] (%)
2008 (Jan. to Dec.)	2,698	2,649	-50 ± 41	-1.9 ± 1.6%	2,654	-44 ± 44	-1.7 ± 1.7%
2009 (Jan. to Dec.)	2,611	2,654	43 ± 41	1.6 ± 1.6%	2,660	49 ± 44	1.8 ± 1.7%
2010 (Jan. to Dec.)	2,568	2,665	98 ± 42	3.7 ± 1.6%	2,670	102 ± 45	3.8 ± 1.7%
2011 (Jan. to Nov.)	2,401	2,530	129 ± 41	5.1 ± 1.6%	2,551	150 ± 45	5.9 ± 1.7%

NOTES:

1) The uncertainties associated with the calculated savings were determined at the 95% level of confidence .

b) Electric Demand

The peak electric demand use models were developed for the years between 2007 and 2011 using the ASHRAE IMT, and the performance changes were calculated against the baseline year 2007.

- Calculation of outdoor temperature indices for peak electric demand model

The ASHRAE PMP does not provide any advice how to select a relevant outdoor temperature index for different types of energy use. Thus to identify the potential outdoor temperature index suitable for a demand model, previous studies on demand savings have been reviewed.

Much fewer efforts were made to estimate weather-normalized demand savings in a building compared to the efforts made in measurement and verification of energy savings. Shonder and Hughes (2006) calculated demand savings from the energy savings performance contract (ESPC) for residential areas in a large army base using monthly utility data. Using the monthly highest temperatures for cooling seasons and the monthly lowest temperatures for heating seasons as independent variables, the pre-retrofit and post-retrofit models were calculated at the community level. A weather-normalized demand savings were then estimated at the community level using the Typical Meteorological Year version 2 (TMY2) file for Lufkin, TX.

Liu et al. (2006) developed a methodology to calculate demand savings from the ESPC for several buildings in an army base using hourly data. Using the ASHRAE Diversity Factor Toolkit (Abushakra et al. 2001), they developed hourly whole-building electricity load profiles for each month, and the maximum 90th percentile of each month were chosen to model the demand use of the building. For each building, the pre-retrofit model was calculated using the maximum daily 24-hour average outdoor temperature as an independent variable. The post-retrofit demand savings were then calculated by comparing the actual demand during the post-retrofit period against the estimated demand using the pre-retrofit model.

Thus, based on the review of previous studies, this study selected the following three maximum temperature indices to determine the most significant outdoor temperature index for the demand model: the maximum daily 24-hour average outdoor temperature (T_{max_24hour}) [55] based

[55] T_{max_24hour} is the highest daily average of the 24 hourly outdoor dry-bulb temperatures in a billing period. The hourly outdoor dry-bulb temperatures were measured by the NOAA NWS using the ASOS at the College Station Easterwood Airport. These data were obtained through the NOAA NCDC weather database (NCDC 2012).

on the study by Liu et al.(2006); the monthly maximum temperature ($T_{max\_monthly}$) [56] based on the study by Shonder and Hughes (2006); and additionally the maximum daily min-max average outdoor temperature (T_{max_minmax})[57] for a comparison. Figure 49 presents the distribution of these three maximum temperature indices for the years between 2007 and 2011 with residuals.

On average, the monthly maximum outdoor temperature, $T_{max\_monthly}$, was about 10.2 F higher than the maximum daily min-max average outdoor temperature, T_{max_minmax}; and about 11.7 F higher than the maximum daily 24-hour average outdoor temperature, T_{max_24hour}. The deviations tend to become larger with increasing temperature. On the other hand, relatively consistent deviations were observed between T_{max_minmax} and T_{max_24hour}.

- Detection of potential outliers

Several data points were found to be inconsistent with other data and noted as outliers. To determine outliers, two different methods were considered. The first method used a quartile analysis (i.e., a box and whisker plot) that has been commonly used in statistics (Emerson and Strenio 1983). The data points beyond the 25th and 75th quartiles by one and a half times the interquartile range (IQR = 75th quartile – 25th quartile) were considered potential outliers (Figure 50). The second method used the IMT 3-P cooling models which were calculated with all data points. The data points beyond $\pm 1.5 \times$ CV-RMSE of the calculated IMT 3-P cooling models were considered suspected outliers. Figure 51 presents the result for 2007. The identified potential outliers were then examined more closely to see if they could be reasonably deemed to be outliers and removed from the next regression.

Using the first method, two outliers were detected: 696 kW in March 2007 and 715 kW in June 2009. This method was found effective to detect extreme outliers, but failed to account for a seasonal variation in the peak demand[58]. In other words, winter peak demands that were higher than expected could not be detected since they were at similar levels to summer peak demands. Using the second method, six outliers were identified including the two extreme outliers identified using the first method (i.e., 696 kW in March 2007 and 715 kW in June 2009)

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[56] $T_{max\_monthly}$ is the highest daily maximum outdoor dry-bulb temperature in a billing period. The daily maximum outdoor dry-bulb temperatures were measured by the NOAA NWS using the ASOS at the College Station Easterwood Airport. These data were also obtained through the NOAA NCDC weather database (NCDC 2012).

[57] T_{max_minmax} is the highest daily average of daily minimum and maximum outdoor dry-bulb temperature in a billing period. The daily minimum and maximum outdoor temperatures were measured by the NOAA NWS using the ASOS at the College Station Easterwood Airport. These data were also obtained through the NOAA NCDC weather database (NCDC 2012).

[58] Peak demand is usually higher in the summer versus in the winter.

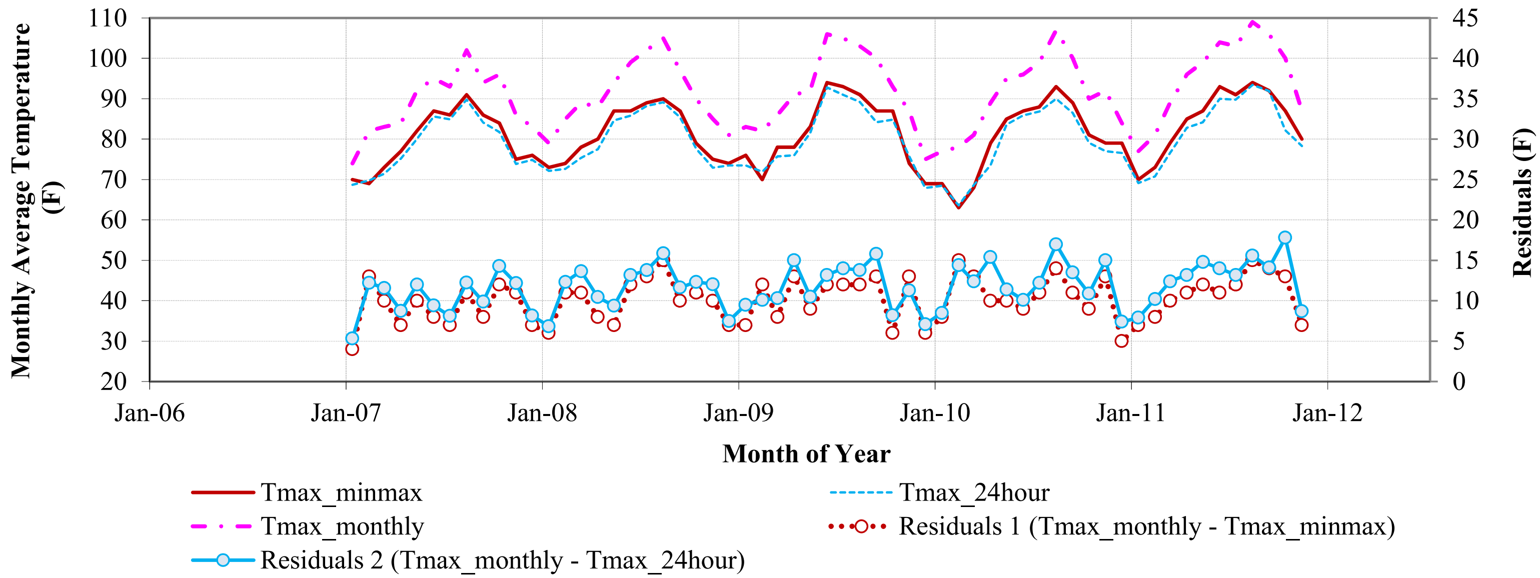


Figure 49: Distribution of Maximum Daily Min-Max Average Temperature (T_{max_minmax}), Maximum Daily 24-Hour Average Temperature (T_{max_24hour}), and Monthly Maximum Temperature ($T_{max\_monthly}$) (Left Axis) with Residuals (Right Axis) for the Years from 2007 to 2011

and the four new potential outliers (i.e., 557 kW in January 2008, 583 kW in February 2008, 581 kW in June 2010, and 598 kW in April 2011).

Finally, the six outliers identified using the second method were excluded to recalculate the IMT models. Per year, one data point was eliminated except in 2008. In 2008, two data points were eliminated, which corresponds to about 17% of data elimination. This is lower than the maximum allowable data elimination to comply with the Whole-Building Performance Path of the ASHRAE Guideline 14-2002, which is 25%. The reasons for the outliers could not be revealed at the Intermediate Level[59]. When examining the outliers all together, two distinct distributions were observed: outliers between 557 and 598 kW; and outliers between 696 and 715 kW, which might indicate two different types of events causing the outliers[60].

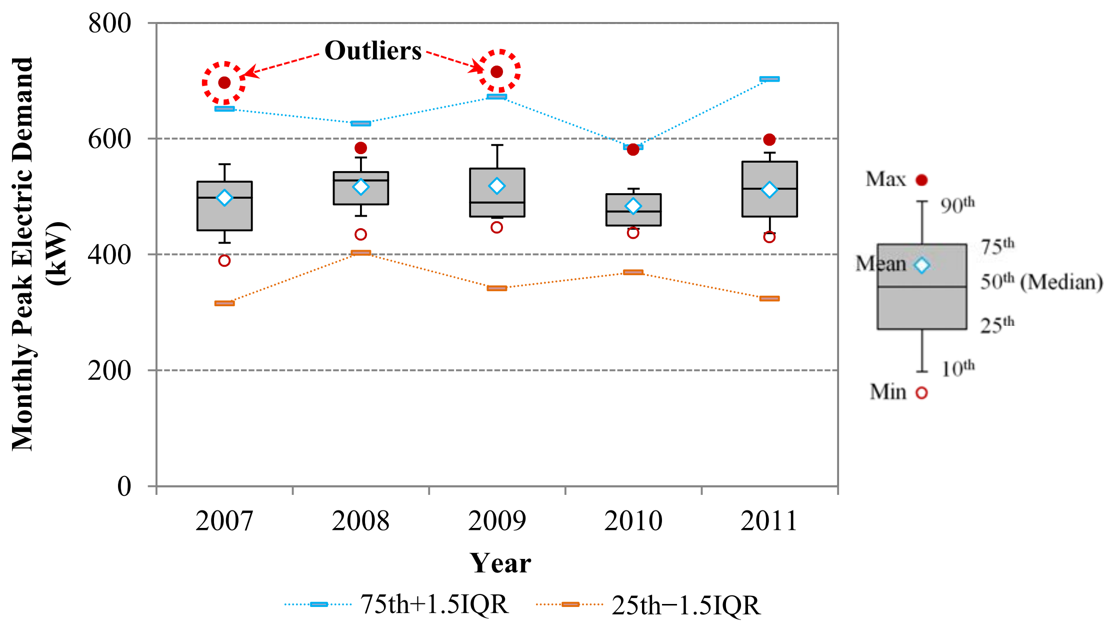


Figure 50: Monthly Peak Electric Demand (2007 to 2011)

[59] The end-use analysis using sub-hourly data at the Advanced Level could begin to diagnose the events causing the outliers and are presented in Section 5.1.3 Level III: Advanced Level.

[60] The four outliers between 557 and 598 kW may occur during sudden startup of certain equipment (i.e., the chiller) after an equipment shutdown. The other two outliers of 696 and 715 kW are suspected to occur due to simultaneous operation of two chillers erroneously.

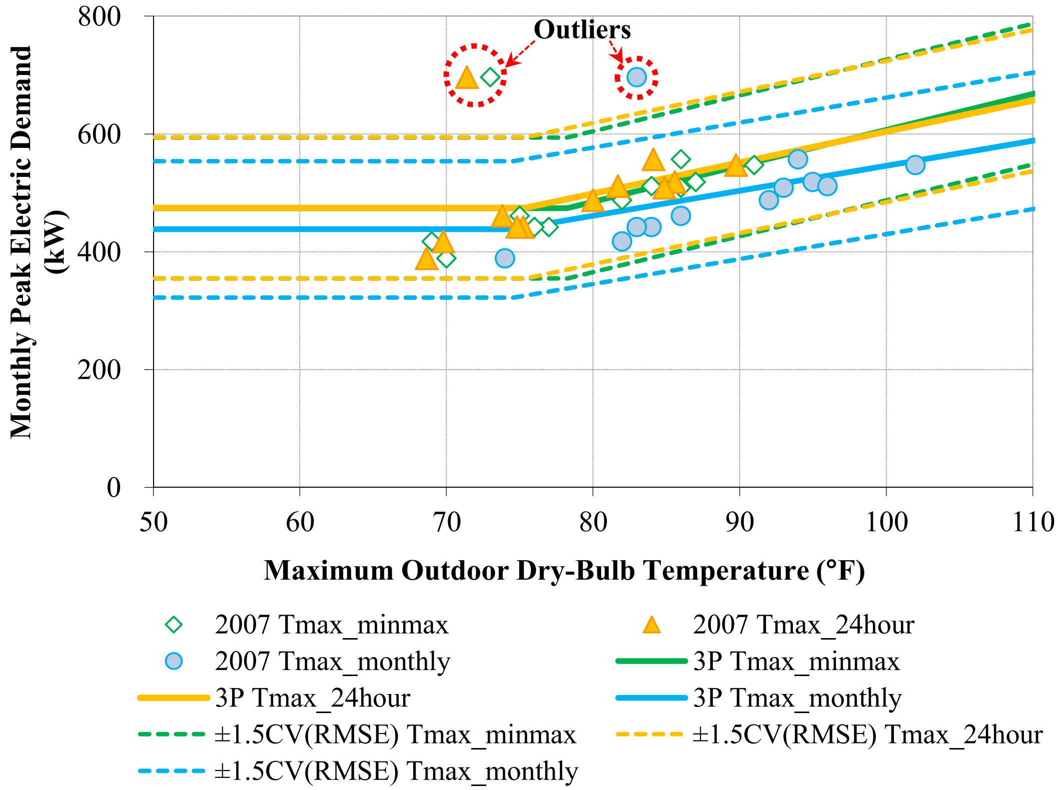


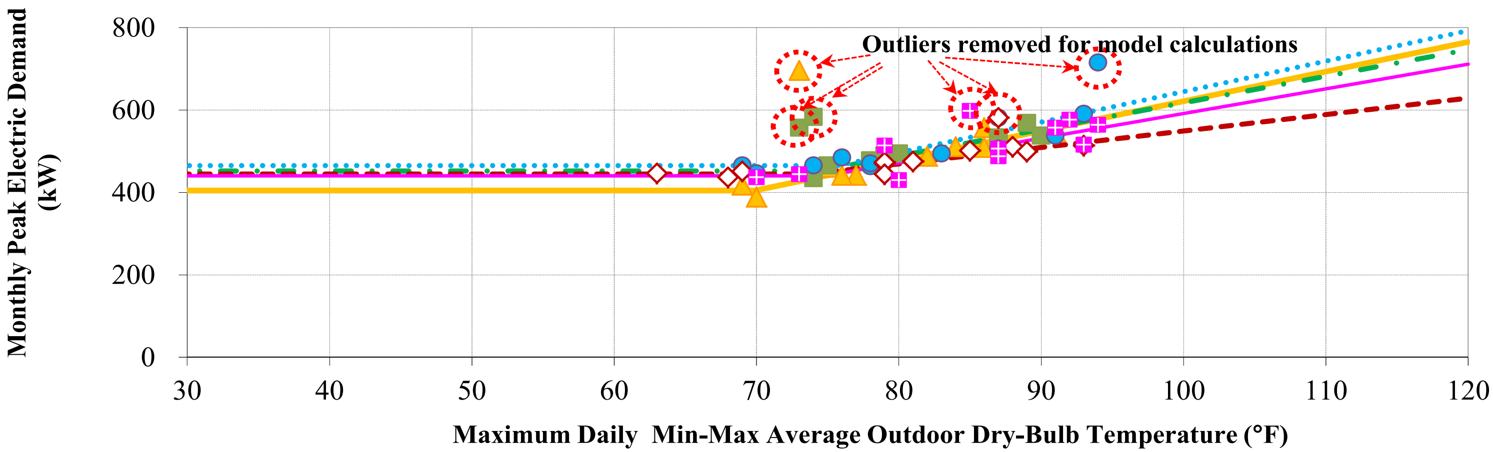
Figure 51: 2007 3-P Cooling Models for Monthly Electric Demand with ±1.5 CV-RMSE Lines

- Peak electric demand inverse model

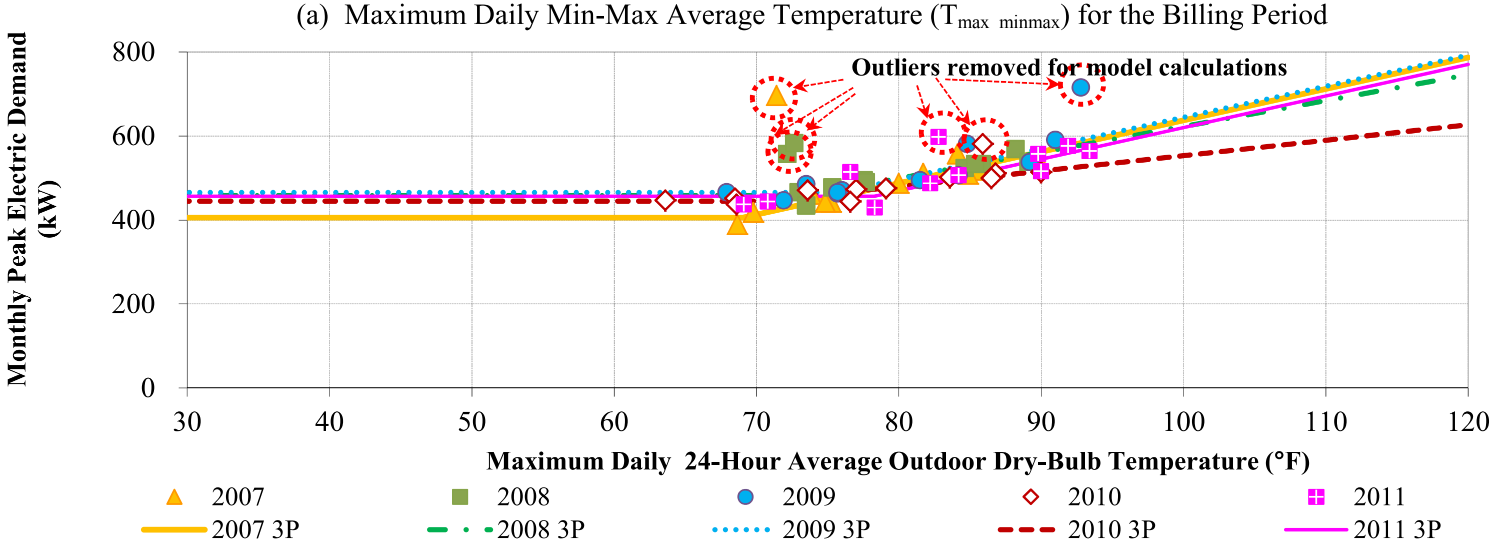
Using the data without outliers, the peak electric demand models were developed for the same years between 2007 and 2011[61]. Figure 52 shows monthly electric demand against three different maximum temperature indices (i.e., T_{max_minmax}, T_{max_24hour}, and $T_{max\_monthly}$) with the 3-P cooling change-point models recalculated without outliers. Table 12 presents the coefficients and statistical indicators of each model for both: (a) with outliers and (b) without outliers by year. Not surprisingly, the models without outliers were better determined with higher coefficients of determination (R^2) between 0.61 and 0.91 as well as lower coefficient of variation of the root mean square error (CV-RMSE) of 1.9% to 6.5%[62]. The weather-independent, base-load electric demand (Ycp) varied between 389 and 465 kW, with the lowest demand in 2007. The temperature-dependent cooling electric demand (i.e., right slope, RS (kW/F)) varied between 3.1 and 7.5 kW/F, and the change-point temperature (i.e., the temperature above which cooling begins, Tcp) was calculated to be between 69.1 and 85.2 F.

The use of three different maximum temperature indices (i.e., T_{max_minmax}, T_{max_24hour}, and $T_{max\_monthly}$) did not have much of an effect on the model's goodness-of-fit statistics except the year 2009. In 2009, the model with $T_{max\_monthly}$ had a slightly worse fit with a lower R^2 and a higher CV-RMSE (i.e., 0.61 R^2 and 6.5% CV-RMSE) than the other models: the model using T_{max_minmax} (i.e., 0.81 R^2 and 4.5% CV-RMSE) or the model using T_{max_24hour} (i.e., 0.80 R^2 and 4.6% CV-RMSE). Regarding the model coefficients, the $T_{max\_monthly}$ models had smaller right slope and a higher change-point temperature. However, the trend between years was very similar to the other models (i.e., T_{max_minmax} and T_{max_24hour}). One reason for this is that the monthly maximum outdoor temperatures, $T_{max\_monthly}$, were consistently higher than the other two maximum temperature indices (i.e., T_{max_minmax} and T_{max_24hour}), which tends to spread the data over a wider range of temperatures.

[61] For the 2011 model, December data was eliminated due to a change of occupancy in a case-study building in December 2011.
[62] The models with outliers had a R^2 between 0.11 and 0.81 and a CV-RMSE between 5.2% and 16.0%.

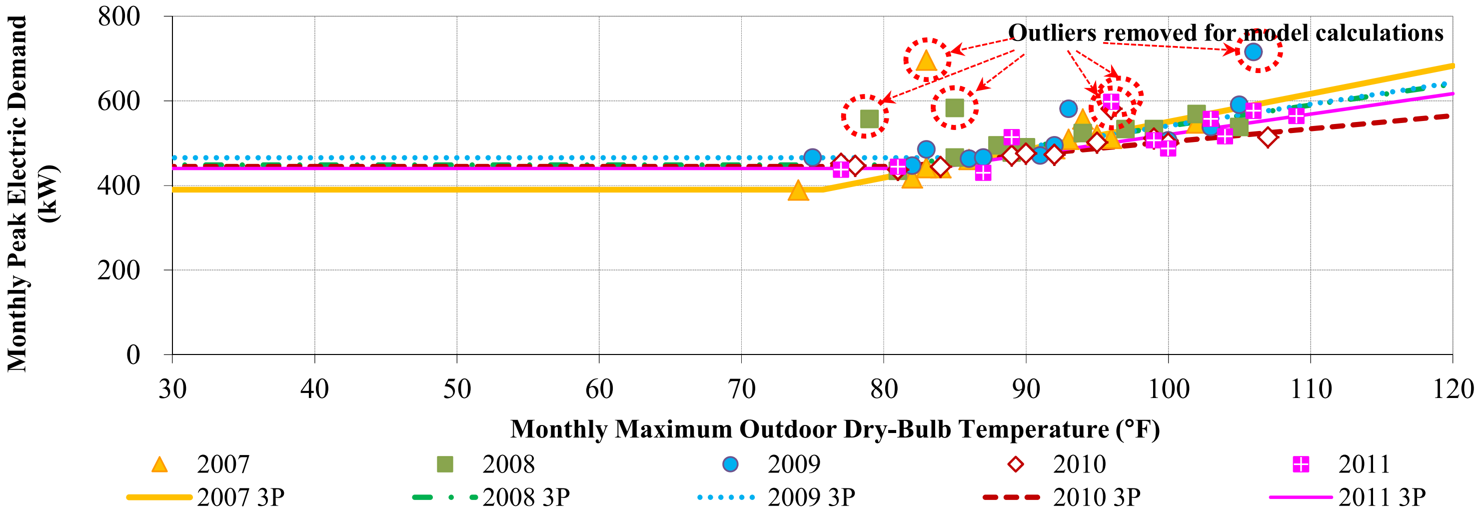


(a) Maximum Daily Min-Max Average Temperature ($T_{max\ minmax}$) for the Billing Period



(b) Maximum Daily 24-Hour Average Temperature (T_{max_24hour}) for the Billing Period

Figure 52: Monthly Peak Electric Demand versus Maximum Outdoor Temperatures, Including 3-P Cooling Change-Point Models (without Outliers) for the Years from 2007 to 2011



(c) Monthly Maximum Temperature ($T_{max\_monthly}$) for the Billing Period

Figure 52: Continued

Table 12: Model Coefficients and Statistical Indicators for Monthly Electric Demand Models: (a) with Outliers; (b) without Outliers

(a) Maximum Daily Min-Max Average Temperature (T_{max_minmax}) for the Billing Period

Coefficient	Description	2007		2008		2009		2010		2011	
		(a) (N=12)	(b) (N=11)	(a) (N=12)	(b) (N=10)	(a) (N=12)	(b) (N=11)	(a) (N=12)	(b) (N=11)	(a) (N=11)	(b) (N=10)
Ycp	Base load (kW)	474	405	500	452	465	465	444	445	436	440
RS	Right slope (kW/ΔF)	6.1	7.2	7.1	6.4	14.3	7.4	4.9	4.0	5.3	6.0
Tcp	Change point temperature (F)	78.2	69.9	82.5	74.3	79.9	75.8	73.8	73.8	70.5	74.8
R^2	Squared correlation coefficients	0.12	0.91	0.22	0.91	0.81	0.81	0.62	0.88	0.54	0.71
CV-RMSE	Coefficient of variation of the root mean square error (%)	16.0%	3.6%	8.0%	2.6%	6.8%	4.5%	5.5%	2.2%	8.1%	6.1%

(b) Maximum Daily 24-Hour Average Temperature (T_{max_24hour}) for the Billing Period

Coefficient	Description	2007		2008		2009		2010		2011	
		(a) (N=12)	(b) (N=11)	(a) (N=12)	(b) (N=10)	(a) (N=12)	(b) (N=11)	(a) (N=12)	(b) (N=11)	(a) (N=11)	(b) (N=10)
Ycp	Base load (kW)	474	406	500	458	467	465	445	445	441	457
RS	Right slope (kW/ΔF)	5.3	7.5	5.8	6.2	15.0	7.4	4.9	3.7	5.4	7.5
Tcp	Change point temperature (F)	75.4	69.1	80.0	73.3	80.4	75.8	71.5	70.5	69.6	78.3
R^2	Squared correlation coefficients	0.11	0.90	0.22	0.89	0.81	0.80	0.66	0.87	0.58	0.77
CV-RMSE	Coefficient of variation of the root mean square error (%)	16.0%	3.8%	8.0%	2.8%	6.8%	4.6%	5.2%	2.2%	7.7%	5.4%

(c) Monthly Maximum Temperature ($T_{max\_monthly}$) for the Billing Period

Coefficient	Description	2007		2008		2009		2010		2011	
		(a) (N=12)	(b) (N=11)	(a) (N=12)	(b) (N=10)	(a) (N=12)	(b) (N=11)	(a) (N=12)	(b) (N=11)	(a) (N=11)	(b) (N=10)
Ycp	Base load (kW)	438	390	502	448	491	465	447	445	437	440
RS	Right slope (kW/ΔF)	4.2	6.6	3.7	5.0	119.3	5.1	3.6	3.1	4.3	4.8
Tcp	Change point temperature (F)	74.6	75.7	89.9	81.5	104.1	85.2	81.2	81.2	78.3	83.4
R^2	Squared correlation coefficients	0.17	0.90	0.21	0.88	0.77	0.61	0.57	0.91	0.59	0.77
CV-RMSE	Coefficient of variation of the root mean square error (%)	15.5%	3.8%	8.0%	2.9%	7.5%	6.5%	5.8%	1.9%	7.7%	5.4%

- Calculation of performance changes in peak electric demand

To track the changes in the electric demand performance of the building over several years, the demand savings[63] were calculated for 2008 to 2011 against the baseline year 2007 by subtracting the billed, actual demand (including outliers) from the predicted demand using the 2007 IMT 3-P demand model generated without outliers. Figure 53 and Table 13 present the results using all three maximum temperature indices, including T_{max_minmax}, T_{max_24hour}, and $T_{max\_monthly}$[64]. The demand savings are reported on a monthly basis in the figure, and in the table, the monthly demand savings are summed up for each year to show the cumulative demand savings (kW/period).

The uncertainties associated with the calculated savings were also determined at the two levels of confidence: 68% and 95%, and the uncertainties with a 95% level of confidence are listed in the table. The uncertainties at the 68% level of confidence were calculated to determine whether they met the requirements specified in the ASHRAE Guideline 14-2002 (ASHRAE 2002). It was found that the uncertainties calculated for 2008 and 2009 to be lower than the maximum level of uncertainty required in the ASHRAE Guideline 14-2002, which is 50% of annual reported savings at 68% confidence, but for 2010 and 2011, the calculated uncertainties did not meet the requirements.

When comparing the net determination biases of three baseline models, the T_{max_minmax} and T_{max_24hour} baseline models met the criteria of the ASHRAE Guideline 14-2002 with net determination biases of 0.000%. However, the $T_{max\_monthly}$ baseline model had a net determination bias of 0.006%, which exceeded the acceptable level required in the ASHRAE Guideline 14-2002 (i.e., 0.005%). Thus the $T_{max\_monthly}$ baseline model would be a statistically less rigorous model that introduces more uncertainty in the calculated savings.

[63] In this dissertation, the word “savings” is used to denote the changes in energy or water use performance against the baseline year. Negative savings means increased energy or water use against the baseline year.
[64] The predicted consumption of the T_{max_24hour} model was omitted for simplicity in the figure since it was similar to the predicted consumption of T_{max_minmax}. The line graphs showing estimated demand savings are presented for all three models (i.e., T_{max_minmax}, T_{max_24hour}, and $T_{max\_monthly}$.)

Overall, compared to 2007, it was estimated that the building's electric demand increased in 2008 and 2009 with an annual savings (i.e., the sum of the monthly demand savings): −374 ± 153 kW/yr in 2008 and −341 ± 155 kW/yr in 2009 at the 95% confidence level using the T_{max_minmax} model; −383 ± 160 kW/yr in 2008 and −329 ± 162 kW/yr in 2009 at the 95% confidence level using the T_{max_24hour} model; and−292 ± 160 kW/yr in 2008 and −252 ± 162 kW/yr in 2009 at the 95% confidence level using the $T_{max\_monthly}$ model. However, it should be noted that a very large negative savings (i.e., increased peak demand) was calculated for the months with outliers in 2008 and 2009: January and February 2008 as well as June 2009. In 2010 and 2011, no demand savings were estimated with uncertainties greater than the calculated savings.

A similar amount of savings was estimated from the use of either T_{max_minmax} or T_{max_24hour}. However, the $T_{max\_monthly}$ model yielded slightly different results from these two indices (i.e., T_{max_minmax} and T_{max_24hour}). The savings estimated using $T_{max\_monthly}$ was about 66 to 112 kW/yr higher than T_{max_minmax} and about 77 to 150 kW/yr higher than T_{max_24hour} due to a larger temperature deviation between $T_{max\_monthly}$ and the other two indices from 2008 to 2011 compared to 2007[65]. However, the differences in the computed savings were within the range of uncertainties.

[65] On average, $T_{max\_monthly}$ was 9.0 and 10.3 F higher than T_{max_minmax} and T_{max_24hour}, respectively in 2007. Since 2008, the average deviation increased by: 10.1 to 10.9 F between $T_{max\_monthly}$ and T_{max_minmax} and 11.6 to 12.9 F between $T_{max\_monthly}$ and T_{max_24hour}.

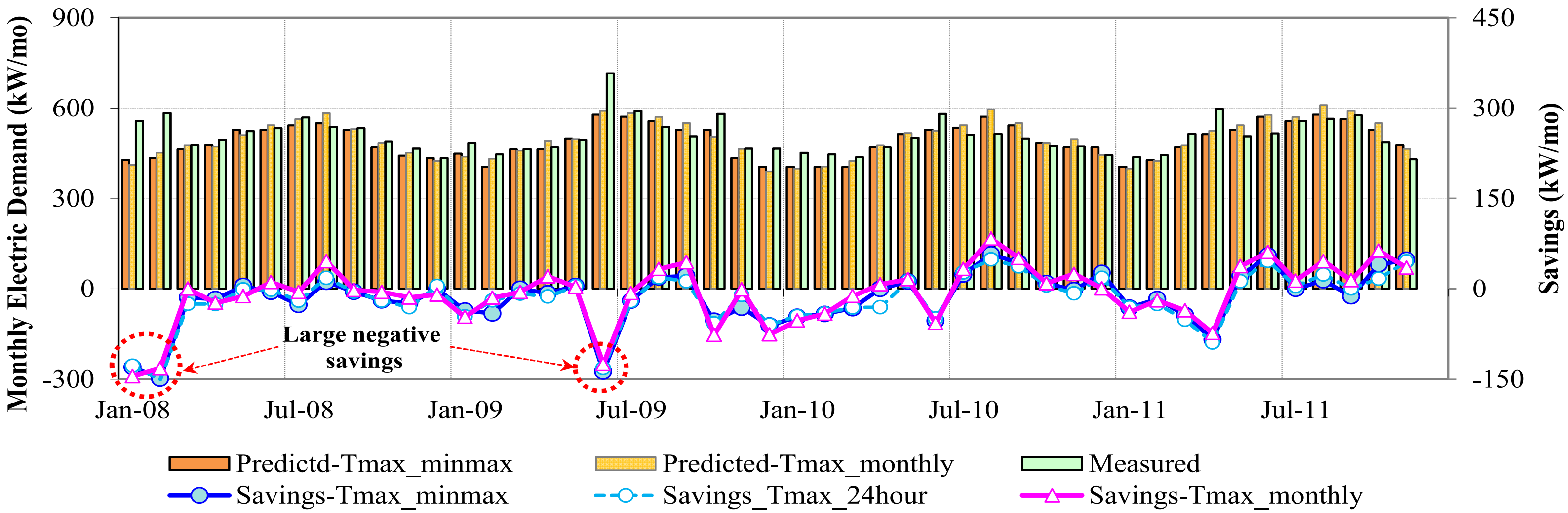


Figure 53: Demand Savings Against the Baseline Year 2007 Using the Monthly 3-P Model for the Years from 2008 to 2011 (T_{max_minmax} = Maximum Daily Min-Max Average Outdoor Temperature in a Billing Period; T_{max_24hour} = Maximum Daily 24-Hour Average Outdoor Temperature in a Billing Period; and $T_{max\_monthly}$ = Monthly Maximum Outdoor Temperature in a Billing Period)

Table 13: Annual Summary of Demand Savings Against the Baseline Year 2007 Using the Monthly 3-P Model

	Sum of Total Billed (kW/period)	(a) Tmax_minmax Model			(b) Tmax_24hour Model			(c) Tmax_monthly Model		
		Sum of Total Predicted (kW/period)	Sum of Savings[1,2]		Sum of Total Predicted (kW/period)	Sum of Savings[1,2]		Sum of Total Predicted (kW/period)	Sum of Savings[1,2]	
			(kW/period)	(%)		(kW/period)	(%)		(kW/period)	(%)
2008 (Jan. to Dec.)	6,197	5,823	-374 ± 153	-6.4 ± 2.6%	5,814	-383 ± 160	-6.6 ± 2.7%	5,905	-292 ± 160	-4.9 ± 2.7%
2009 (Jan. to Dec.)	6,221	5,880	-341 ± 155	-5.8 ± 2.6%	5,891	-329 ± 162	-5.6 ± 2.7%	5,969	-252 ± 162	-4.2 ± 2.7%
2010 (Jan. to Dec.)	5,803	5,799	-4 ± 153	-0.1 ± 2.6%	5,749	-54 ± 158	-0.9 ± 2.7%	5,865	62 ± 159	1.1 ± 2.7%
2011 (Jan. to Nov.)	5,628	5,619	-9 ± 155	-0.2 ± 2.8%	5,581	-47 ± 160	-0.8 ± 2.9%	5,731	103 ± 162	1.8 ± 2.8%

NOTES:
1) This is the sum of the monthly demand savings.
2) The uncertainties associated with the calculated savings were determined at the 95% level of confidence .

c) Natural Gas Use

The natural gas models were developed for the years between 2009 and 2011 using the ASHRAE IMT, and the performance changes were calculated against the baseline year 2009. For the billing periods before February 2009, the original natural gas utility bills were not available[66], although the natural gas use data were available from a database without specific billing dates. Thus in this study, the 2009 data from February to December were selected for natural gas baseline instead of the 2007 data, which allows a baseline model against the actual billing period temperatures[67].

- Calculation of outdoor temperature indices for natural gas use model

The ASHRAE PMP does not provide any advice how to select a relevant outdoor temperature index for different types of energy use. To determine the most significant outdoor temperature index for the natural gas use model, this study tested the following two monthly temperature indices: (a) the monthly average of daily minimum and maximum temperatures (T_{minmax}) [68,69] and the monthly average of daily minimum temperatures (T_{min}) [70] for each billing period of natural gas. Figure 54 presents the distribution of these two temperature indices for the years from February 2009 to November 2011 with residuals.

On average, the monthly average of daily minimum and maximum temperatures, T_{minmax}, was about 10.9 F higher than the monthly average of daily minimum temperatures, T_{min}. The residuals (i.e., $T_{minmax} - T_{min}$) varied between 8.1 F and 13.5 F. No obvious pattern was observed in residuals. The high residuals occurred in the situation when the temperature differences between night and day were relatively large, while the residuals lower than average occurred in the reverse situation.

[66] Before February 2009, the case-study building was part of overall natural gas transportation invoice, which covered about 60 buildings.
[67] There is a statistical procedure proposed by Reddy et al. (1997), although not considered in this study, to minimize the limitations associated with mismatches between consumption and temperature data when the actual billing dates are not available.
[68] T_{minmax} is the average monthly value calculated using the daily minimum and maximum outdoor dry-bulb temperatures measured by the National Oceanic and Atmospheric Administration (NOAA) National Weather Service (NWS) using the Automated Surface Observation Station (ASOS) at the College Station Easterwood Airport. These data were obtained through the NOAA National Climatic Data Center (NCDC) weather database (NCDC 2012).
[69] Since it was found that monthly average of daily minimum and maximum temperatures (T_{minmax}) and monthly average of hourly temperatures (T_{hourly}) had almost identical distributions (Figure 43), T_{minmax} was selected as a representative to calculate natural gas IMT models.
[70] T_{min} is the average monthly value calculated using the daily minimum outdoor dry- bulb temperatures measured by the NOAA NWS using the ASOS at the College Station Easterwood Airport. These data were also obtained through the NOAA NCDC weather database (NCDC 2012).

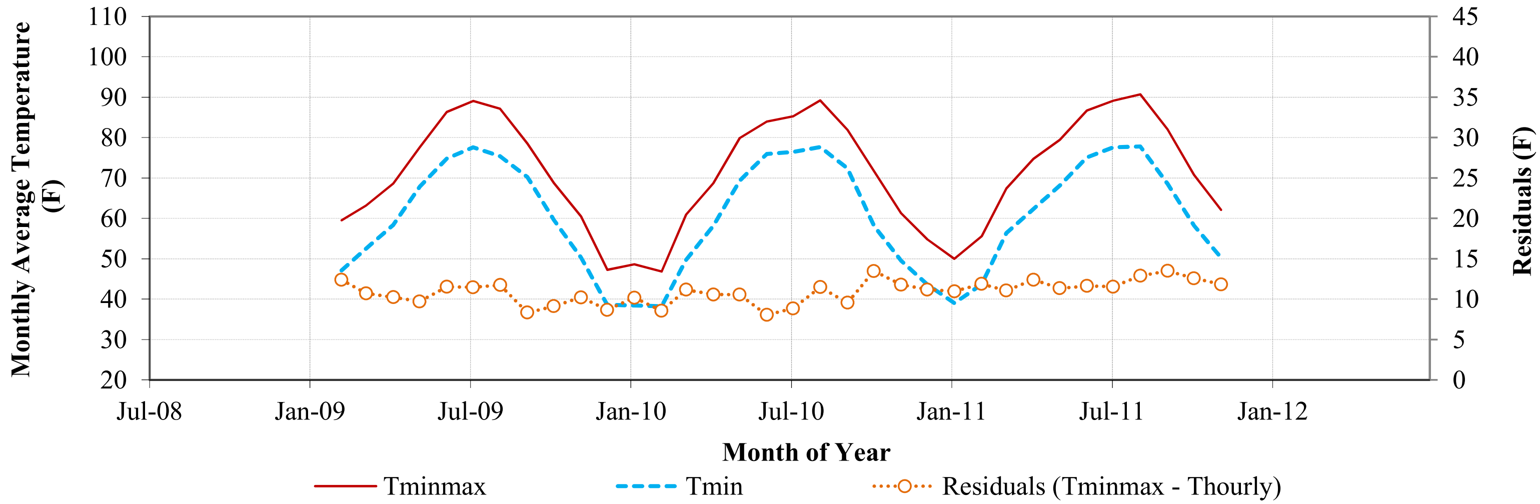


Figure 54: Distribution of Monthly Average of Daily Minimum and Maximum Temperatures (T_{minmax}) and Monthly Average of Daily Minimum Temperatures (T_{min}) (Left Axis) with Residuals (Right Axis) for the Years from 2009 to 2011

- Natural gas use inverse model

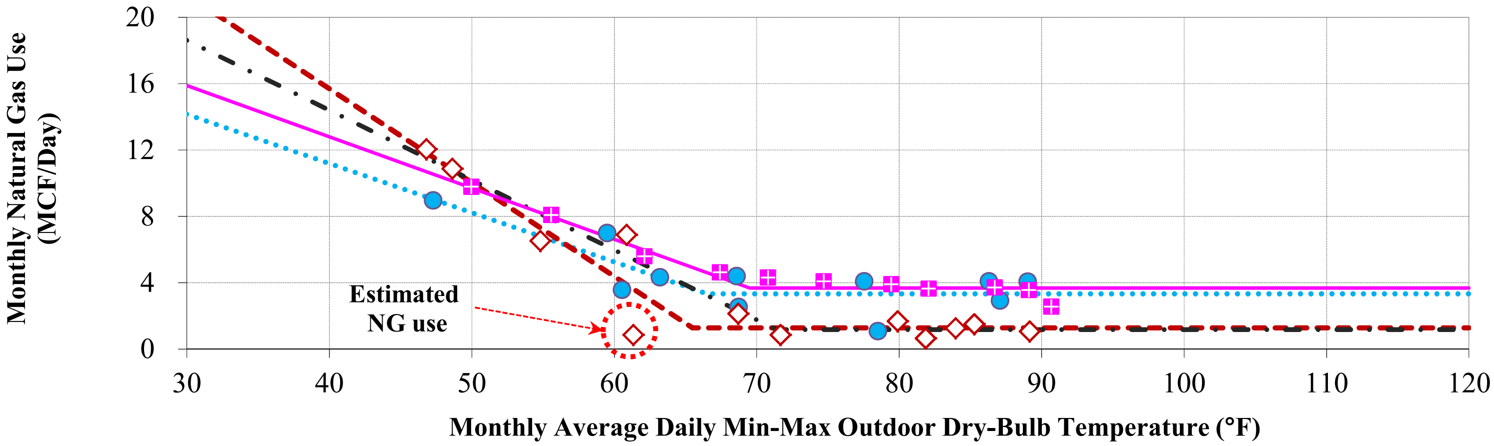
Figure 55 shows monthly natural gas use normalized on a daily average basis against the two different monthly outdoor temperature indices for a natural gas billing period (i.e., T_{minmax} and T_{min}) modeled with the 3-P heating change-point models. To eliminate net bias error due to billing period variation, each of the eleven or twelve data points was weighted by the number of days in the corresponding billing period, which is one of the compliance requirements of the ASHRAE Guideline 14-2002[71]. The model coefficients and statistical indicators of the four models are listed in Table 14.

For 2010, two models were calculated: a model with all twelve data points including an estimated data point (i.e., outlier) in November 2010; and another model with eleven data points excluding an estimated data point. It was suspected that the billed natural gas use data of 0.0 MCF/day for November 2010 was estimated rather than actually measured. Thus, in this analysis, the billed data for November 2010 was adjusted to match the consumption of the previous month, which is 0.9 MCF/day for October 2010. The data for December 2010 was also adjusted by subtracting 0.9 MCF/day from the initially billed data of 6.5 MCF/day.

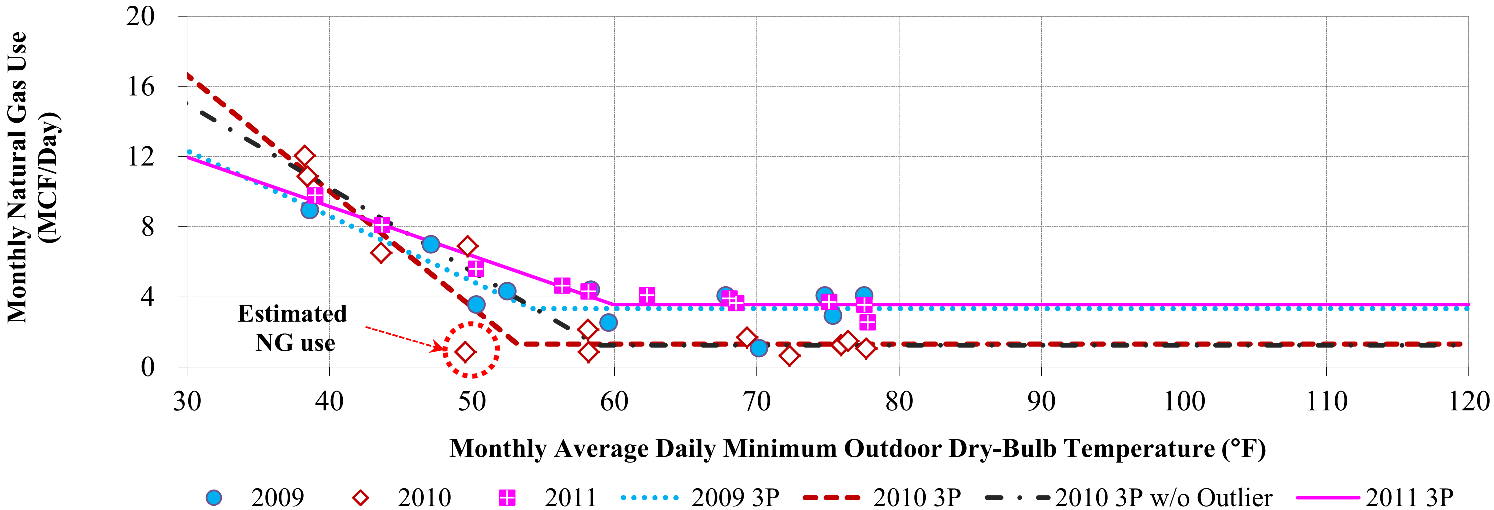
The models had R^2 between 0.70 and 0.96 and CV-RMSE between 8.9% and 36.7%, as shown in Table 14. Not surprisingly, the models without an outlier were better determined with higher R^2 of 0.97 (T_{minmax} model) and 0.95 (T_{min} model) as well as lower CV-RMSE of 17.6% (T_{minmax} model) and 21.3% (T_{min} model)[72]. The use of different outdoor temperatures (i.e., T_{minmax} and T_{min}) did not have much of an effect on the model's goodness-of-fit statistics except the year 2009. In 2009, the T_{min} model had a slightly better fit with a higher R^2 and a lower CV-RMSE (i.e., 0.75 R^2 and 23.5% CV-RMSE) than the T_{minmax} model (i.e., 0.70 R^2 and 25.7% CV-RMSE).

The weather-independent, base-load natural gas use (Ycp) varied between 1.2 and 3.6 MCF/day per year, with the highest consumption in 2011 and the lowest consumption in 2010. The temperature-dependent heating energy consumption (i.e., heating slope, HS (MCF/day/F)) varied between −0.28 and −0.66 MCF/day/F for the different year, and the change-point temperature (i.e., the temperature below which heating begins, Tcp) was calculated to be between 65.5 and 72.0 F (T_{minmax} model) and between 53.2 and 59.9 F (T_{min} model)

[71] Section 6.1.3.3 of the ASHRAE Guideline 14-2002 says "By using the average daily consumption (monthly consumption divided by reading period days), the regression procedure must use a weighted regression technique."
[72] The models including an estimated data point had a R^2 of 0.87 and 0.89 and a CV-RMSE of 33.6% (T_{minmax} model) and 36.7% (T_{min} model).



(a) Monthly Average of Daily Minimum and Maximum Outdoor Temperatures (T_{minmax}) for the Billing Period



(b) Monthly Average of Daily Minimum Outdoor Temperatures (T_{min}) for the Billing Period

Figure 55: Monthly Natural Gas Use versus Monthly Outdoor Temperatures, Including 3-P Heating Change-Point Models for the Years from 2009 to 2011

Table 14: Model Coefficients and Statistical Indicators for Monthly Natural Gas Use Models: (a) with Outliers; (b) without Outliers

(a) Monthly Average of Daily Minimum and Maximum Outdoor Temperatures (T_{minmax}) for the Billing Period

Coefficient	Description	2009	2010		2011
		(N=11)[1]	(a) (N=12)	(b) (N=11)	(N=11)[2]
Ycp	Base load (MCF/day)	3.33	1.28	1.18	3.68
HS	Heating slope (MCF/day/ΔF)	-0.30	-0.57	-0.42	-0.31
Tcp	Change point temperature (F)	66.5	65.5	71.4	69.5
R^2	Squared correlation coefficients	0.70	0.89	0.97	0.95
CV-RMSE	Coefficient of variation of the root mean square error (%)	25.7%	33.6%	17.6%	8.9%

(b) Monthly Average of Daily Minimum Outdoor Temperatures (T_{min}) for the Billing Period

Coefficient	Description	2009	2010		2011
		(N=11)[1]	(a) (N=12)	(b) (N=11)	(N=11)[2]
Ycp	Base load (MCF/day)	3.33	1.30	1.25	3.56
HS	Heating slope (MCF/day/ΔF)	-0.37	-0.66	-0.48	-0.28
Tcp	Change point temperature (F)	54.2	53.2	58.8	59.9
R^2	Squared correlation coefficients	0.75	0.87	0.95	0.96
CV-RMSE	Coefficient of variation of the root mean square error (%)	23.5%	36.7%	21.3%	8.9%

NOTES:

1)January NG data is not available.

2) December data was eliminated due to a change of occupancy in a case-study building in December 2011.

- Calculation of performance changes in natural gas use

To track the changes in natural gas energy performance of the building over several years, the savings[73] were calculated for 2010 to 2011 against the baseline year 2009 by subtracting the billed, actual consumption from the predicted consumption using the 2009 IMT 3-P heating model, as shown in Figure 56 and Table 15. The uncertainties associated with the calculated savings were also determined at the two levels of confidence: 68% and 90% and are listed in the table.[74]. The calculated uncertainties at the 68% level of confidence were higher than the maximum level of uncertainty required in the ASHRAE Guideline 14-2002 (ASHRAE 2002) (i.e., 50% of annual reported savings at 68% confidence) except for the savings computed for 2010 with T_{min} model[75]. The uncertainties for 2010 with T_{min} model marginally met the requirements with 47% of the reported savings. The net determination biases of the baseline models were also higher than the acceptable level required in the ASHRAE Guideline 14-2002 (i.e., 0.005%): −0.020% for the T_{minmax} model and 0.007% for the T_{min} model. The high uncertainties in the natural gas savings as well as net determination biases are mainly due to poor model fits with high CV-RMSE.

In spite of the issue with high net determination biases of the baseline models, the savings were calculated[76]. Overall, the savings calculated from the two different models were found to be similar within the range of uncertainties[77]. Compared to 2009, the building's natural gas energy use decreased in 2010, although a large savings was calculated for November 2010 of which natural gas use was estimated[78]: 19.9% ± 11.1% with a savings of 349 ± 196 MCF/yr at the 68% level of confidence and 19.9% ± 20.4% with a savings of 349 ± 358 MCF/yr at the 90% level of confidence with the T_{minmax} model; and 21.6% ± 10.2% with a savings of 389 ± 183 MCF/yr at the 68% level of confidence and 21.6% ± 18.6% with a savings of 389 ± 335 MCF/yr

[73] In this dissertation, the word "savings" is used to denote the changes in energy or water use performance against the baseline year. Negative savings means increased energy or water use against the baseline year.
[74] The uncertainties in savings were calculated based on the revised ASHRAE Guideline 14-2012 working draft, Measurement of Energy and Demand Savings (ASHRAE 2012).
[75] The computed uncertainties were 56% of the reported savings for 2010 and 69% of the reported savings for 2011 with the T_{minmax} model; and 47% of the reported savings for 2010 and 82% of the reported savings for 2011 with the T_{min} model.
[76] The compliance with the ASHRAE Guideline 14-2002 is not required in the current version of the ASHRAE PMP.
[77] The savings calculated with the T_{min} model was slightly higher than the savings with the T_{minmax} model by 40 to 47 MCF/yr per year, but the difference was with the range of uncertainties.
[78] A large savings of 125 MCF/mo (i.e., about 36% of total annual savings in 2010) with the T_{minmax} model and of 131 MCF/mo (i.e., about 33% of total annual savings in 2010) with the T_{min} model was predicted for November 2010 of which natural gas use was estimated.

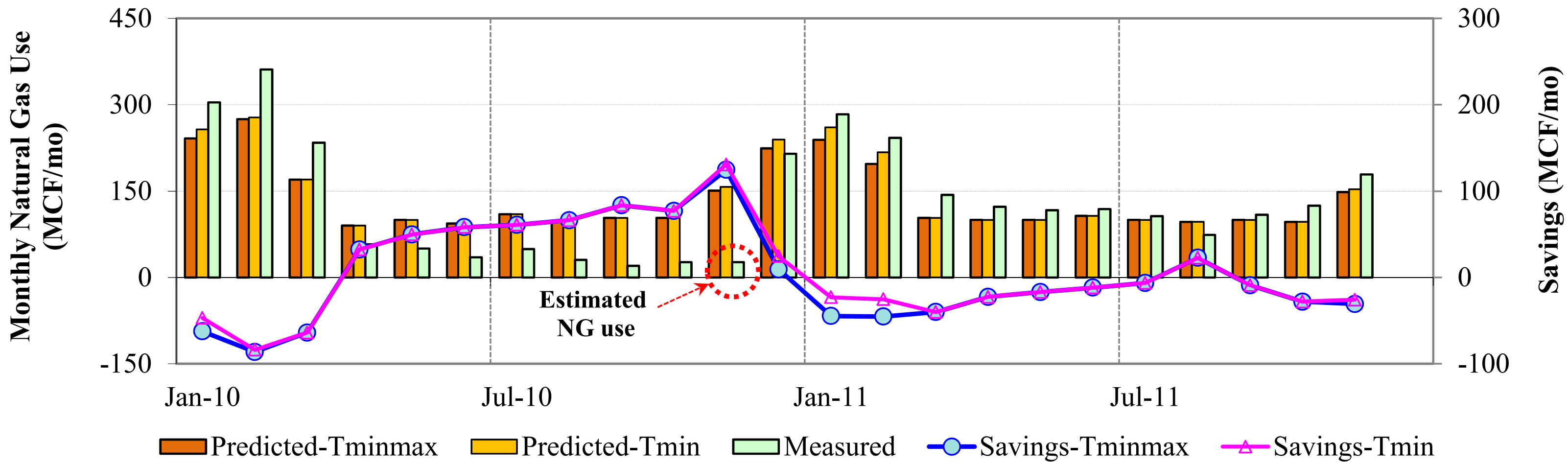


Figure 56: Natural Gas Savings Against the Baseline Year 2009 Using the Monthly 3-P Model for the Years of 2010 and 2011

Table 15: Annual Summary of Natural Gas Savings Against the Baseline Year 2009 Using the Monthly 3-P Model

	Total Billed (MCF/period)	(a) Tminmax Model					(b) Tmin Model				
		Total Predicted (MCF/period)	Savings with 68% Confidence		Savings with 90% Confidence		Total Predicted (MCF/period)	Savings with 68% Confidence		Savings with 90% Confidence	
			(MCF/period)	(%)	(MCF/period)	(%)		(MCF/period)	(%)	(MCF/period)	(%)
2010 (Jan. to Dec.)	1,410	1,759	349 ± 196	19.9±11.1%	349 ± 358	19.9±20.4%	1,798	389 ± 183	21.6±10.2%	389 ± 335	21.6±18.6%
2011 (Jan. to Nov.)	1,620	1,388	-233 ± 161	-16.8±11.6%	-233 ± 295	-16.8±21.3%	1,434	-186 ± 152	-13.0±10.6%	-186 ± 279	-13.0±19.5%

at the 90% level of confidence with the T_{min} model. In 2011, the natural gas consumption of the building increased by: 16.8% ± 11.6% with a negative savings of −233 ± 161 MCF/yr at the 68% level of confidence and 16.8% ± 21.3% with a negative savings of −233 ± 295 MCF/yr at the 90% level of confidence; and 13.0% ± 10.6% with a negative savings of −186 ± 152 MCF/yr at the 68% level of confidence and 13.0% ± 19.5% with a negative savings of −186 ± 279 MCF/yr at the 90% level of confidence. Thus, at the 90% confidence level, it would be difficult to justify a decrease or an increase of natural gas use in 2010 and 2011 except for the savings computed for 2010 with T_{min} model. At the 90% confidence level, a small improvement in natural gas use performance was observed in 2010 with the T_{min} model, which was mainly attributed to a decrease in base-load natural gas use in summer.

5.1.2.3. *Observations*

Observations from the field test of the ASHRAE PMP Intermediate Level energy protocol are as follows[79]:

- The ASHRAE PMP Intermediate Level energy protocol requires calculating the inverse energy use models that relate energy use to the appropriate independent variables (i.e., outdoor temperature) for a self-reference comparison. However, the current version of the ASHRAE PMP Intermediate Level energy protocol does not provide any advice about how to ensure a fair level of confidence in the calculated model as well as performance changes (i.e., savings). In this study, the Whole-Building Performance Path of the ASHRAE Guideline 14-2002 (ASHRAE 2002) was referenced in the entire calculation procedure, although the compliance with the ASHRAE Guideline 14-2002 is not required in the current version of the ASHRAE PMP.
- The ASHRAE PMP does not provide any advice about how to calculate a suitable outdoor temperature index for different types of energy use (i.e., whole-building electricity, peak demand, and whole-building natural gas use). In this study, two different monthly average temperature indices (i.e., monthly average of daily minimum and maximum temperatures, T_{minmax}; and monthly average of hourly temperatures, T_{hourly}) were calculated for each billing period, and their impacts on calculated WBE inverse models as well as the savings were compared. For cooling demand models, three maximum temperature indices were compared: maximum daily min-max average outdoor temperature (T_{max_minmax}); maximum daily 24-hour

[79] A shorter observation listed in this section is repeated as an issue in Section 5.1.4.

average outdoor temperature (T_{max_24hour}); and monthly maximum outdoor temperature ($T_{max\_monthly}$) in a billing period. For natural gas use models, two temperature indices were compared: monthly average of daily minimum and maximum temperatures, T_{minmax}; and monthly average of daily minimum temperatures, T_{min} in a natural gas billing period.
As a result, almost identical findings were obtained for the WBE models from the use of either T_{minmax} or T_{hourly}[80]. However, for cooling demand models, slightly different results were obtained by using $T_{max\_monthly}$ compared to the other two indices (i.e., T_{max_minmax} or T_{max_24hour}), although the differences in the computed savings were within the range of uncertainties[81]. For natural gas models, the savings calculated with the T_{min} model were slightly higher than the savings with the T_{minmax} model by 40 to 47 MCF/yr per year. However, the difference was within the range of uncertainties.

- Consistently lower (or negative) savings were observed in February of each year. This may indicate an under-prediction of the base-load consumption using the base year 2007 model due to holidays in December and January. When the building has a different operating mode for holidays, the monthly IMT 3-P cooling model is likely to under-predict the base-load consumption due to holiday periods in December and January when energy use was less. At the annual-level calculation, a lower savings in February may be offset by an over-predicted savings in December and January. However, the accuracy of such a model is limited. Not surprisingly, the computed net determination biases of the baseline models were higher than the acceptable level required in the ASHRAE Guideline 14-2002, which indicates a high level of uncertainty in the baseline models based on the 3-P cooling change-point models with a single independent variable (i.e., outdoor temperature).
- The ASHRAE PMP does not describe how to deal with outliers for the inverse regression models when they are present in the dataset. In this study, several data points of peak demand were found to be inconsistent with other data, and therefore, the models calculated with these outlying data points did not represent the dataset well (i.e., a low R^2 and a high CV-RMSE[82]).

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[80] However, it should be noted that different climate conditions may yield different results.
[81] About 66 to 150 kW/yr higher savings was estimated using $T_{max\_monthly}$ due to a larger temperature deviation between $T_{max\_monthly}$ and the other two indices from 2008 to 2011 compared to 2007. On average, $T_{max\_monthly}$ was 9.0 and 10.3 F higher than T_{max_minmax} and T_{max_24hour}, respectively in 2007. Since 2008, an average deviation increased: 10.1 to 10.9 F between $T_{max\_monthly}$ and T_{max_minmax} and 11.6 to 12.9 F between $T_{max\_monthly}$ and T_{max_24hour}.
[82] The models with outliers had a R^2 between 0.11 and 0.81 as well as CV-RMSE between 5.2% and 16.0%.

However, the models without outliers were significantly improved with a higher R^2 between 0.61 and 0.91 as well as a lower CV-RMSE between 1.9% and 6.5%.

To identify potential outliers, this study compared two different methods[83]. The first method used a quartile analysis. In this analysis, the data points beyond the 25th and 75th quartiles by one and a half times the interquartile range (IQR = 75th quartile – 25th quartile) were considered potential outliers, which is commonly used in statistics (Emerson and Strenio 1983). The second method used the IMT 3-P cooling models that were initially calculated with all data points. The data points beyond ±1.5 CV-RMSE of the calculated IMT 3-P cooling models were considered suspected outliers. As a result, the quartile method was found to be effective at detecting extreme outliers, but failed to account for a seasonal variation in peak demand[84]. Therefore, in this study, the outliers were identified using the second method, and were excluded in the final IMT models.

It was also found that the monthly outliers can provide useful information that may be helpful to detect some operational problems in the building. In this study, when examining the outliers all together, two distinct distributions were observed: outliers between 557 and 598 kW range; and outliers between 696 and 715 kW range, which might indicate two different types of events causing outliers. The four outliers between 557 and 598 kW may occur during sudden startup of certain equipment (i.e., chiller) after an equipment shutdown. The other two outliers in the 696 and 715 kW range are suspected to occur due to simultaneous operation of two chillers erroneously. The end-use analysis which included chiller sub-hourly data at the Advanced Level could begin to diagnose the events causing the outliers and are presented in Section 5.1.3 Level III: Advanced Level.

- One of the energy performance metrics required at the Intermediate Level is the measurement of major end-use energy use, which requires that a high level of effort go towards data collection, data management and analysis. However, the ASHRAE PMP does not provide any advice about end-use benchmarks or how to benchmark the calculated energy use indices from the end-use data. In this study, sub-hourly end-use data were available that allowed for the annual electricity use intensities to be calculated for the following major end-uses: office building electricity use (OBE, including fans, lighting and equipment), chiller, motor control

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[83] The potential outliers were examined more closely to see if they could be reasonably determined to belong to different statistical population groups.

[84] Winter peak demands that were higher than expected could not be detected since they were at similar levels to summer peak demands.

center (MCC), and other electricity use. However, the ASHRAE PMP does not provide a reliable, external reference for benchmarking the calculated energy use indices from an end-use assessment.

5.1.3. *Level III: Advanced Level*

5.1.3.1. *Performance Metrics*

The energy performance metrics required at the ASHRAE PMP Advanced Level are daily or hourly energy use measurements for the whole-building and major end-uses.

a) Daily Electricity Use

Figure 57 shows the daily electricity use of the case-study building for the whole-building and the following end-uses: office building electricity use (OBE including fans, lighting and equipment), chiller, and motor control center electricity use (MCC including chilled water pumps, condenser water pumps, hot water pumps, cooling tower fans, and boiler auxiliaries), and other electricity use[85]. To accomplish this, the 15 minute sub-hourly data collected from May 2008 to November 2011were converted to daily usage.

The daily whole-building electricity (WBE) usage follows the expected seasonal trends (i.e., lowest consumption in winter, increasing consumption in spring, highest consumption in summer, and decreasing consumption in fall) and weekly trends (i.e., weekdays, weekends and holidays) except one outlier of 10,500 kWh/day in the summer of 2009. This abnormally high peak resulted from the extended use of both chillers. This can be determined from an inspection of the chiller electricity use as well as from an inspection of chiller operation data (i.e., supply and return temperature and water flow), which revealed both chillers in operation for one hour after a short-term shutdown[86]. After excluding this high peak, the daily electricity use was in the range of 4,134 to 9,399 kWh/day.

Not surprisingly, a consistently lower energy consumption pattern was observed for weekdays and weekends. In addition, very low electricity use was observed during the holidays in November and December. This very low level of whole-building electricity consumption

[85] Other electricity consumption was determined by subtracting the sum of all end-uses from whole-building electricity (WBE) consumption.

[86] The cooling loads of the case-study building are normally met by running one chiller. Normally, the chillers are sequenced to run equal amounts of time each year. This high peak occurred near 9:00 a.m. on June 17th 2009 after a complete shutdown of chiller No. 1 around 8:30 a.m. and startups of both chiller No. 1 and chiller No. 2 around 8:45 a.m. Although, from the 15 minute data, it was determined that both chillers operated less than one hour, it contributed an increase in the WBE peak demand over 30% when compared to the 2009 August peak demand (538 kW).

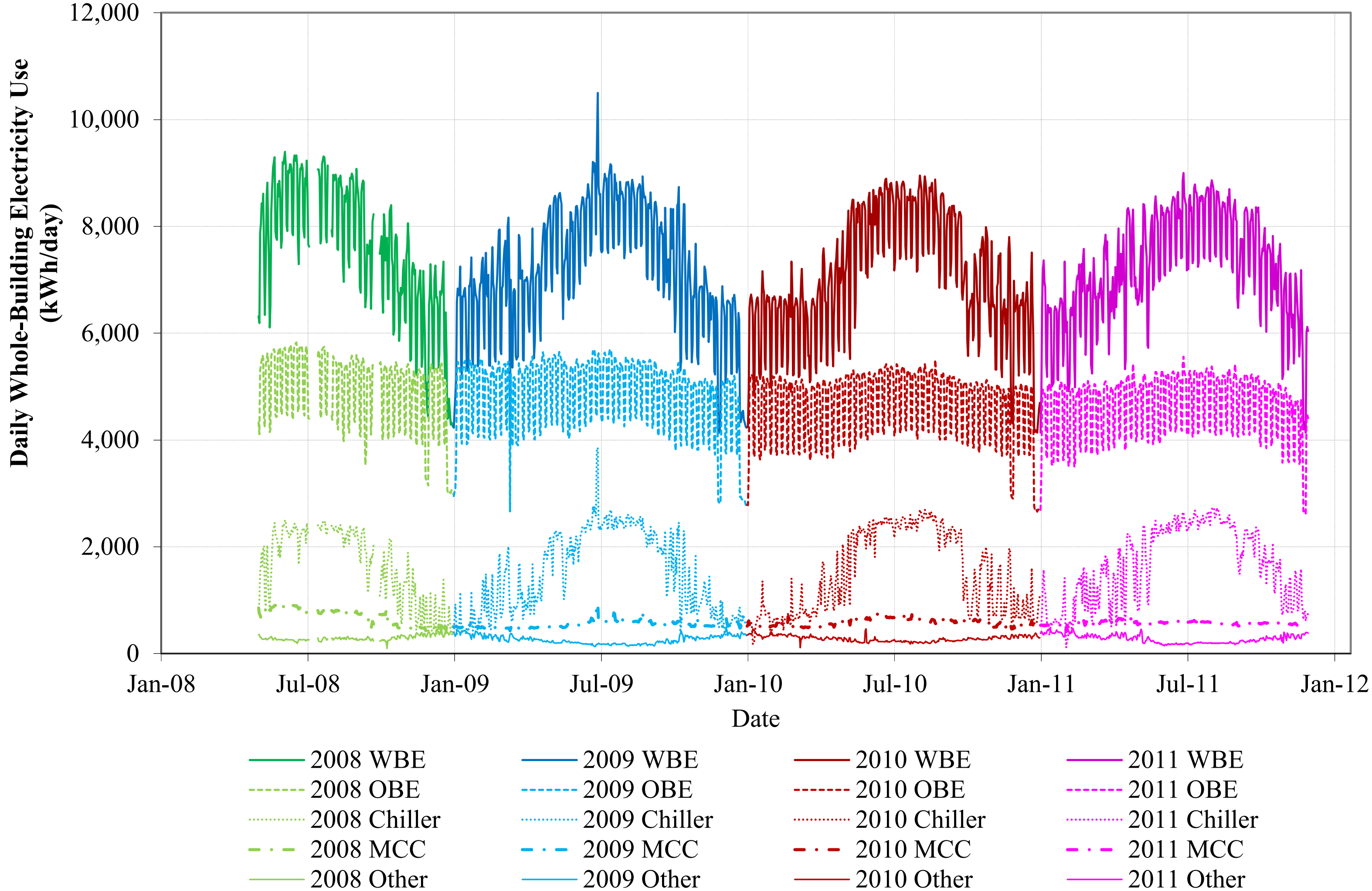


Figure 57: Daily Electricity Use of the Case-Study Building for the Whole-Building and Major End-Uses: May 2008 to November 2011

during the holidays resulted primarily from a decrease in office building electricity use that includes fans, lighting and equipment. This may show that, during the holidays, the building had significantly reduced electricity use for fans and lighting, which may be indicating that the occupants were more likely to completely shut-down their computers and other equipment during a longer holiday[87].

In general, the office building electricity use that includes fans, lighting and equipment varied between 2,610 to 5,828 kWh/day. The low end of the range occurred during the holidays while the high end took place during weekdays in summer. The usage follows the expected seasonal trends (i.e., smaller amplitude of seasonal variation) and weekly trends (i.e., weekdays, weekends, and holidays). A small seasonal variation is expected due to a large portion of internal loads (i.e., lighting and equipment) as well as the power consumption of 230 series fan powered terminal boxes that have fairly constant electricity consumption of about 42.3 kW throughout the year.

The chiller electricity use[88] varied between 112 and 2,760 kWh/day except the high peaks, which occurred in the summer of 2009 due to an error in the chiller operation. The chiller electricity usage also follows the expected seasonal trend which is similar to the whole-building electricity usage seasonal trend. However, no distinct difference was observed between

[87] From the hourly WBE and OBE usage profiles in Figures 58 and 59, it was confirmed that in some portion of the office building, the fans were shut down for the Thanksgiving and Christmas holidays. Additional discussions on how to interpret hourly profiles can be found at the end of this section.

[88] The electricity use of the chiller No.2 was synthesized by adding the residuals that were calculated by subtracting the modeled Other electricity use from the measured Other electricity use, to the measured chiller electricity use when the chiller NO.2 was run. The modeled Other electricity use was calculated using the temperature dependent regression models of hourly Other electricity use when the chiller No.1 was run. This data synthesis was made on the basis of the following observations. It was found that hourly Other electricity consumption, which was determined by subtracting the sum of all end-uses from WBE consumption, consistently increased whenever the chiller No.2 was operated. Meanwhile, the electricity use of the chiller No.2 was consistently lower than the chiller No.1 at the same weather or chiller operating conditions, and the magnitude of the difference in the measured electricity use between two chillers was similar to the increase in Other electricity use whenever the chiller No.2 was run. Other electricity use is the calculated residuals that mainly consist of the exterior lighting electricity use for parking lots. The hourly profiles of Other electricity use that were calculated using the ASHRAE RP-1093 Diversity Factor Toolkit (Abushakra et al. 2001) showed that the profile followed the expected trend (i.e., constant electricity consumption in nighttime and lower consumption in daytime) when the chiller No.1 was run. On the other hand, when the chiller No.2 was run, the profile does not yield a regular repeating pattern by the hour of day. Thus, this study calculated temperature dependent regression models of hourly Other electricity use when the chiller No.1 was run for nighttime and daytime, separately. Using the calculated models, the hourly Other electricity use when the chiller NO.2 was run was predicted and subtracted from the measured hourly Other electricity use when the chiller No.2 was run. These residuals were then added to the measured hourly chiller electricity use when the chiller No.2 was operated. Details are presented in Appendix D.

weekdays and weekends. Quite surprisingly, it was also found that the building required cooling even during the winter over a short period of time.

The MCC and Other electricity consumption occupied a small but significant percentage of the total consumption,[89] which varied between 412 and 936 kWh/day, and between 97 and 497 kWh/day, respectively. The MCC electricity use increased slightly in the summer. However, no obvious weekly pattern was observed. Some fluctuations were observed in the Other electricity consumption, and slightly higher consumption was observed in winter compared to the summer.

b) Hourly Electricity Use

Figures 58 to 62 display the hourly electricity usage profiles for the whole-building electricity use and the other major electricity end-uses for each year as three dimensional surface plots, which is the graphical approach taken by Haberl et al. (1988a). To accomplish this, the 15 minute sub-hourly data collected from May 2008 to November 2011were converted to hourly usage.

First, in Figure 58, it was observed that the building's electricity loads were controlled in a reasonably consistent fashion. In general, the building's mechanical systems, including chillers, fans for the AHUs and terminal boxes, start running at 6:00 a.m. during the weekdays, which is about two hours before the building is occupied. The systems turn-off around 6:30 p.m., which is controlled by a setback/setup schedule in the EMCS. When one compares the profiles of the weekdays versus the weekends, it can be observed that the systems had the same operating schedule for both weekdays and weekends, although the building was not occupied on weekends. The Thanksgiving and Christmas holidays were the only period that the fans were shut down in 2008 to 2011.

The lighting and equipment load shapes that can be approximated from the OBE usage profiles (Figure 59) were found to be similar to the typical profiles for large office buildings developed under ASHRAE Research Project RP-1093 (Claridge et al. 2004)[90]. In the ASHRAE RP-1093 report, the large office buildings were observed to have relatively high nighttime weather-independent loads (i.e., lighting and equipment loads) compared to the smaller office

[89] On an annual basis from the hourly measurements, 8% and 4% of the whole-building electricity is consumed by the MCC and by the Other electricity consumption, respectively.

[90] In Section 5.1.3.2, the weekday and weekend hourly profiles were calculated using the ASHRAE RP-1093 Diversity Factor Toolkit (Abushakra et al. 2001), as part of demand analysis. Figure 68 displays the calculated diversity factor for July and December 2009, including 10^{th}, 25^{th}, 50^{th}, 75^{th}, and 90^{th} percentiles as well as minimum, mean, and maximum values.

buildings. In the case-study building, an inspection of the OBE usage profiles showed that the loads start increasing one or two hour before the building is fully occupied and start decreasing to a constant nighttime level after 5:00 pm. It was also observed that the fans remained on all night for few days, which might indicate that someone manually activated the fan override switch.

The chiller hourly electricity usage profiles in Figure 60 confirmed that several of high peak outliers for the WBE use were caused by improper chiller operation. These outliers were previously identified from the monthly and daily level analysis. First, after inspecting the chiller operation data, it was confirmed that both chillers were running simultaneously two times in 2009: one hour on June 17th (Wednesday); and from June 27th (Saturday) to 29th (Monday). Since both occasions happened when the building's cooling demands were not high[91], it can be concluded that there were operational issues that required both chillers to operate. Both occasions caused high peak demands of June (715 kW) and July (590 kW) 2009, respectively,[92] with an increase in the corresponding demand charges of about 10 to 30%[93].

Four other peaks were observed in October 2009, June 2010, April 2011 and July 2011, and confirmed to occur during periods when there was a re-startup of a chiller after a short-term shutdown. In several cases, the lag chiller turned-on until the lead chiller restarted. These short-term stoppages happened only when the chiller No.1 was the lead chiller. Finally, the peak in August 2011 occurred during the sequencing of the two chillers. The lag chiller started running around 7:30 a.m. after a two-hour lag time, which increased the chiller peak for the following two to three hours.

The MCC hourly electricity usage profiles in Figure 61 revealed some issues related to the pump operations. In general, the two chillers and the corresponding pumps of the case-study building were operated in a sequence. However, occasionally, both pumps were run together, for example on the weekends in 2009 and 2010, which caused a higher consumption that remained constant for one or two days.

The Other hourly electricity usage profiles in Figure 62 are comprised of the calculated residuals by subtracting the sum of all end-uses from WBE consumption when the chiller No.1

[91] The first event on June 17th occurred at 9:00 a.m. after a complete shutdown of chiller No.1. The second event occurred at 8:00 p.m. on June 27th, Saturday.

[92] The billing period for July 2009 began on June 26th and ended on July 29th.

[93] Against the 2009 August peak demand (538 kW), the calculated increases are expected to be $1,847 and $549, respectively, based on $10.4/kW demand charge.

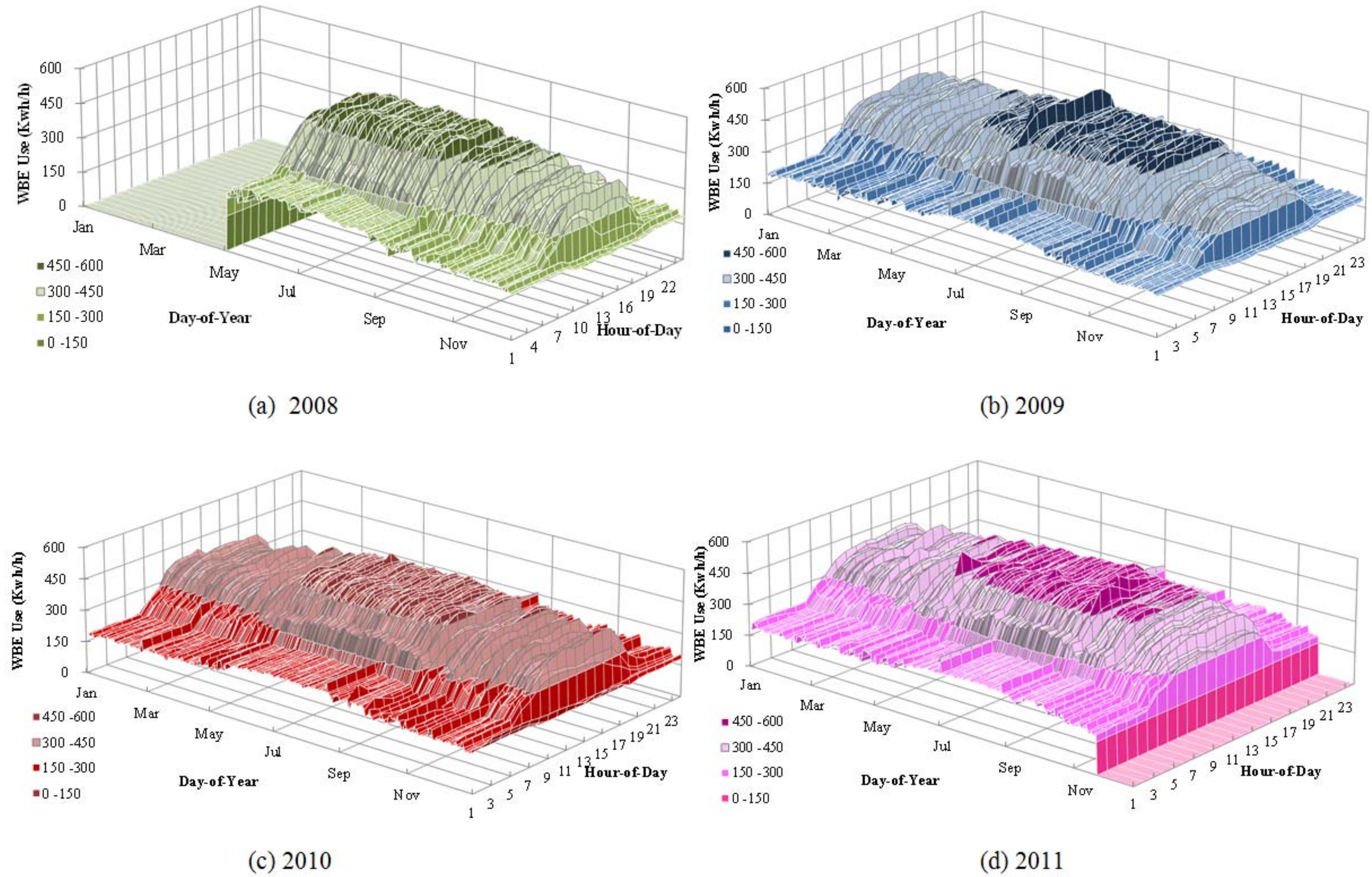
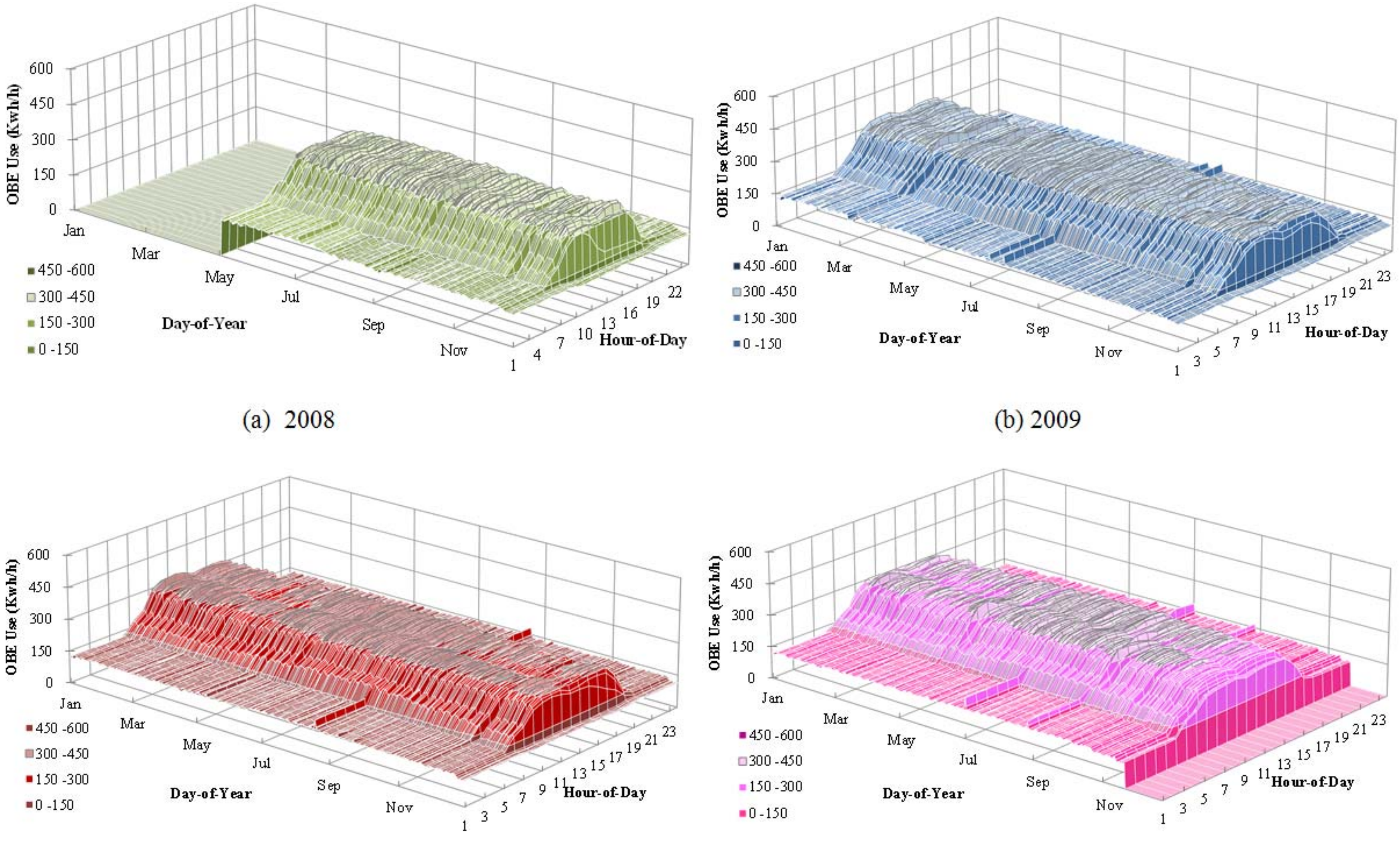


Figure 58: Hourly WBE Usage Profiles of the Case-Study Building: May 2008 to November 2011



(a) 2008

(b) 2009

(c) 2010

(d) 2011

Figure 59: Hourly OBE Usage Profiles of the Case-Study Building: May 2008 to November 2011

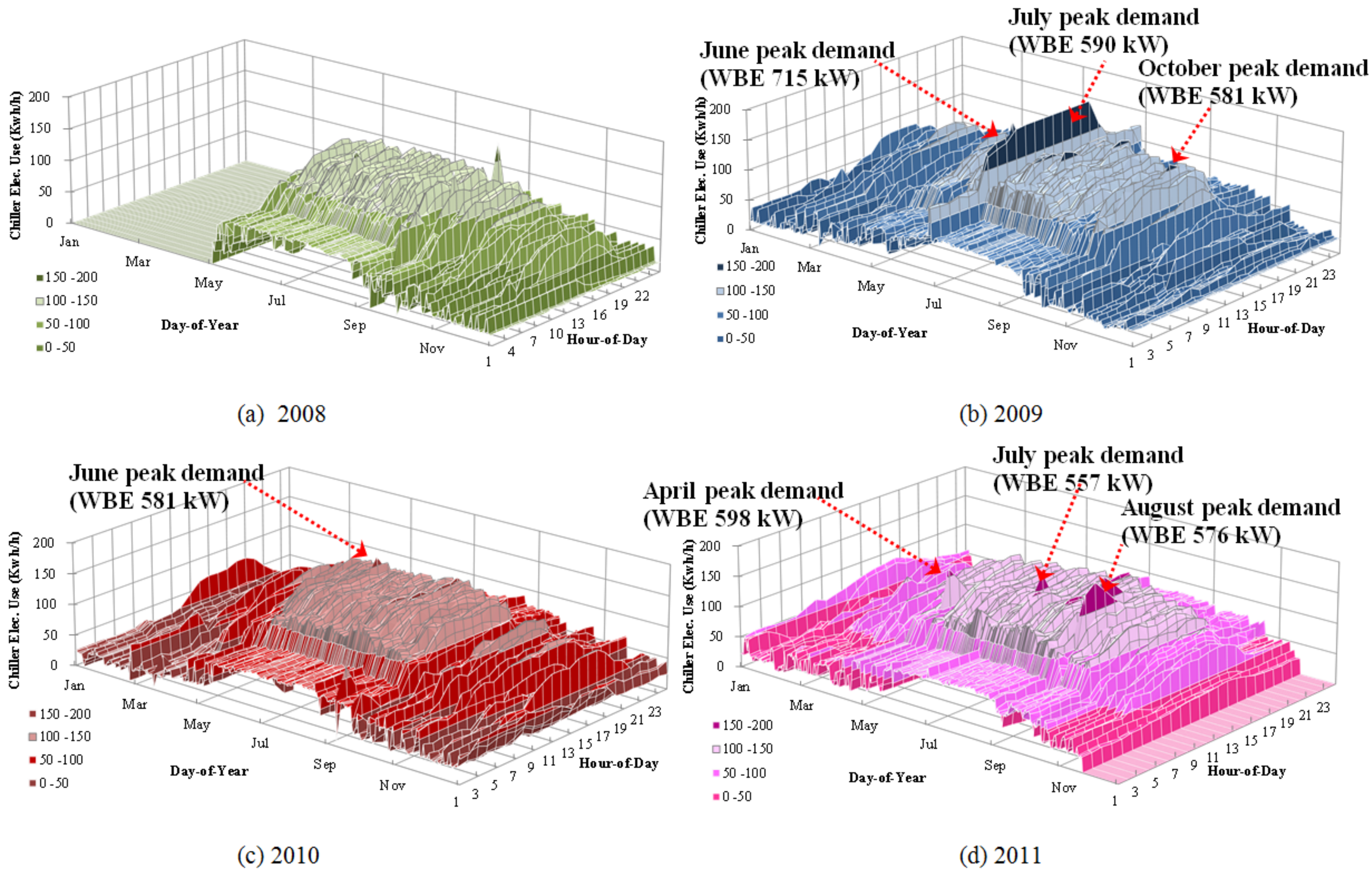


Figure 60: Hourly Chiller Electricity Usage Profiles of the Case-Study Building: May 2008 to November 2011

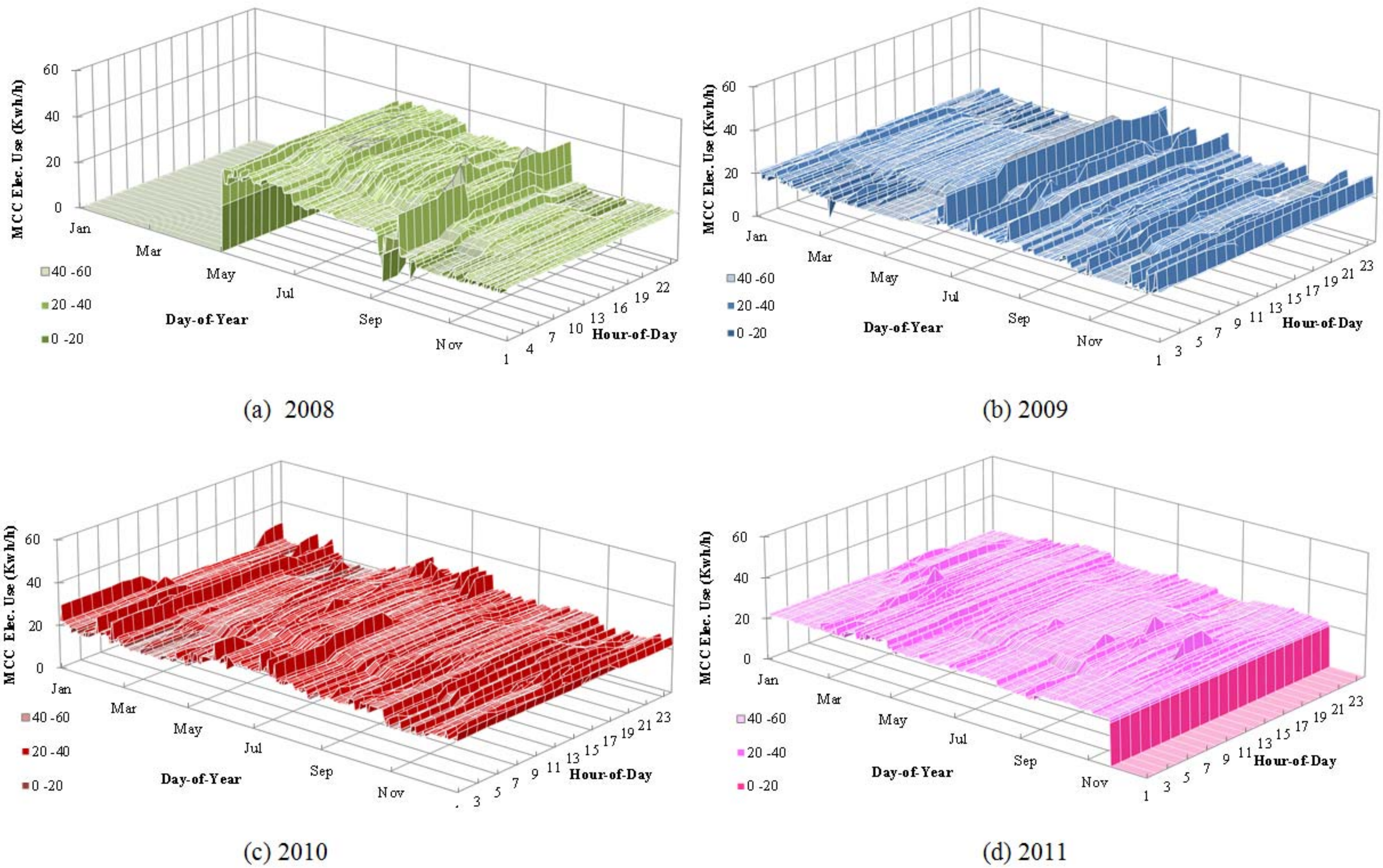


Figure 61: Hourly MCC Electricity Usage Profiles of the Case-Study Building: May 2008 to November 2011

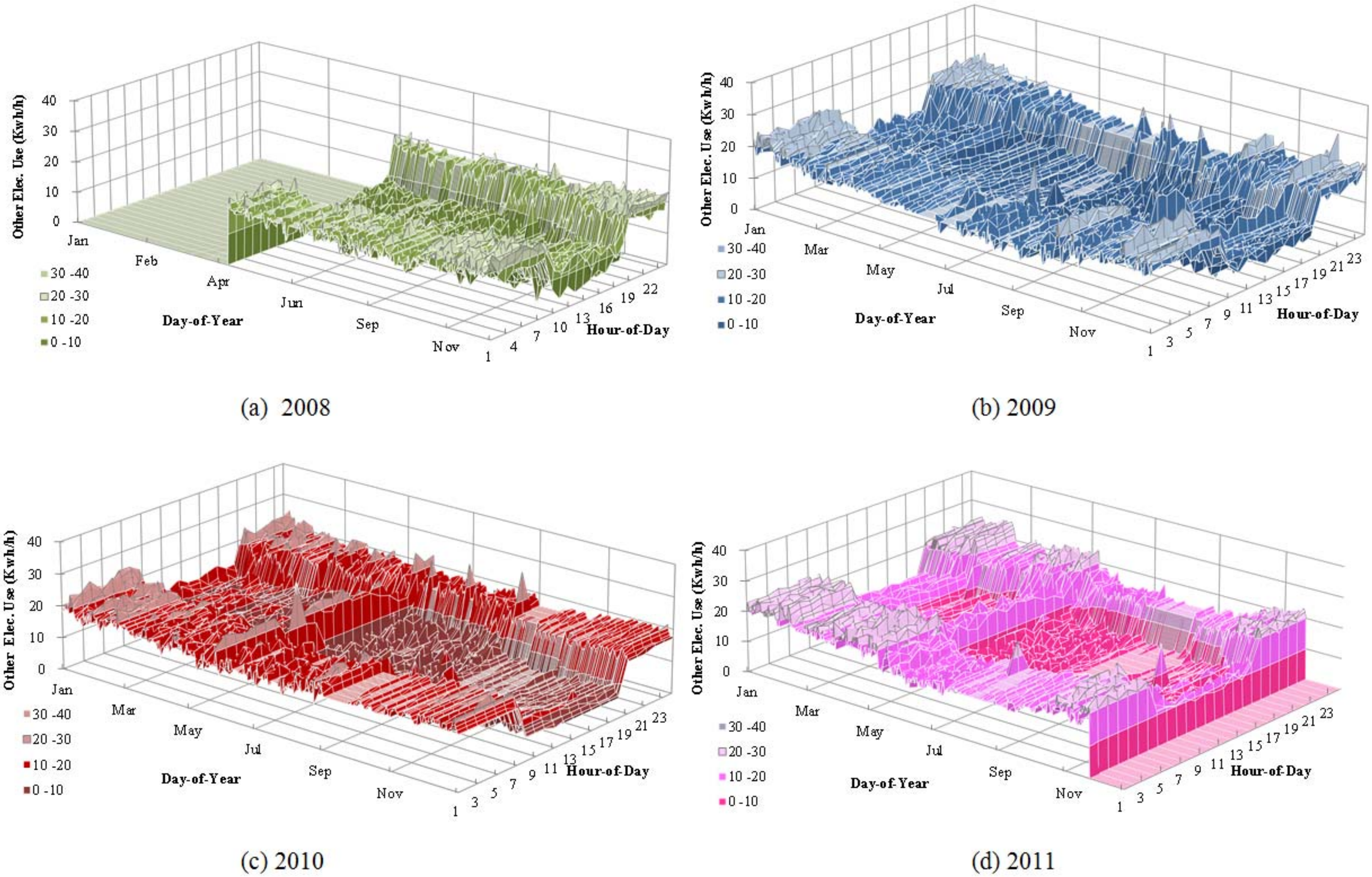


Figure 62: Hourly Other Electricity Usage Profiles of the Case-Study Building: May 2008 to November 2011

was run; and the modeled Other electricity use when the chiller No.2 was run[94]. Other electricity use is the calculated residuals that mainly consist of the exterior lighting electricity use for parking lots and miscellaneous consumed at the thermal plant. From the figure, it was observed that Other electricity loads were controlled in a consistent fashion, which followed the expected trend (i.e., relatively constant electricity consumption in nighttime and lower consumption in daytime).

5.1.3.2. *Performance Evaluation/Benchmarking*

The evaluation of energy performance at the Advanced Level requires energy use analysis with inverse energy use models calculated using daily electricity use as well as demand analysis with hourly load profiles calculated using hourly or sub-hourly electricity use data.

a) Daily Electricity Use Analysis

Using the ASHRAE Inverse Modeling Toolkit (IMT) (Kissock et al. 2004), the daily electricity models were developed for the whole-building and the major end-uses (i.e., office building, chiller, and MCC) from May 2008 to November 2011. The savings[95] were then calculated against the baseline year 2008. Figure 63 presents daily whole-building electricity use against the daily 24-hour average outdoor air temperatures and includes three-parameter (3-P) cooling change-point models for weekdays, weekends, and holidays. The weekday and weekend models were well determined with high coefficients of determination (R^2) between 0.90 and 0.95 as well as low coefficient of variation of the root mean square error (CV-RMSE) between 2.9% and 4.2%, as shown in Table 16.

The weather-independent, base-load electricity use (Ycp) varied between 6,407 and 6,711 kWh/day for weekdays and between 5,141 and 5,398 kWh/day for weekends for the different years. The temperature-dependent cooling energy consumption (i.e., cooling slope, CS (kWh/day/F)) varied between 67.4 and 88.0 kWh/day/F for weekdays and between 71.1 and 97.8 kWh/day/F for weekends. The change-point temperature (i.e., the temperature above which cooling begins, Tcp) was calculated to be between 57.0 and 61.9 F for weekdays and between 58.2 and 64.1 F for weekends for the different years. The 2011 model has the lowest base load as

[94] As mentioned in Footnote 82, this study calculated temperature dependent regression models of hourly other electricity use when the chiller No.1 was run for nighttime and daytime, separately. Using the calculated models, the hourly Other electricity use when the chiller NO.2 was run was predicted. Details are presented in Appendix D.

[95] In this dissertation, the word “savings” is used to denote the changes in energy or water use performance against the baseline year. Negative savings means increased energy or water use against the baseline year.

well as the lowest cooling slope for both weekdays and weekends, which means an improvement occurred in both weather dependent and independent loads.

Figure 64 presents the daily office building electricity use against the daily 24-hour average outdoor air temperatures and shows the 3-P cooling change-point models for weekdays, weekends, and holidays. The weekday and weekend models were well determined with low CV-RMSE between 2.4% and 3.9%, as shown in Table 17. However, the R^2 of the models were low, between 0.34 and 0.69 since a large portion of the office building electricity use consists of fairly constant loads on a daily basis, including lighting, equipment, and series fan powered terminal boxes.

The weather-independent, base-load electricity use (Ycp) had decreased since 2008 from 5,265 to 4,806 kWh/day for weekdays and from 4,075 to 3,561 kWh/day for weekends. The cooling slope (CS) varied between 12.1 and 18.3 kWh/day/F for weekdays and between 16.2 and 47.3 kWh/day/F for weekends. The change-point temperature was calculated to be between 58.4 and 72.0 F for weekdays and between 53.0 and 78.1 F for weekends by year. The small cooling slopes simply indicate that the office building electricity use is not highly sensitive to the outdoor temperature changes. The exception to this is the 2008 weekend model, which had a high cooling slope of 47.3 kWh/day/F because it had a high change-point temperature of 78.1 F.

Figure 65 presents daily chiller electricity use against the daily 24-hour average outdoor air temperatures and includes the four parameter (4-P) cooling change-point models for weekdays, weekends, and holidays. The weekday and weekend models were well determined with high R^2 between 0.92 and 0.96 and acceptable CV-RMSE between 9.1% and 12.6%, as shown in Table 18. The cooling slopes varied between 5.7 and 18.9 kWh/day/F for temperatures below the change-point temperature; and between 60.7 and 79.0 kWh/day/F for temperatures above the change-point temperature. The change-point temperature (Tcp) was calculated to be between 55.0 and 67.8 F.

Figure 66 presents daily MCC electricity use against the daily 24-hour average outdoor air temperatures with the 3-P cooling change-point models shown for each year. Since no difference was found between weekday and weekend MCC electricity use, a combined model was calculated rather than three separate models for weekdays, weekends, and holidays. The models were well determined with low CV-RMSE between 5.2% and 12.5%, as shown in Table 19. However, the R^2 of the models ranged between 0.28 and 0.72. Except the 2008 model, the MCC models had a relatively low R^2 due to a large, constant year-round base load occupying the

MCC electricity use. The 2011 model had a very low R^2 of 0.28 due to a decrease in the MCC electricity use during the summer, which made the model have a low slope. In 2008, two distinct usage patterns were observed by seasons, which resulted in the highest R^2 of 0.72.

The weather-independent, base-load electricity use (Ycp) varied between 489 and 517 kWh/day during the four year period. The cooling slope (CS) had decreased since 2008 from 14.5 to 1.2 kWh/day/F. The change-point temperature (Tcp) was calculated to be between 25.6 and 74.5 F. Distinctly high summer MCC electricity use in 2008 indicates that there were some changes in MCC operations since fall 2008.

To track changes in energy performance of the building over several years, the differences in consumption were calculated for 2009 to 2011 against the baseline year 2008 by subtracting the measured, actual consumption from the predicted consumption using the 2008 regression models. Figure 67 and Table 20 present the results for the whole-building and major end-uses. Overall, the building's electricity energy performance had continuously improved: 2.9% in 2009; 5.0% in 2010; and 7.2% in 2011, which coincides with the results at the Level II: Intermediate Level (Figure 48 and Table 11) using monthly billed data within 0.6% by year[96]. However, unlike the Intermediate Level analysis as shown in Figure 48, no distinct seasonal trend (i.e., lower or negative savings in February due to under-predicted base-load consumption by the baseline model) was observed. The major improvement occurred in office building electricity use, including fans, lighting, and equipment. A savings in office building electricity use began to appear in the middle of 2009 and continuously increased. The cumulative of savings calculated from individual, end-use models were almost same as or slightly lower than the savings calculated from the WBE use model[97].

[96] The savings against the year 2008 estimated using the 2007 WBE monthly regression model in Section 5.1.2 Level II: Intermediate Level are: 3.5% in 2009; 5.5% to 5.6% in 2010; and 7.0% to 7.6% in 2011.
[97] The small difference between these two savings can be explained by some changes in Other electricity use or the uncertainties in model prediction.

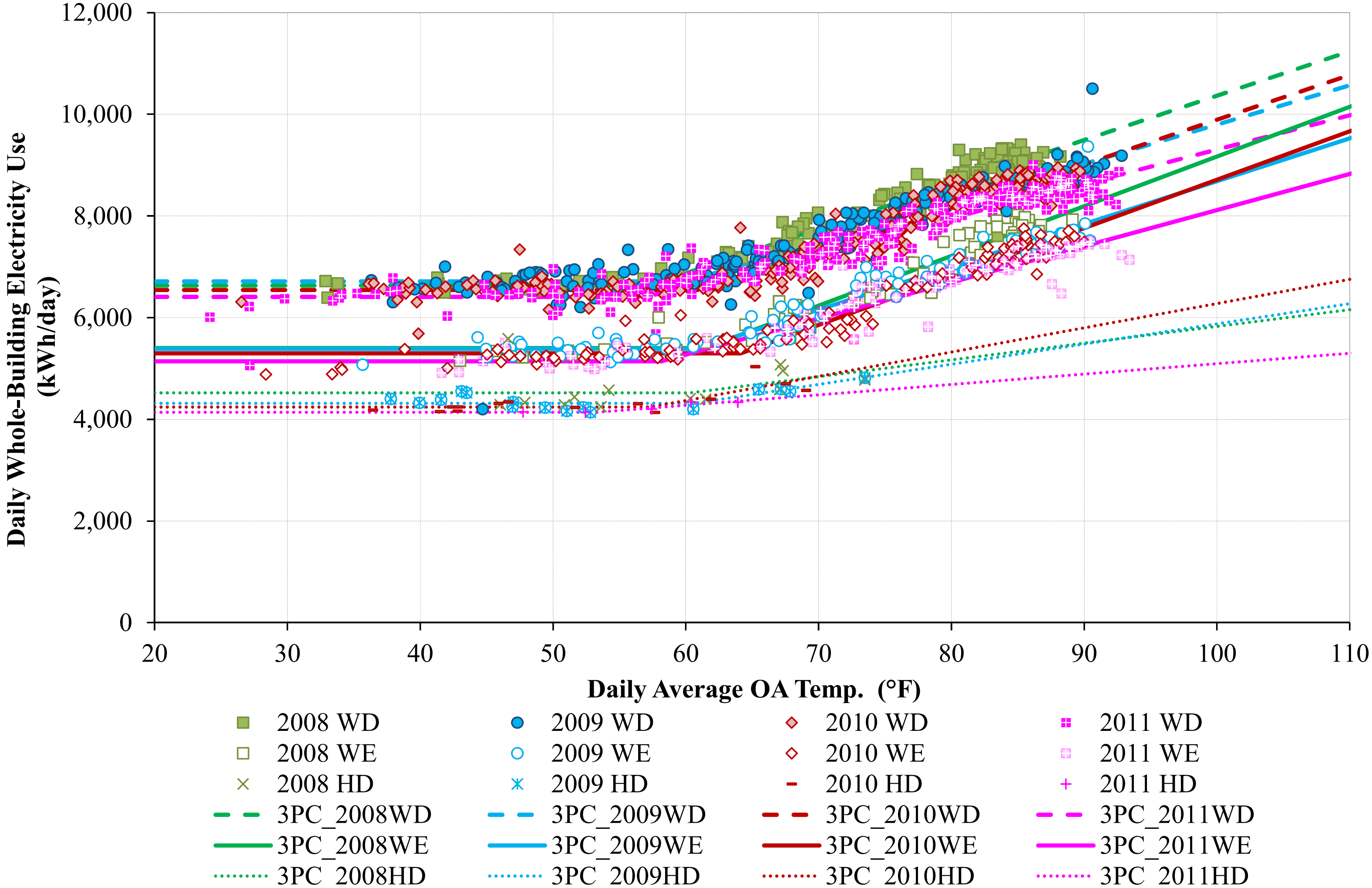


Figure 63: Daily WBE Use versus Daily Outdoor Temperature, Including 3-P Cooling Change-Pont Models for Weekdays (WD), Weekends (WE), and Holidays (HD): May 2008 to November 2011

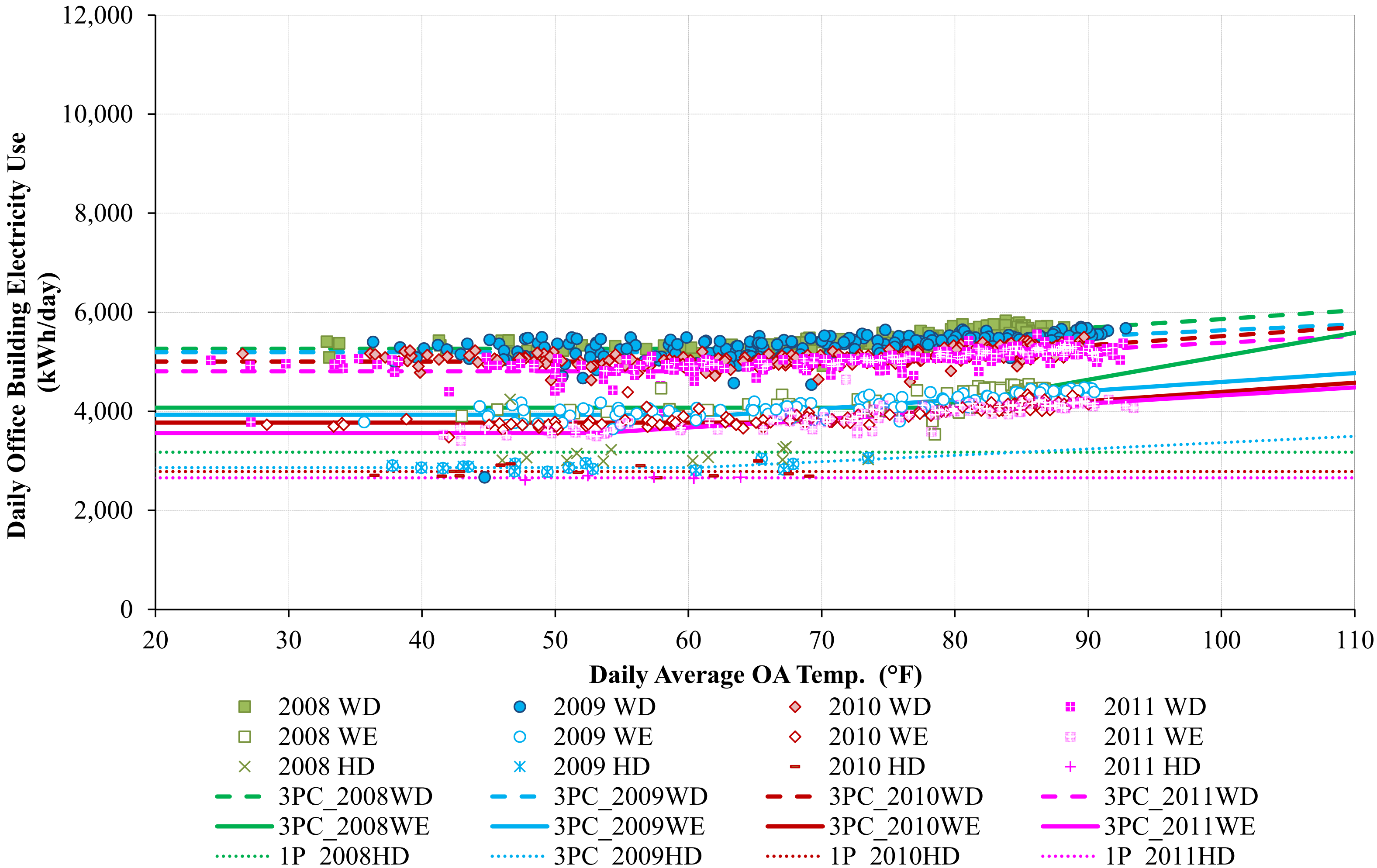


Figure 64: Daily OBE Use versus Daily Outdoor Temperature, Including 1-P and 3-P Cooling Change-Pont Models for Weekdays (WD), Weekends (WE), and Holidays (HD): May 2008 to November 2011

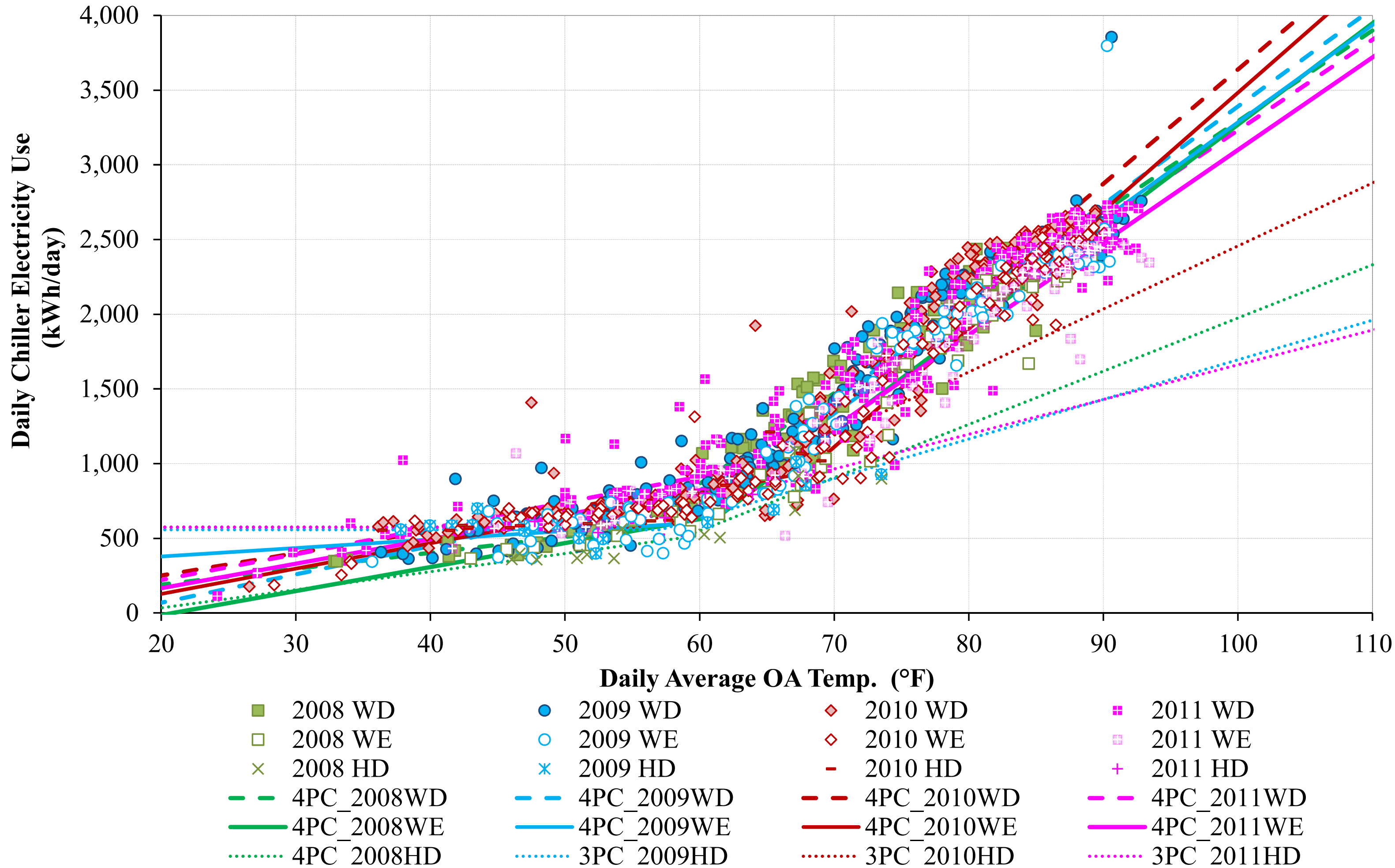


Figure 65: Daily Chiller Electricity Use versus Daily Outdoor Temperature, Including 3-P and 4-P Cooling Change-Pont Models for Weekdays (WD), Weekends (WE), and Holidays (HD): May 2008 to November 2011

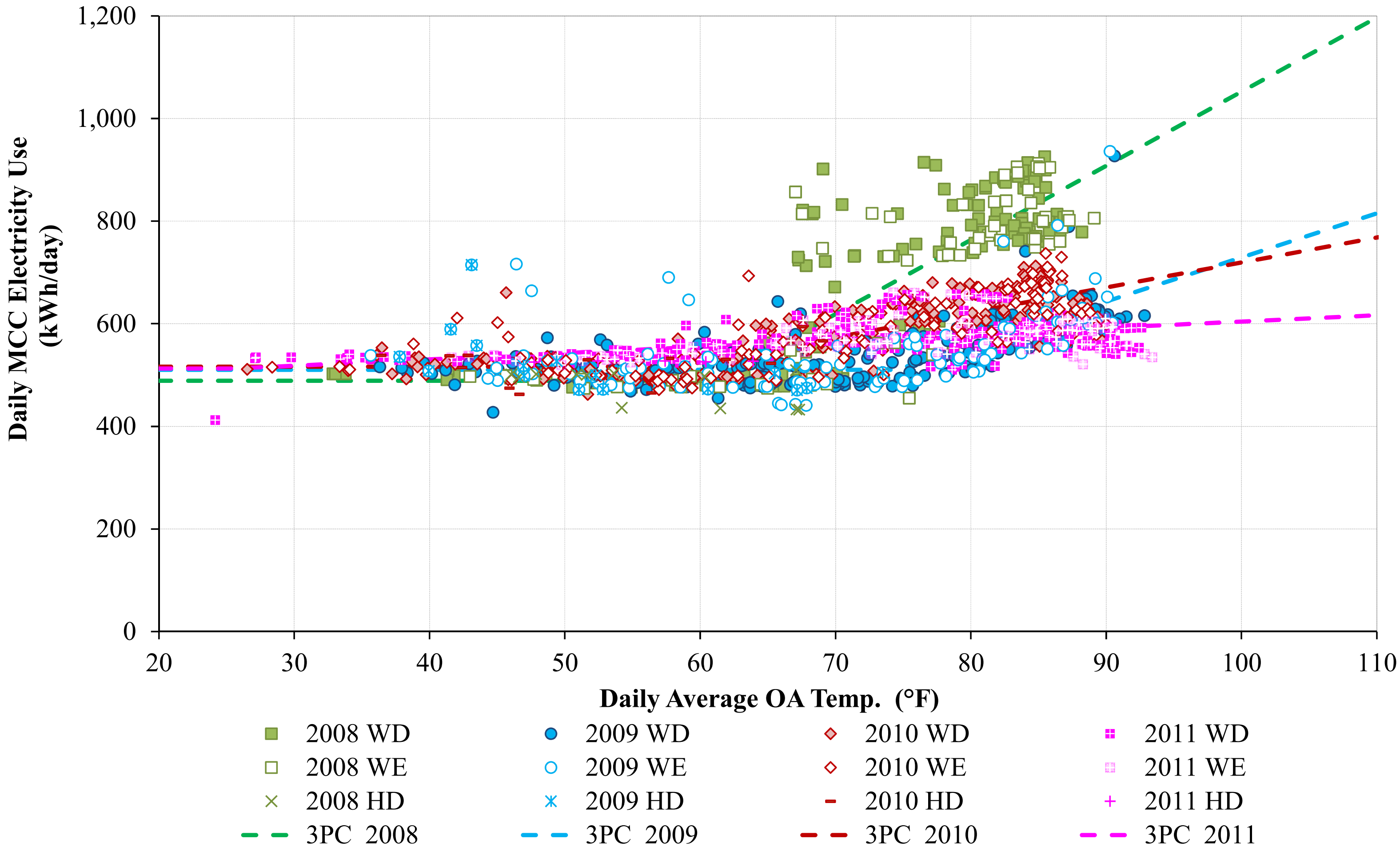


Figure 66: Daily MCC Electricity Use versus Daily Outdoor Temperature, Including 3-P Cooling Change-Pont Models for All Data: May 2008 to November 2011

Table 16: Model Coefficients and Statistical Indicators for Daily WBE Use Models

Coefficient	Description	2008		2009		2010		2011	
		WD (N=145)	WE (N=64)	WD (N=244)	WE (N=104)	WD (N=245)	WE (N=104)	WD (N=218)	WE (N=93)
Ycp	Base load (kWh/day)	6,633	5,398	6,711	5,386	6,542	5,294	6,407	5,141
CS	Cooling slope (kWh/day/ΔF)	87.3	97.8	77.2	84.2	88.0	95.3	67.4	71.1
Tcp	Change point temperature (F)	57.2	61.5	60.1	60.9	61.9	64.1	57.0	58.2
R^2	Squared correlation coefficients	0.93	0.93	0.93	0.93	0.93	0.95	0.91	0.90
CV-RMSE	Coefficient of variation of the root mean square error (%)	2.9%	3.6%	3.0%	3.8%	3.2%	3.5%	3.5%	4.2%

Table 17: Model Coefficients and Statistical Indicators for Daily OBE Use Models

Coefficient	Description	2008		2009		2010		2011	
		WD (N=145)	WE (N=64)	WD (N=244)	WE (N=104)	WD (N=245)	WE (N=104)	WD (N=218)	WE (N=93)
Ycp	Base load (kWh/day)	5,265	4,075	5,193	3,929	5,004	3,770	4,806	3,561
CS	Cooling slope (kWh/day/ΔF)	17.6	47.3	12.1	17.9	18.3	18.6	13.9	16.2
Tcp	Change point temperature (F)	66.1	78.1	63.5	63.1	72.0	66.6	58.4	53.0
R^2	Squared correlation coefficients	0.52	0.49	0.34	0.69	0.44	0.69	0.52	0.68
CV-RMSE	Coefficient of variation of the root mean square error (%)	2.5%	3.9%	3.1%	2.9%	2.4%	2.7%	3.2%	3.5%

Table 18: Model Coefficients and Statistical Indicators for Daily Chiller Electricity Use Models

Coefficient	Description	2008		2009		2010		2011	
		WD (N=145)	WE (N=64)	WD (N=244)	WE (N=104)	WD (N=245)	WE (N=104)	WD (N=218)	WE (N=93)
Ycp	Energy use at Tcp (kWh)	563	653	850	598	915	938	956	894
CS_1	Cooling slope for temperature below Tcp (kWh/day/ΔF)	10.6	16.1	18.9	5.7	14.9	16.9	17.3	16.4
CS_2	Cooling slope for temperature above Tcp (kWh/day/ΔF)	60.7	68.0	65.5	65.1	76.5	79.0	60.7	62.0
Tcp	Change point temperature (F)	55.0	61.5	61.2	58.7	64.4	67.8	62.5	64.4
R^2	Squared correlation coefficients	0.95	0.94	0.96	0.95	0.95	0.96	0.93	0.92
CV-RMSE	Coefficient of variation of the root mean square error (%)	9.1%	10.0%	10.2%	12.6%	11.6%	10.3%	11.8%	11.5%

Table 19: Model Coefficients and Statistical Indicators for Daily MCC Electricity Use Models

Coefficient	Description	2008 (N=222)	2009 (N=364)	2010 (N=362)	2011 (N=303)
Ycp	Base load (kWh/day)	489	510	517	513
CS	Cooling slope (kWh/day/ΔF)	14.5	8.6	4.9	1.2
Tcp	Change point temperature (F)	61.0	74.5	58.3	25.6
R^2	Squared correlation coefficients	0.72	0.50	0.63	0.28
CV-RMSE	Coefficient of variation of the root mean square error (%)	12.5%	8.6%	7.1%	5.2%

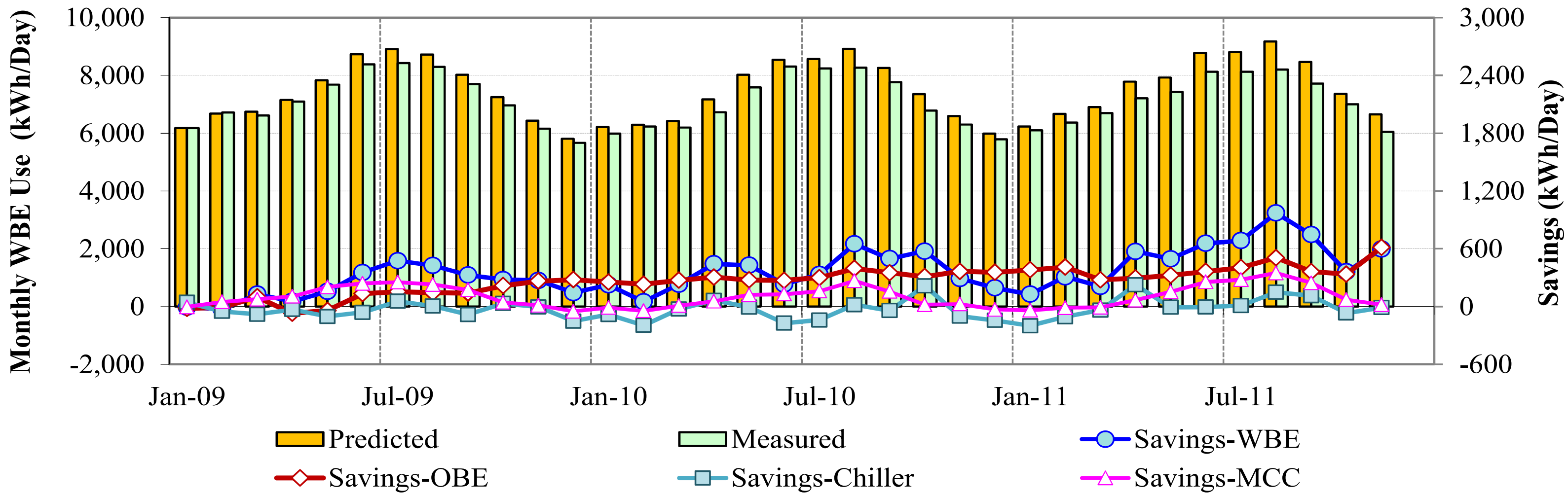


Figure 67: Monthly WBE, OBE, Chiller, and MCC Electricity Savings Against the Baseline Year 2008 Using the Daily Models for the Years from 2009 to 2011

Table 20: Annual Summary of WBE, OBE, Chiller, and MCC Savings Against the Baseline Year 2008 Using the Daily Models

		WBE		OBE		Chiller		MCC	
		(kWh/yr)	(%)	(kWh/yr)	(%)	(kWh/yr)	(%)	(kWh/yr)	(%)
2009 (N=365)	Weekdays	62,240	-	26,464	-	-2,809	-	29,376	-
	Weekends	13,550	-	8,241	-	-7,941	-	11,206	-
	Holidays	3,173	-	4,660	-	-2,403	-	-56	-
	Total	**78,964**	**2.9%**	**39,365**	**2.2%**	**-13,153**	**-2.5%**	**40,527**	**17.0%**
2010 (N=365)	Weekdays	92,854	-	77,839	-	-9,325	-	18,833	-
	Weekends	31,121	-	28,882	-	-5,697	-	7,529	-
	Holidays	3,023	-	5,521	-	-3,391	-	-214	-
	Total	**126,998**	**5.0%**	**112,243**	**6.2%**	**-18,413**	**-3.5%**	**26,147**	**11.0%**
2011 (N=334)	Weekdays	127,249	-	95,115	-	2,160	-	28,490	-
	Weekends	45,215	-	31,763	-	458	-	13,678	-
	Holidays	1,582	-	2,613	-	-840	-	-144	-
	Total	**174,046**	**7.2%**	**129,490**	**7.7%**	**1,778**	**0.3%**	**42,024**	**18.1%**

b) Demand Analysis

Using the ASHRAE Diversity Factor Toolkit (Abushakra et al. 2001), the hourly WBE load profiles were calculated for the years from 2009 to 2011. The demand savings[98] were then calculated against the baseline year 2009 using the 90th percentile of the diversity factor for each month[99]. As an example to show a diversity factor analysis, the weekday and weekend hourly profiles were displayed in Figure 68 for July and December 2009, including 10th, 25th, 50th, 75th, and 90th percentiles as well as minimum, mean, and maximum values. The results show the building's electricity loads were controlled in a pretty consistent fashion, following the expected seasonal and weekly pattern. In the data shown in Figure 68, the predicted monthly demands (i.e., maximum 90th percentile) for July and December 2009 are 522 kW and 387 kW, respectively.

Figure 69 shows the monthly demand predicted using the maximum 90th percentiles of each month versus the maximum daily 24-hour average outdoor temperatures along with the ASHRAE IMT 3-P cooling change-point demand models calculated for each year. The results show the demand models were well determined with high coefficients of determination (R^2) between 0.84 and 0.97 as well as low coefficient of variation of the root mean square error (CV-RMSE) between 1.8% and 3.1%, as shown in Table 21. The weather-independent, base-load electric demand (Ycp) varied between 399 and 415 kW. The temperature-dependent cooling electric demand (i.e., the right slope, RS (kW/F)) varied between 4.0 and 5.8 kW/F, and the change-point temperature (Tcp) was calculated to be between 68.4 and 70.3 F.

To track changes in the electric demand performance of the building over years, the demand savings were calculated for 2010 and 2011 against the 2009 baseline year by subtracting the actual demand (i.e., the maximum 90th percentile) from the predicted demand using the 3-P demand model based on 2009 data, as shown in Figure 70 and Table 22. Compared to 2009, the building's electric demand performance has improved slightly: 1.1% in 2010 with a savings of 58 kW/yr; and 3.1% in 2011 with a savings of 162 kW/yr, which are smaller savings than the results at the Level II: Intermediate Level (Figure 53 and Table 13) using monthly billed demand data[100]. An increase in the demand was observed in the summer of 2010 and the winter of 2011.

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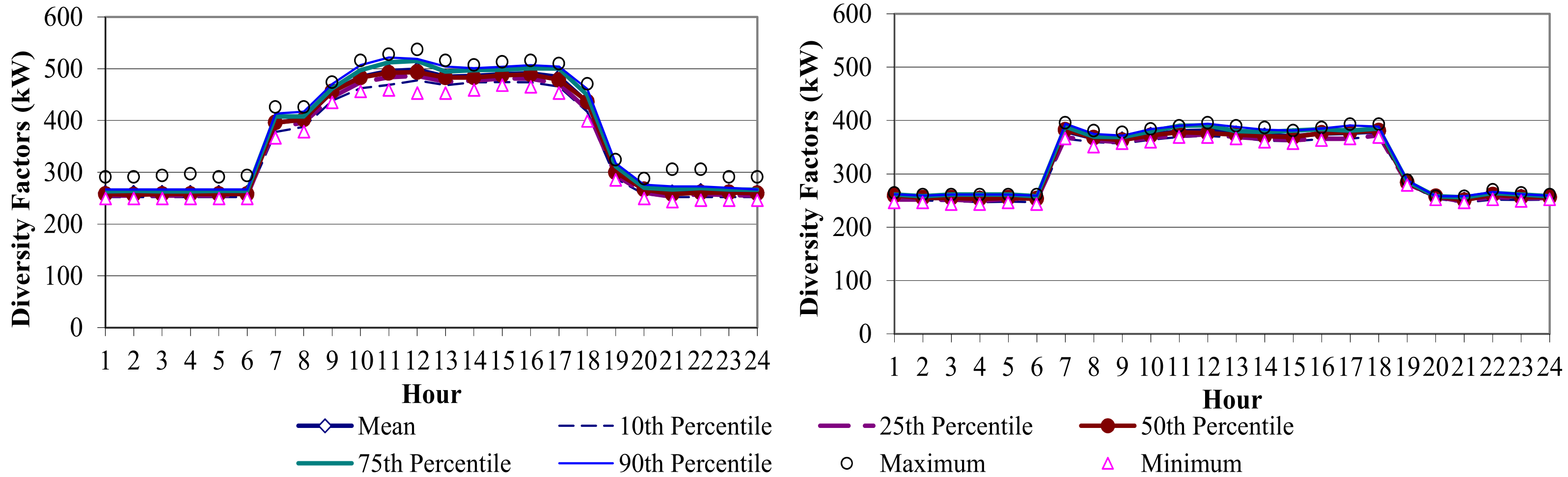
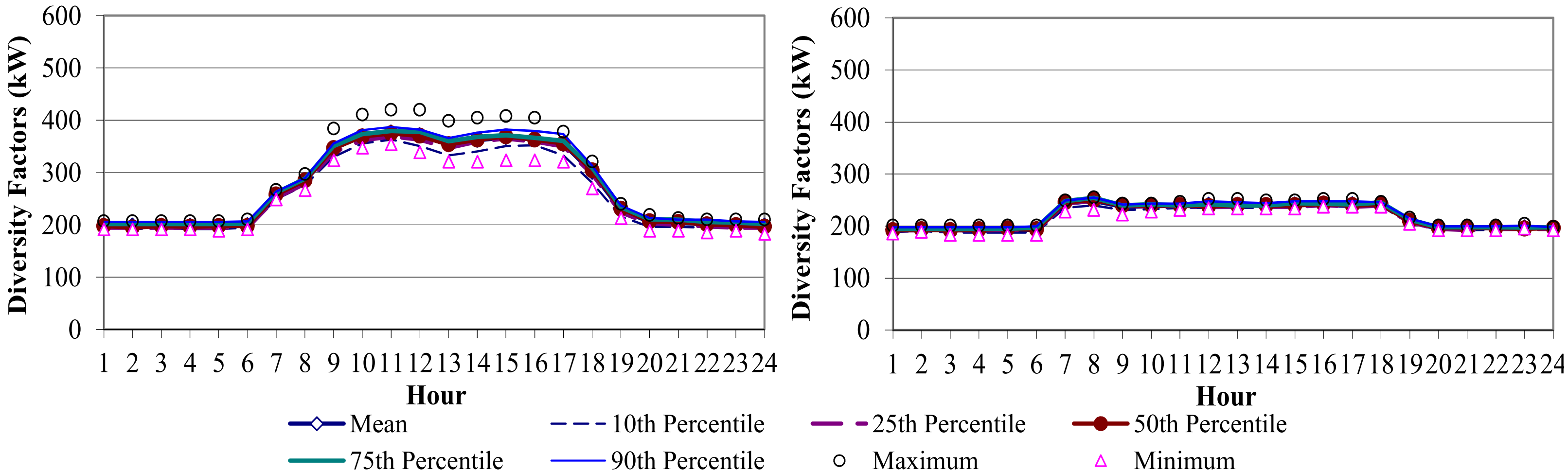
[98] In this dissertation, the word "savings" is used to denote the changes in energy or water use performance against the baseline year. Negative savings means increased energy or water use against the baseline year.

[99] Since twelve months of data are recommended to establish a baseline for demand analysis (ASHRAE 2002), 2009 was selected for the baseline period rather than 2008, which only had eight months of data.

[100] The demand savings against the 2009 base year estimated using the 2007 demand model in Section 5.1.2 Level II: Intermediate Level are: 337 kW (5.8%) in 2010; and 332 kW (5.9%) in 2011.



(a) July 2009: Weekday (Left) and Weekend (Right) Profiles



(b) December 2009: Weekday (Left) and Weekend (Right) Profiles

Figure 68: WBE Hourly Profiles for Weekdays and Weekends: July and December 2009

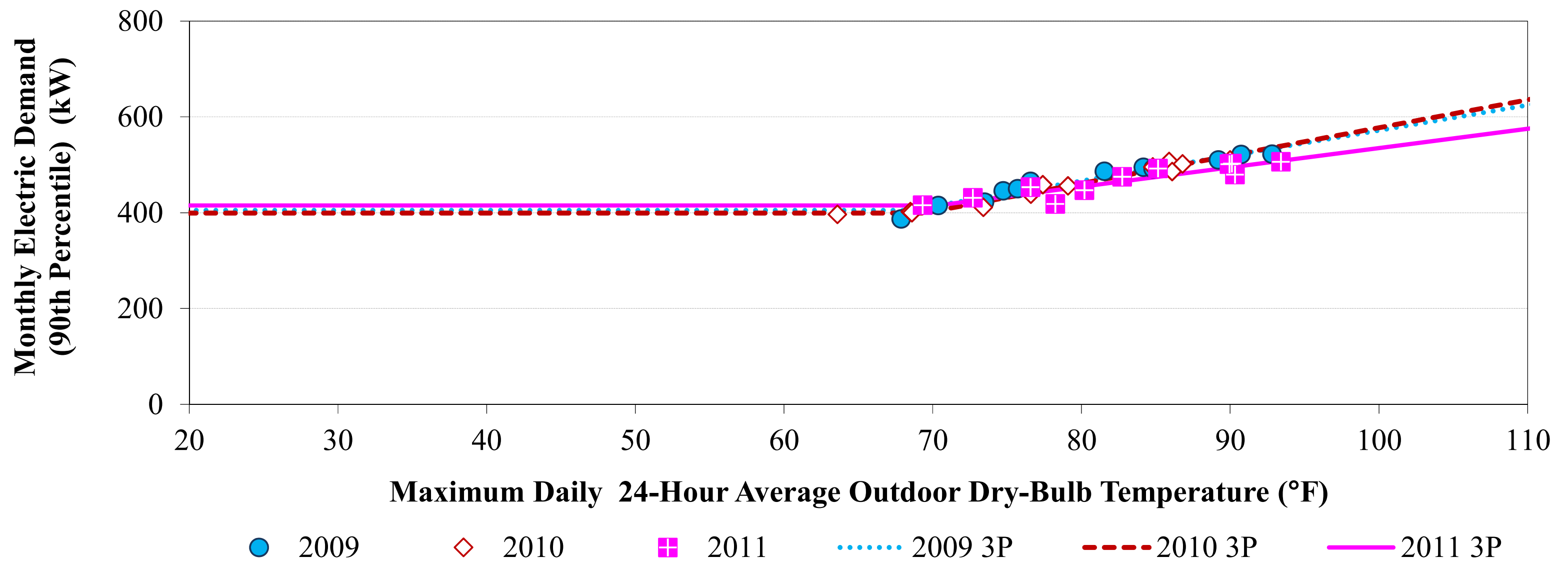


Figure 69: Monthly Electric Demand (90th Percentile) versus Maximum Outdoor Temperatures, Including 3-P Cooling Change-Point Models for the Years 2010 and 2011

Table 21: Model Coefficients and Statistical Indicators for Electric Demand Models Using the 90th Percentiles of Diversity Factor

Coefficient	Description	2009 (N=12)	2010 (N=12)	2011 (N=11)
Ycp	Base load (kW)	405	399	415
β_1	Right slope (kW/ΔF)	5.3	5.8	4.0
Tcp	Change point temperature (F)	68.4	69.4	70.3
R^2	Squared correlation coefficients	0.95	0.97	0.84
CV-RMSE	Coefficient of variation of the root mean square error (%)	2.3%	1.8%	3.1%

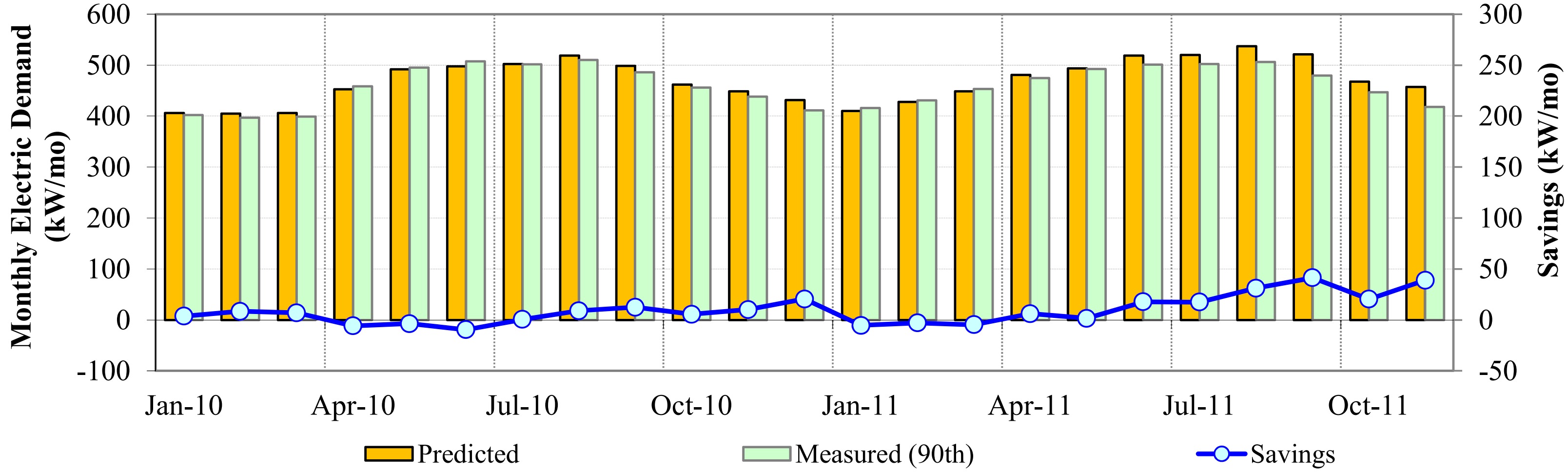


Figure 70: Demand Savings Against the Baseline Year 2009 Using the 90th Percentiles of Diversity Factor for the Years 2010 and 2011

Table 22: Annual Summary of Demand Savings Against the Baseline Year 2009 Using the 90th Percentiles of Diversity Factor

	Annual Total Measured (90th) (kW/yr)	Annual Total Predicted (kW/yr)	Savings	
			(kW/yr)	(%)
2010 (N=12)	5,462	5,520	58.4	1.1%
2011 (N=11)	5,120	5,281	162.0	3.1%

5.1.3.3. Observations

Observations from the field test of the ASHRAE PMP Advanced Level energy protocol are as follows[101]:

- The energy performance metrics required at the Advanced Level used daily or hourly energy use for the whole building and major end-uses. However, a review of the literature showed there are very few references that provide detailed techniques or data analysis procedures that show how to interpret and analyze data at the daily or hourly level. In this study, a multi-year time-series plot was used to interpret data on a daily basis for the whole-building as well as major end-uses. The hourly data were also reviewed with three-dimensional, hourly usage profiles suggested by Haberl and Komor (1990b) for the whole-building and major end-uses. These plots revealed interesting qualitative features that were helpful in understanding the building's energy use behavior and were helpful in identifying potential energy efficiency measures for the building.
- The current version of the ASHRAE PMP Advanced Level energy protocol relies on external standards and protocols, which prevents the ASHRAE PMP from being a stand-alone document. The reader must obtain the referenced standards and protocols to fully understand the details of the recommended procedures. Currently, it does not provide details that are sufficient enough for the users to perform the measurements of daily or hourly energy use without referring to external documents, including the ASHRAE Guideline 14 (ASHRAE 2002) and CIBSE TM39 (CIBSE 2006b), both of which will be soon out of date.
- The sub-hourly chiller electricity use data was helpful in diagnosing the causes of the observed abnormally high peak demand. The use of the sub-hourly end-use data showed that the chillers' abnormal energy use behavior was responsible for high peak demand of the entire building. An inspection of additional chiller operation data (i.e., supply and return temperature and water flow) along with the 15 minute chiller electricity use data revealed that several abnormally high peaks occurred during the erroneous simultaneous operation of the two chillers or during periods of startup of a chiller after a short-term shutdown.
- To track changes in energy performance of the building over several years, the energy and demand savings were calculated against the baseline year using the ASHRAE IMT, with daily or hourly data. As a result, the calculated energy savings were found to be in good agreement with the results at the Level II: Intermediate Level analysis using monthly billed data.

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[101] A shorter observation listed in this section is repeated as an issue in Section 5.1.4.

However, the demand savings calculated using the maximum 90th percentile of the diversity factor was slightly less than the demand savings calculated at the Intermediate Level results, which were based on monthly billed electricity demand.

5.1.4. *Summary of Energy Protocol Field-Testing Results*

The energy performance metrics required at the ASHRAE PMP Basic, Intermediate, and Advanced Levels energy protocol were calculated and compared against the benchmarks (either self or external reference) provided in the ASHRAE PMP using a case-study building. Thirteen issues were noted from the field test and summarized in this section[102]. The recommendations for each identified issue are provided in Section 6.1.1.1. For the selected issues, new or modified approaches are discussed in Section 6.2.1.

- **Issue E-1**: The perceived energy performance of the case-study building is highly dependent on which benchmark the user utilizes. However, different benchmarking sources yield very different results: i.e., worse than average performance against the ASHRAE benchmarks versus average performance against the ENERGY STAR Portfolio Manager benchmarks.
- **Issue E-2**: The energy performance metrics required at the ASHRAE PMP Basic Level are the annual whole-building EUI as well as ECI. However, since the ECI is calculated using unit costs of energy, which were not fixed costs over time. Therefore, there may be time-dependent differences in trends derived between the two indices (i.e., EUI and ECI).
- **Issue E-3:** The energy performance metrics required at the ASHRAE PMP Basic Level are indices at the whole-building level, which are the sum of all energy used in the building. Unfortunately, when the building consumes different energy from two or more sources, the metrics calculated separately for each energy source may provide additional insights compared to the combined metrics at the whole-building level without any extra data collection efforts since the data were collected separately for each energy source.
- **Issue E-4**: The ASHRAE PMP suggests two different EUI calculation procedures that are based on different adjustment methods[103]. In this study, for the case-study building, no

[102] A shorter observation listed in Sections 5.1.1.3, 5.1.2.3, and 5.1.3.3 is repeated as an issue in this section.
[103] In one method, the ENERGY STAR Portfolio Manager adjusted the consumption to fit the calendar month, while in the other method, the ASHRAE Standard 105-2007 selects the analysis period based on the billing period of the energy type with the largest total used to minimize errors associated with the adjustments.

significant differences were revealed in the EUIs calculated using these two procedures: resulting in a percentage error between -0.39% and 0.69%.

- **Issue E-5**: The ASHRAE PMP Intermediate Level energy protocol requires calculating the inverse energy use models that relate energy use to the appropriate independent variables (i.e., outdoor temperature) for a self-reference comparison. However, the current version of the ASHRAE PMP Intermediate Level energy protocol does not provide any advice about how to ensure a fair level of confidence in the calculated model as well as performance changes (i.e., savings). In this study, the Whole-Building Performance Path of the ASHRAE Guideline 14-2002 (ASHRAE 2002) was referenced in the entire calculation procedure, although the compliance with the ASHRAE Guideline 14-2002 is not required in the current version of the ASHRAE PMP.
- **Issue E-6**: The ASHRAE PMP does not provide any advice about how to calculate a suitable outdoor temperature index for different types of energy use (i.e., electricity, peak demand, and natural gas use). Although it should be noted that different climate conditions can yield different results, in this study, almost identical results were obtained for the WBE use models from the use of either monthly average of daily minimum and maximum temperatures (T_{minmax}) or monthly average of hourly temperatures (T_{hourly}). However, for cooling demand models, slightly different results were obtained by using monthly maximum outdoor temperature in a billing period ($T_{max\_monthly}$) compared to the other two indices (i.e., maximum of daily min-max average outdoor temperature (T_{max_minmax}); or maximum of daily 24-hour average outdoor temperature (T_{max_24hour})), although the differences were within the range of uncertainties [104]. For natural gas models, the savings calculated with the T_{min} model were slightly higher than the savings with the T_{minmax} model by 40 to 47 MCF/yr per year. However, the difference was within the range of uncertainties.
- **Issue E-7**: In the calculated savings at the Intermediate Level (Figure 45), consistently lower (or negative) savings were observed in February of each year. This may indicate an under-prediction of the base-load consumption using the base year 2007 model due to holiday periods in December and January when energy use was less. When the building has a different operating mode for holidays, the monthly 3-P cooling model is likely to under-predict the base-load consumption due to holidays in December and January. At the annual-

[104] About 66 to 150 kW/yr higher savings were estimated using $T_{max\_monthly}$ due to a larger temperature deviation between $T_{max\_monthly}$ and the other two indices from 2008 to 2011 compared to 2007.

level calculation, a lower savings in February may be offset by an over-predicted savings in December and January. However, the accuracy of such a model is limited. Not surprisingly, the computed net determination biases of the baseline models were higher than the acceptable level required in the ASHRAE Guideline 14-2002, which indicates a high level of uncertainty in the baseline models based on the 3-P cooling change-point models with a single independent variable (i.e., outdoor temperature). Therefore, an issue was found that the instructions in the current version of the ASHRAE PMP are not enough about the building that has a different operating mode for holidays.

- **Issue E-8**: The ASHRAE PMP does not describe how to deal with outliers for the inverse regression models when they are present in the dataset. In this study, several data points of peak demand were found to be inconsistent with other data, and therefore, the models calculated with these outlying data points did not represent the dataset well (i.e., a low R^2 and a high CV-RMSE[105]). However, the models without outliers were better determined with a higher R^2 between 0.61 and 0.91 as well as a lower CV-RMSE between 1.9% and 6.5%[106]. In addition, it was found that the monthly outliers can provide useful information that may be helpful to detect some operational problems in the building.
- **Issue E-9**: One of the energy performance metrics required at the Intermediate Level is the measurement of major end-use energy use, which requires a high level of data collection, data management and analysis. However, the ASHRAE PMP does not provide any advice about end-use benchmarks or how to benchmark the calculated energy use indices from the end-use data against a reliable, external reference.
- **Issue E-10**: The energy performance metrics required at the Advanced Level used daily or hourly energy use for the whole building and major end-uses. However, the ASHRAE PMP does not provide detailed techniques or data analysis procedures that show how to interpret and analyze data at the daily or hourly level.

[105] The models with outliers had a R^2 between 0.11 and 0.81 as well as CV-RMSE between 5.2% and 16.0%.

[106] To identify potential outliers, this study compared two different methods. The first method used a box and whisker plot. The data points beyond 25th and 75th quartiles by one and a half times the interquartile range (IQR = 75th quartile – 25th quartile) were considered potential outliers, which is commonly used in statistics (Emerson and Strenio 1983). The second method used the IMT 3-P cooling models that were initially calculated with all data points. The data points beyond ±1.5 CV-RMSE of the calculated IMT 3-P cooling models were considered suspected outliers. As a result, the box and whisker plot method was found effective to detect extreme outliers. However, it failed to account for a seasonal variation in peak demand. Thus the outliers that were identified using the second method were excluded in the final IMT models.

- **Issue E-11**: The current version of the ASHRAE PMP Advanced Level energy protocol relies on external standards and protocols, which prevents the ASHRAE PMP from being a stand-alone document. Currently, it does not provide details that are sufficient enough for the users to install and calibrate the equipment to take the measurements of daily or hourly energy use without referring to external documents, including the ASHRAE Guideline 14 (ASHRAE 2002) and CIBSE TM39 (CIBSE 2006b).
- **Issue E-12**: The ASHRAE PMP does not provide discussions about how to use chiller operation data to investigate a building's energy performance as well as how to evaluate the chiller performance data against external benchmarks in the ASHRAE PMP. It was found that sub-hourly chiller electricity use data was helpful in diagnosing the causes of the observed abnormally high peak demand. In this study, an inspection of additional chiller operation data (i.e., supply and return temperature and water flow) along with the 15 minute chiller electricity use data revealed that several abnormally high peaks occurred during the erroneous simultaneous operation of the two chillers or during periods of the startup of a chiller after a short-term shutdown.
- **Issue E-13**: Different levels of the ASHRAE PMP procedures yield different performance evaluations of the same building. For example, slightly lower savings were indicated with the Advanced Level electric demand analysis using the maximum 90th percentile of the diversity factor compared to the electric demand savings calculated at the Intermediate Level based on monthly billed electric demand.

5.2. Water Use

5.2.1. *Level I: Basic Level*

5.2.1.1. *Performance Metrics*

The water performance metrics required at the Basic Level are an annual total site water use index (WUI) and water cost index (WCI). Figures 71 and 72 show the annual moving average total site WUI and WCI of the case-study building adjusted to cover the 365 days as suggested in the ASHRAE PMP. The line graphs (right axis) show two different WUIs (Figure 71) and WCIs (Figure 72) calculated using different normalization factors in the denominator: per gross floor area of a building ($gal/ft^2 \cdot yr$, $\$/ft^2 \cdot yr$) and per number of occupants[107] (gal/employee-day, $/employee-day). The bar charts (left axis) show the annual moving average total site water use (kgal/yr) and water cost (thousands$/yr) before applying normalization.

The water performance of the case-study building varied between 22.9 and 33.7 $gal/ft^2 \cdot yr$ and between 24.1 and 35.4 gal/employee-day. During the analysis period, there was one sudden increase in water consumption in October-November 2010. The cause for this increase remains unknown. The WCI of the case-study building was stable until July 2010, between $0.113 and $\$0.125/ft^2 \cdot yr$ ($0.119 and $0.132/employee-day). However, since then, the cost index increased to $\$0.158/ft^2 \cdot yr$ ($0.166/employee-day) in September 2011. The water and sewer rates for the analysis period had been slightly increased from $2.22 to $2.49/kWh (i.e., 12% increase) for a water usage charge, from $2.22 to $2.68/kgal (i.e., 21% increase) for a sprinkler water usage charge, and from $3.94 to $4.06/kgal for sewer charge (i.e., 3% increase) (Figure 73).

[107] Conversations with the facility personnel revealed that there were no noticeable changes in occupancy of the building. Therefore, a constant value of 323 was used for the number of employees to calculate the case-study building's WUIs.

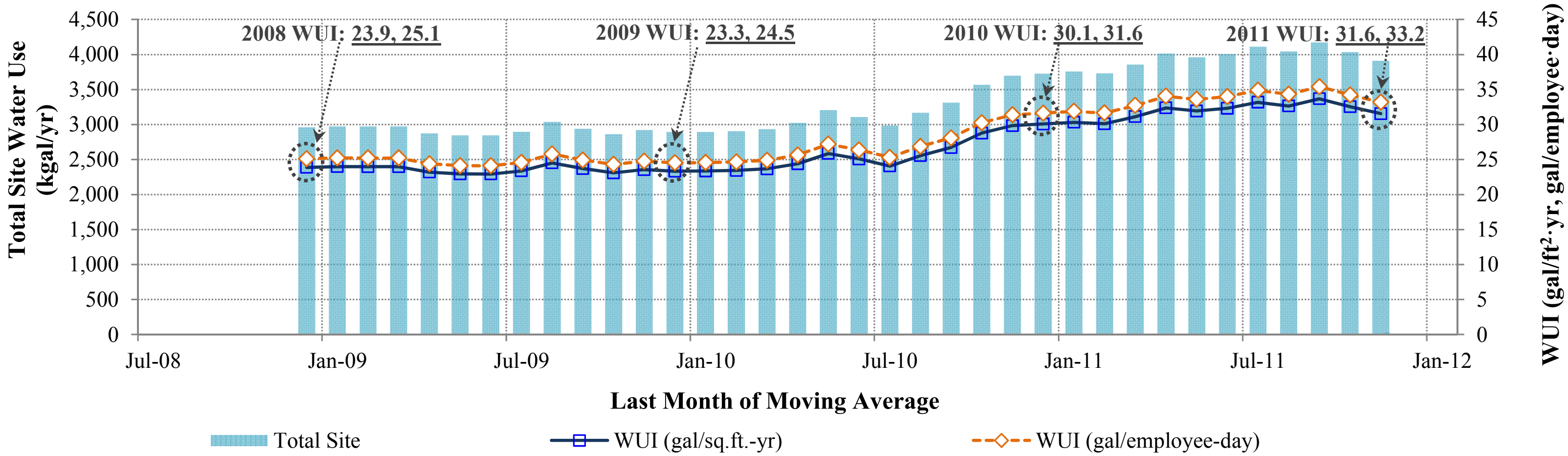


Figure 71: Annual Moving Average Total Site Water Use (Left Axis) and WUIs (Right Axis) of the Case-Study Building

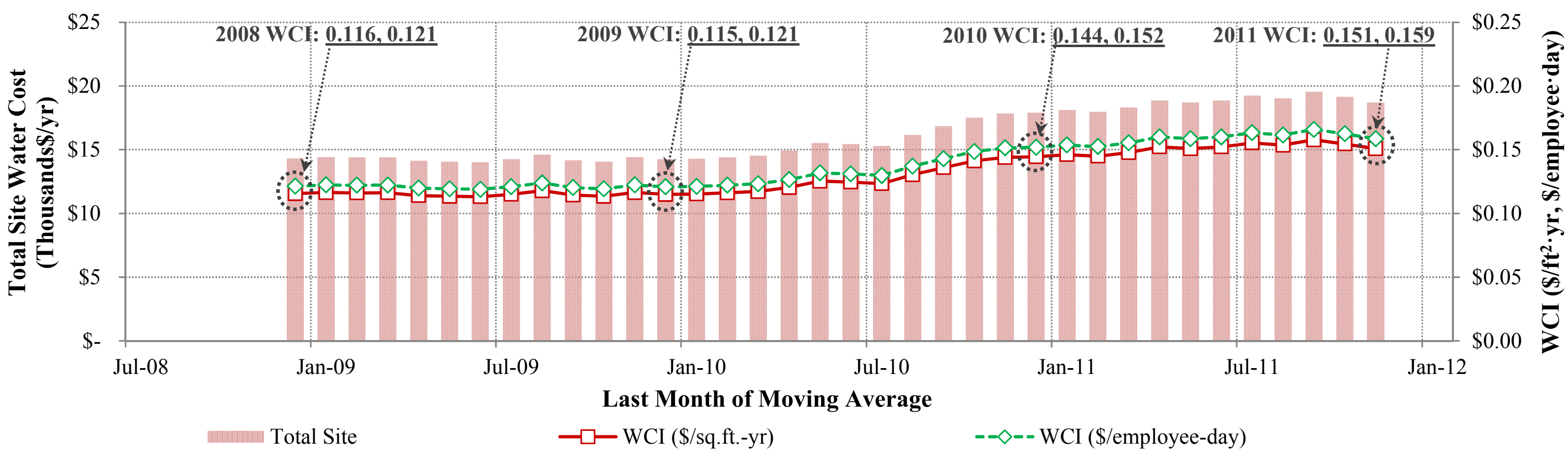


Figure 72: Annual Moving Average Total Site Water Cost (Left Axis) and WCIs (Right Axis) of the Case-Study Building

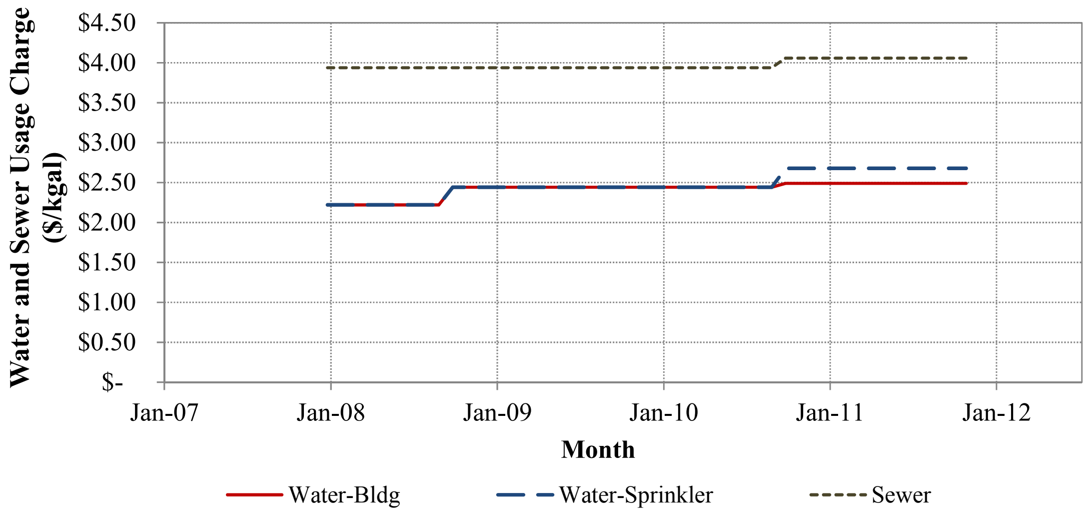


Figure 73: College Station Utilities' Commercial (3" Meter Size) Water and Sewer Charge for the Analysis Period

5.2.1.2. Performance Evaluation/Benchmarking

The evaluations of water performance metrics were performed by comparing the calculated WUIs to three sources of benchmarking data: the U.S. Department of Energy (DOE) Federal Energy Management Program (FEMP) Federal Water Use Indices (FEMP 2009), the Verein Deutscher Ingenieure (VDI, The Association of German Engineers) 3807 Part 3 (VDI 2000), and the Chartered Institution of Building Services Engineers (CIBSE) Guide G, Public Health Engineering (CIBSE 2004). Figures 74 and 75 show a comparison of the calculated annual moving average total WUI for the main building and the landscape watering with the appropriate benchmarks. For the main buildings, unfortunately, there were no benchmarks provided for the offices with gymnasium shower facilities[108]. Thus the comparison was made against the category for general office spaces.

For the main building's water consumption, different benchmarking sources yielded different results. The results show that the office WUIs have never met the CIBSE guideline value for offices without canteen: 10.6 gal/employee-day. However, when compared against the VDI and FEMP benchmarks for offices, the building's water performance has met the guideline values (VDI: 12.9 gal/employee-day; and FEMP: 15.0 gal/employee-day) for a 28% (from June 2009 to March 2010) and a 69% (from December 2008 to August 2010 and from August 2011 to

[108] The case-study building has a gymnasium with shower facilities that are frequently used by building occupants. There are a total of six shower stalls.

November 2011) of the analysis period, respectively. On the other hand, the landscape watering has never met the FEMP benchmarks for landscape with turf (1,571 gal/acre-day), with the WUI suddenly increasing by a factor of 1.5 since October 2010.

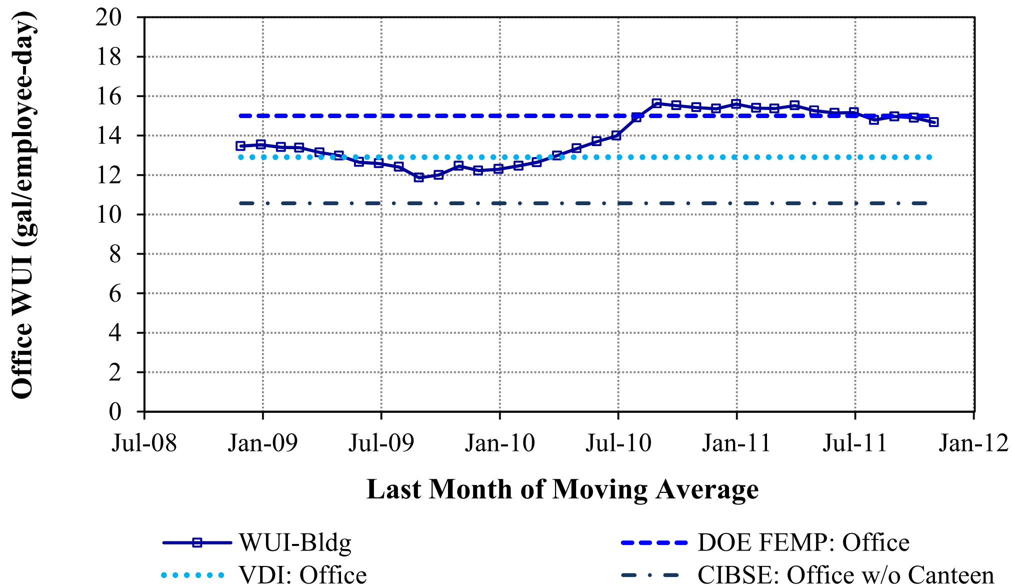


Figure 74: Annual Moving Average Office WUI of the Case-Study Building Compared to the U.S. DOE FEMP, CIBSE, and VDI Benchmarks for Office

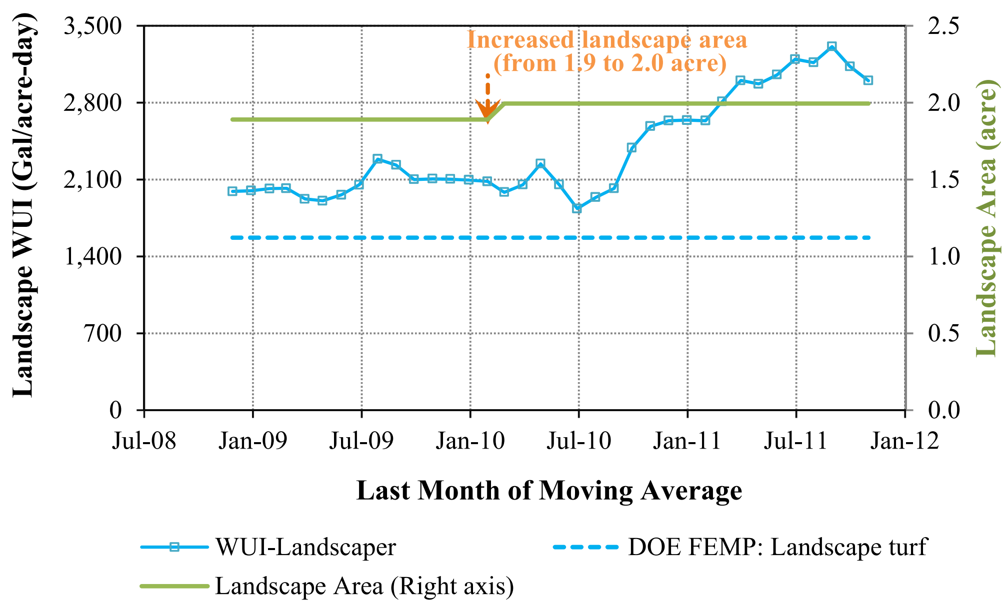


Figure 75: Annual Moving Average Landscape WUI (Left Axis) of the Case-Study Building Compared to the U.S. DOE FEMP Benchmarks for Landscape with Turf

5.2.1.3. *Observations*

Observations from the field test of the ASHRAE PMP Basic Level water protocol are as follows[109]:

- The observed water performance of the case-study building is highly dependent on the benchmark the user utilizes. However, there were no benchmarks provided for buildings that have atypical spaces (i.e., office building with gymnasium shower facilities). Furthermore, different benchmarking sources may yield different results. In this study, the case-study building's water performance met the DOE FEMP and the VDI benchmarking values for 69% and 28% of the analysis period, respectively, but never met the CIBSE guideline value for offices without canteen.
- The water performance metric required at the ASHRAE PMP Basic Level is the annual total site WUI, including water consumption of a building as well as landscape. However, the ASHRAE PMP benchmark data sets are provided separately for a building and landscape.
- The ASHRAE PMP Basic Level water protocol requires users to normalize water consumption of the building by the number of occupants or landscape areas. However, there are no clear guidelines how to estimate and track the number of occupants and/or landscape areas. For example, there is no guideline about how to differentiate part-time and full-time employees since the water consumption may be different between these two groups.

[109] A shorter observation listed in this section is repeated as an issue in Section 5.2.3.

5.2.2. *Level II: Intermediate Level*

5.2.2.1. *Performance Metrics*

The water performance metrics required at the Intermediate Level water protocol are an annual and periodic (i.e., monthly) water use index (WUI) separately for a total building (per gross floor area of a building and per number of occupants), landscape (per landscape area), and wastewater (per gross floor area of a building and per number of occupants).

a) Annual Water Use Index

Figure 76 shows the annual moving average building WUI and landscape WUI of the case-study building adjusted to cover the 365 days as suggested in the ASHRAE PMP. Annual wastewater WUI of the case-study building is same as annual total building WUI. The line graphs (right axis) show two different building WUIs calculated using different normalization factors in the denominator (i.e., per gross floor area of a building (gal/ft^2·yr) and per number of occupants (gal/employee-day)) as well as one landscape WUI normalized by the irrigated landscape area. The stacked bar charts (left axis) show the annual moving average building and landscape water use (kgal/yr) before applying normalization. The total height of the stacked bar represents represents the annual moving average total site water use, including building and landscape water use.

For the main building's water consumption, the calculated WUI varied between 11.3 and 14.9 gal/ft^2·yr and between 11.9 and 15.6 gal/employee-day. The landscape WUI had increased from 15.4 to 27.7 gal/ft^2·yr. Thus, at the Intermediate Level, it was confirmed that the sudden increase in total site water consumption identified at the Basic Level in October-November 2010 was because of an increase in landscape water use rather than in building water use. The cause for this increase in landscape water use still remains unknown. About 0.1 acres of irrigation turf, which corresponding to approximately 5% of total landscape area of the case-study building, were added during the winter of 2009-2010. However, this may not be enough to explain more than 20% increase in landscape water consumption of the building: from 16.9 gal/ft^2·yr (September 2010) to 21.7 gal/ft^2·yr (November 2010).

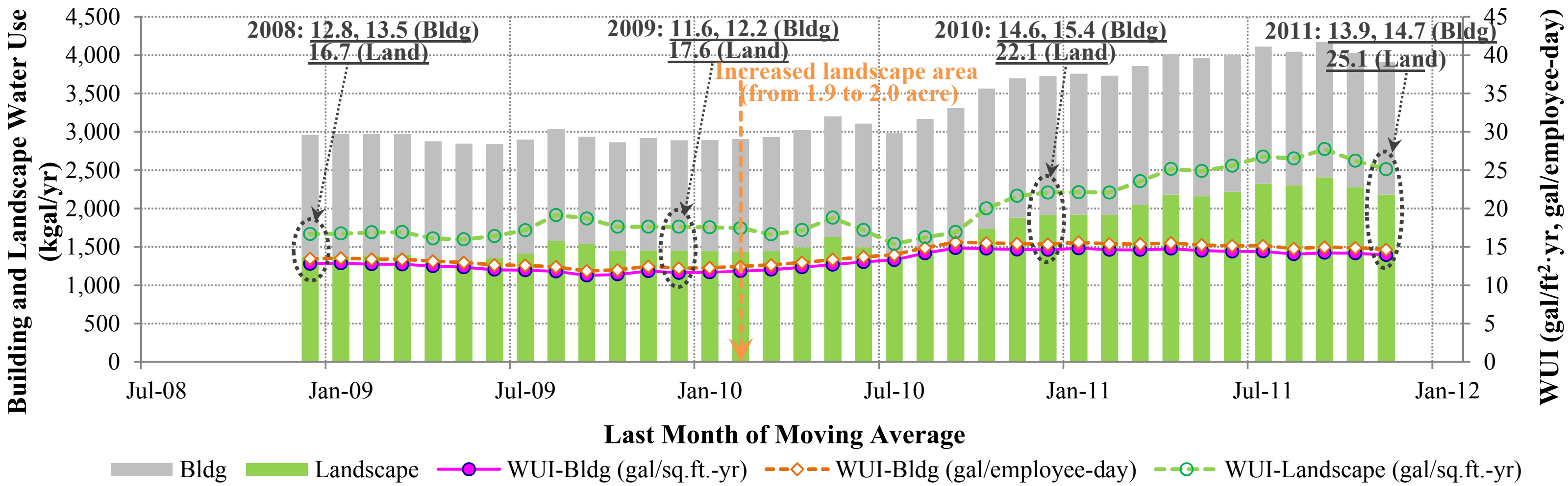


Figure 76: Annual Moving Average Building and Landscape Water Use (Left Axis) and WUIs (Right Axis) of the Case-Study Building

b) Monthly Water Use Index

Figure 77 shows the monthly building and landscape water use metrics of the case-study building normalized and displayed as a daily average basis. Not surprisingly, it was revealed that the monthly metrics gave additional information that was helpful in understanding the water performance of a building compared to the annual WUI. First, the analysis using the monthly metrics could help identify a seasonal pattern in the water usage. During the analysis period, the monthly total site water use varied between 1.8 and 22.3 kgal/day, including the building use, which was between 1.7 and 9.0 kgal/day, and the landscape use, which was between 0.0 and 13.3 kgal/day. The increase in usage followed the expected seasonal curve[110] (i.e., the lowest consumption in the winter with no consumption for landscape, an increasing consumption in the spring, the highest consumption in the summer, and a decreasing consumption in the fall).

Interestingly, year-to-year variations were observed in the seasonal trends of building water use as well as the landscape water use. For example, the lowest annual peak landscape water use, 11.0 kgal/day in 2008, differed by approximately 20% compared to the peak landscape water use in 2010 (13.3 kgal/day). The lowest annual peak building water use was 6.2 kgal/day in 2009, which was about 31% lower than the highest annual peak building water use, 9.0 kgal/day in 2010. For the landscape water use, random fluctuations were also noted, which caused unpredictable curves, especially in 2010 and 2011. The observed random fluctuations may indicate that there is another parameter (i.e., precipitation) affecting the landscape water use beyond outdoor temperature[111].

The monthly metrics also provided useful information on the base load and the weather-dependent water use. The base load of the total site water use (i.e., the lowest values in the 12-month period) was fairly stable during the analysis period: between 1.8 and 2.3 kgal/day[112,113]. In contrast, during this same period, the annual average weather-dependent total site water use, which is the consumption calculated by subtracting the base-load water use from the monthly total site water use, was observed to fluctuate: 6.3 kgal/day in 2008, 5.9 kgal/day in 2009; and 8.0 kgal/day in 2010. Thus, the case-study building consumes water primarily for a weather-

[110] The case-study building has a gymnasium with shower facilities that are frequently used by building occupants year around. There are a total of six shower stalls.
[111] The seasonal trends of outdoor temperature follow the expected seasonal curve, without any noticeable fluctuations (Figure 43).
[112] The base-load of the total site water use is the winter water consumption for the building.
[113] The base-load and weather-dependent water use was not calculated for 2011 since one full year of data was not available.

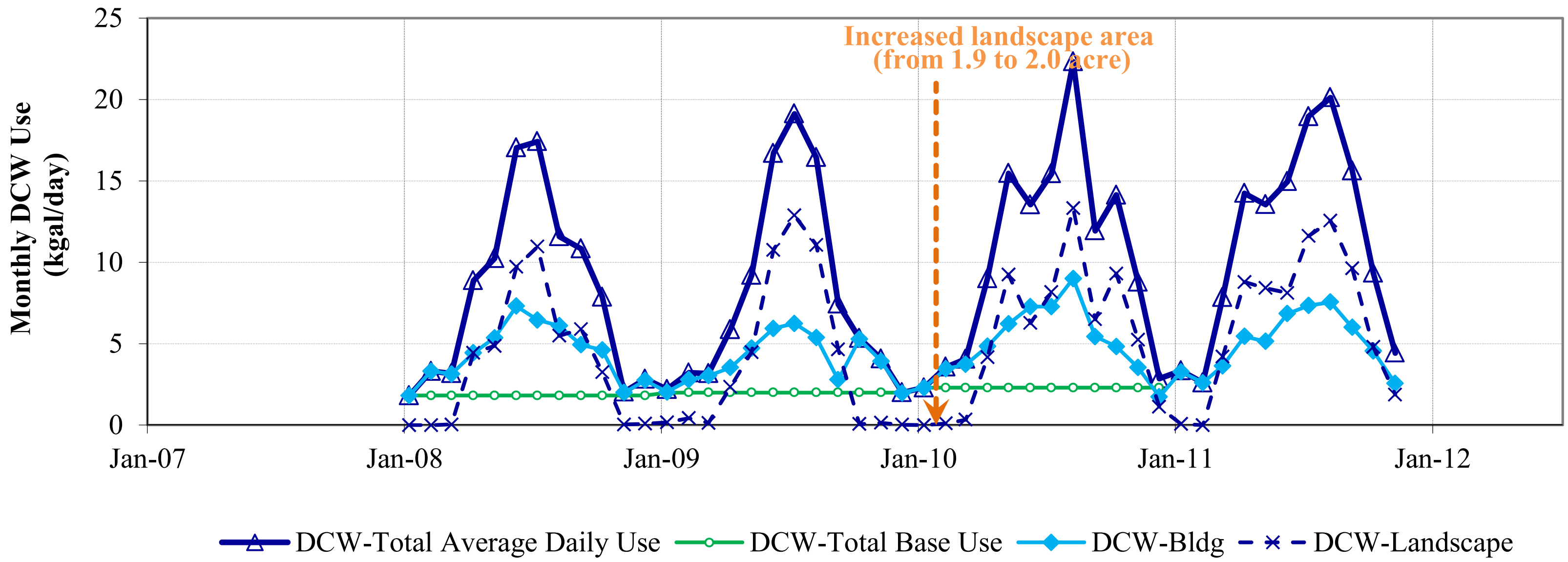


Figure 77: Monthly Building and Landscape Water Use Profiles for the Case-Study Building

dependent load which accounts for around 75% to 78% of total consumption during the analysis period. Therefore, to improve the overall water efficiency of the building, an assessment of weather-dependent load would take priority over the base-load.

5.2.2.2. *Performance Evaluation/Benchmarking*

In the ASHRAE PMP, the Intermediate Level water protocol does not provide any external-reference benchmarking data and requires self-reference comparisons between years. Table 23 shows the annual building WUI (i.e., per gross floor area of a building (gal/ft^2·yr) and per number of occupants (gal/employee-day)) and annual landscape WUI (i.e., per irrigated landscape area of a building (gal/ ft^2·yr)) of the case-study building for 2008, 2009, 2010, and 2011[114] with a percentage change of a WUI compared to 2008 (baseline year). Compared to 2008, the annual building WUI improved with a highest percentage savings of 9.2% in 2009. On the other hand, the annual landscape WUI worsened steadily and considerably with a percentage increase of 50.7% in 2011. However, since the ASHRAE PMP water protocol does not require normalizing landscape water use data for weather, it is hard to confirm whether this high increase was affected by changing weather conditions or other operation and maintenance (O&M) issues.

Table 23: Annual Building and Landscape WUI of the Case-Study Building

Year	WUI-Bldg			WUI-Landscape	
	(gal/ft^2-yr)	(gal/employee-day)	% change against 2008	(gal/ft^2-yr)	% change against 2008
2008 (Baseline year)	12.8	13.5	-	16.7	-
2009	11.6	12.2	-9.2%	17.6	5.6%
2010	14.6	15.4	14.1%	22.1	32.4%
2011	13.9	14.7	8.9%	25.1	50.7%

[114] The 2011 WUI was calculated using the data collected from December 2010 to November 2011 due to a change of occupancy in a case-study building in December 2011.

5.2.2.3. Observations

Observations from the field test of the ASHRAE PMP Intermediate Level water protocol are as follows[115]:

- The water performance metrics required at the ASHRAE PMP Intermediate Level are the annual and monthly water use index (WUI) separately for a total building, landscape, and wastewater. Unfortunately, the current version of the ASHRAE PMP does not provide any external-reference benchmarking data for these metrics. However, there are separate benchmarks for the annual WUI that can be directly comparable to the required Intermediate Level water performance metrics based on the findings in Section 5.2.1.3. One of the issues found in Section 5.2.1.3 was with the Basic Level benchmarks provided separately for a building and landscape since they cannot be directly comparable to the required Basic Level metrics (i.e., annual total site WUI, including water consumption of a building as well as landscape). Thus there are separate benchmarks for the annual index that can be used to evaluate Intermediate Level water performance metrics.
- Currently, there are few detailed techniques or modeling methods to analyze and evaluate a building's water performance beyond a log of the calculated WUIs. For example, the ASHRAE PMP water protocol does not require normalizing water use data for weather, it is hard to confirm whether this high increase was affected by changing weather conditions or other operation and maintenance (O&M) issues. In the current version of the ASHRAE PMP in the Section on Performance Evaluation/Benchmarking, several water savings strategies are discussed instead of evaluation/benchmarking methods. Although these savings strategies are helpful information for the users, they do not provide information about any benchmarks.

5.2.3. *Summary of Water Protocol Field-Testing Results*

The water performance metrics required at the ASHRAE PMP Basic and Intermediate Levels water protocol were calculated and compared against the benchmarks provided in the ASHRAE PMP using a case-study building. Five issues were noted from the field test and summarized in this section[116]. The recommendations for each identified issue are provided in Section 6.1.1.2. For the selected issues, new or modified approaches are discussed in Section 6.2.2.

[115] A shorter observation listed in this section is repeated as an issue in Section 5.2.3.
[116] A shorter observation listed in Sections 5.2.1.3 and 5.2.2.3 is repeated as an issue in this section.

- **<u>Issue W-1</u>**: The observed water performance of the case-study building is highly dependent on the benchmark the user utilizes. However, there were no benchmarks provided for buildings that have atypical spaces (i.e., office building with gymnasium shower facilities). Furthermore, different benchmarking sources may yield different performance ratings.
- **<u>Issue W-2:</u>** The water performance metric required at the ASHRAE PMP Basic Level is the annual total site WUI, including water consumption of a building as well as landscape. However, the ASHRAE PMP benchmark data sets are provided separately for a building and landscape. Therefore, the water performance metric required at the ASHRAE PMP Basic Level cannot be directly compared to the benchmark references provided in the PMP.
- **<u>Issue W-3:</u>** The ASHRAE PMP Basic Level water protocol requires users to normalize water consumption of the building by the number of occupants or landscape areas. However, there are no clear guidelines about how to estimate and track the number of occupants and/or irrigated landscape areas associated with a building.
- **<u>Issue W-4:</u>** The water performance metrics required at the ASHRAE PMP Intermediate Level are the annual and monthly water use index (WUI) separately for a total building, landscape, and wastewater. Unfortunately, the current version of the ASHRAE PMP does not provide any external-reference benchmarking data for these metrics. However, there are separate benchmarks for the annual index that can be directly comparable to the required Intermediate Level water performance metrics based on the findings in Section 5.2.1.3.
- **<u>Issue W-5:</u>** There are few detailed analysis techniques or modeling methods to analyze and evaluate a building's water performance beyond a log of the calculated WUIs. For example, the ASHRAE PMP water protocol does not require normalizing water use data for weather, it is hard to confirm whether this high increase was affected by changing weather conditions or other operation and maintenance (O&M) issues. In the current version of the ASHRAE PMP in the Section on Performance Evaluation/Benchmarking, several water savings strategies are discussed instead of evaluation/benchmarking methods. Although these savings strategies are helpful information for the users, they do not provide information about any benchmarks.

5.3. IEQ (Thermal Comfort, IAQ, Lighting, and Acoustics)

5.3.1. *Level I: Basic Level*

5.3.1.1. <u>Performance Metrics</u>

The IEQ performance metrics required at the Basic Level are the results of the occupant IEQ satisfaction survey and spot measurements of several IEQ parameters. First, paper-based IEQ assessment questionnaire surveys were conducted using the survey tool developed by the CBE at the University of California, Berkeley for the summer (May 2010) and winter (February 2011) periods. Follow-up spot measurements of several IEQ parameters were then performed in June 2010 for 17 offices.

a) IEQ Satisfaction Survey

- Demographic and workspace information

Figures 78 to 83 present the frequency and percentage distributions of respondents' demographic information for the summer and winter surveys, including: years worked in the building, years worked at the workstation, weekly working hours, job description, age, and gender. The surveys revealed that more than 80% of respondents worked in the case-study building over one year for both the summer and winter surveys. About 72% and 60% of summer and winter survey respondents, respectively, had worked at their present workspace more than one year. In a typical week, most respondents (87% and 75% of summer and winter respondents, respectively) spent more than 30 hours in their workspace. The job description of respondents varied. The three most common occupational groups of the respondents were administrative support (38% for summer and 45% for winter), professional (30% for summer and 23% for winter), and managerial/supervisory (21% for summer and 18% for winter). By age, about 49% and 41% of summer and winter respondents, respectively, were in their thirties or forties, and about 37% of summer respondents and 44% of winter respondents were over fifty years old. The respondents were composed of 55% females and 45% males in the summer survey and 64% females and 36% males in the winter survey.

Figures 84to 88 present the frequency distributions of respondents' workspace information for the summer and winter surveys, including: space type, floor, orientation, and nearness to an exterior wall as well as nearness to a window. About 83% and 65% of summer and winter survey respondents, respectively, worked in enclosed, private offices. Relatively fewer responses were collected from the offices on the first and seventh floors as well as the interior (core) offices. The majority of respondents had an exterior wall or a window within 15 feet of their workspaces; 86% (summer) and 76% (winter) had an exterior wall, and 84% (summer) and 77% (winter) had a window.

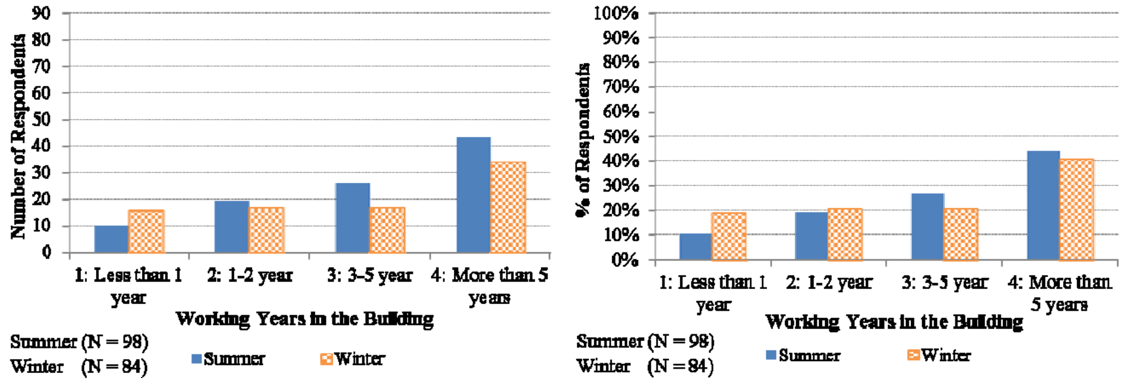


Figure 78: Respondent Demographics: Working Years in the Building

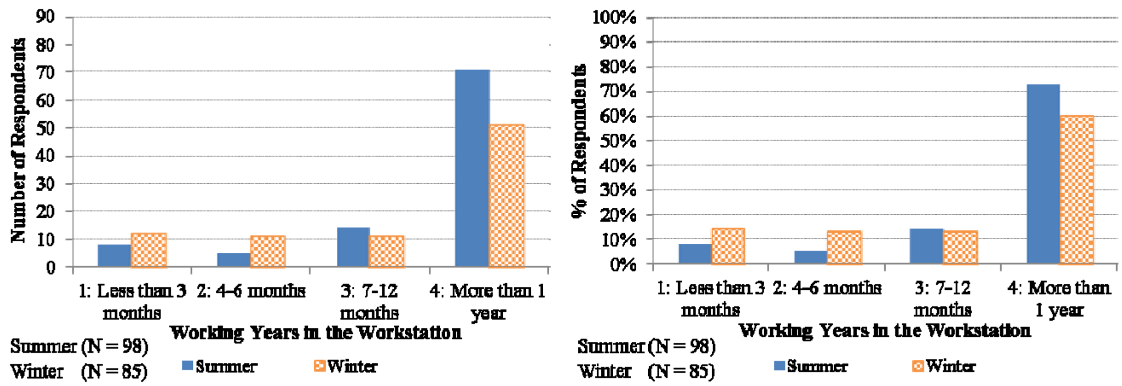


Figure 79: Respondent Demographics: Working Years in the Workstation

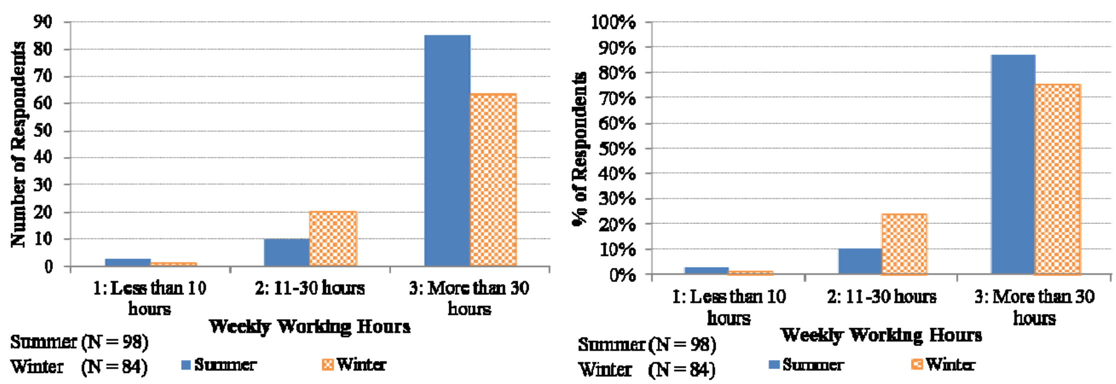


Figure 80: Respondent Demographics: Weekly Working Hours

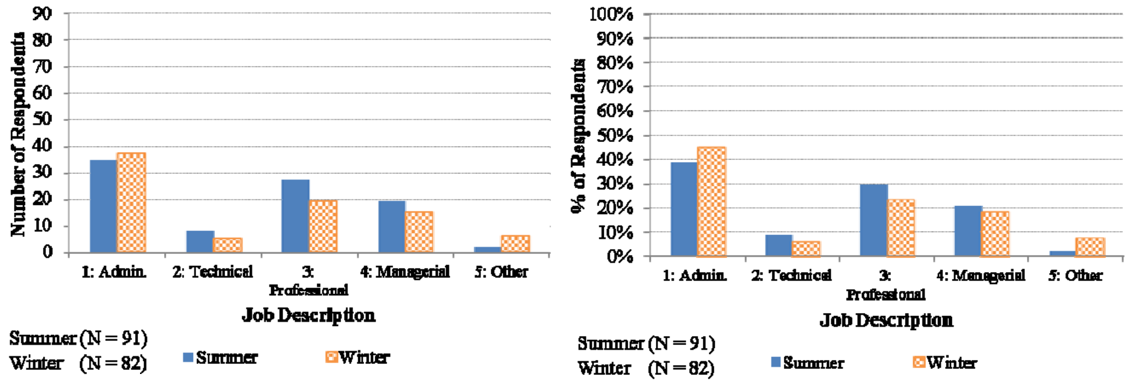


Figure 81: Respondent Demographics: Job Description

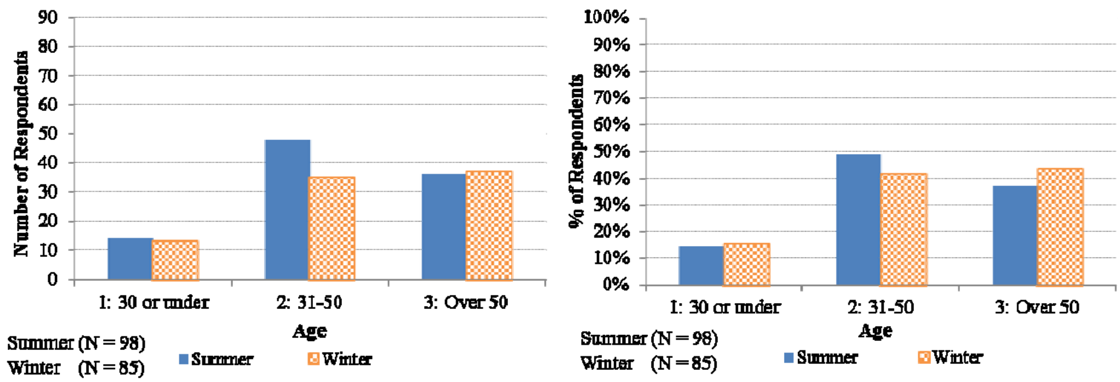


Figure 82: Respondent Demographics: Age

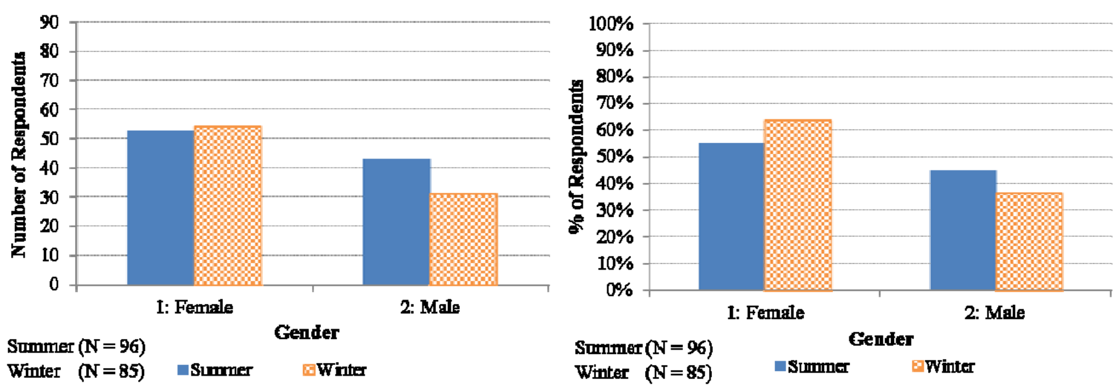


Figure 83 Respondent Demographics: Age

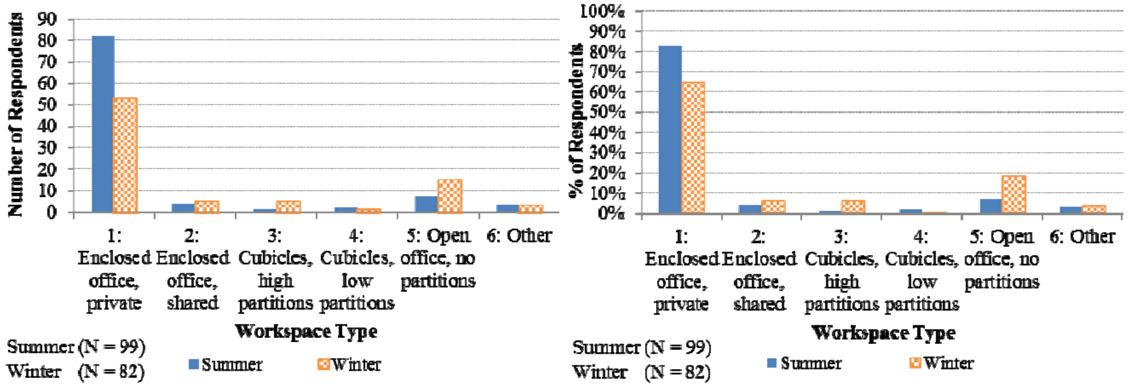


Figure 84: Respondent Workspace Information: Type

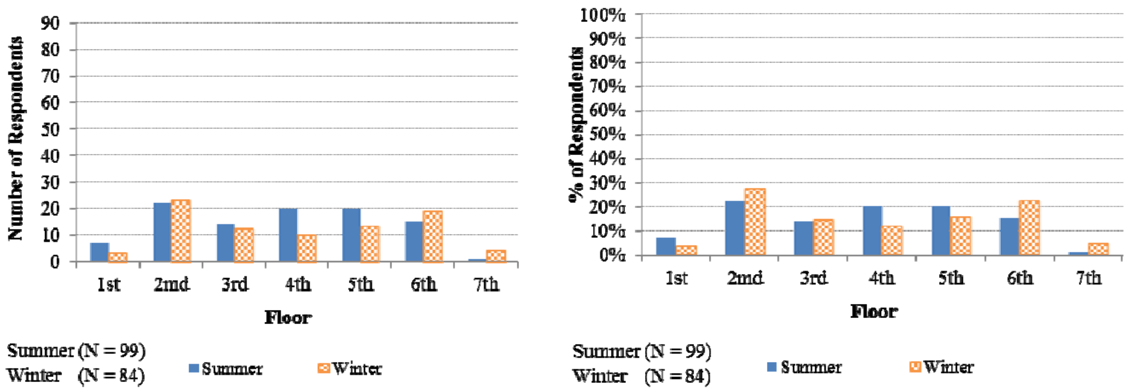


Figure 85: Respondent Workspace Information: Floor

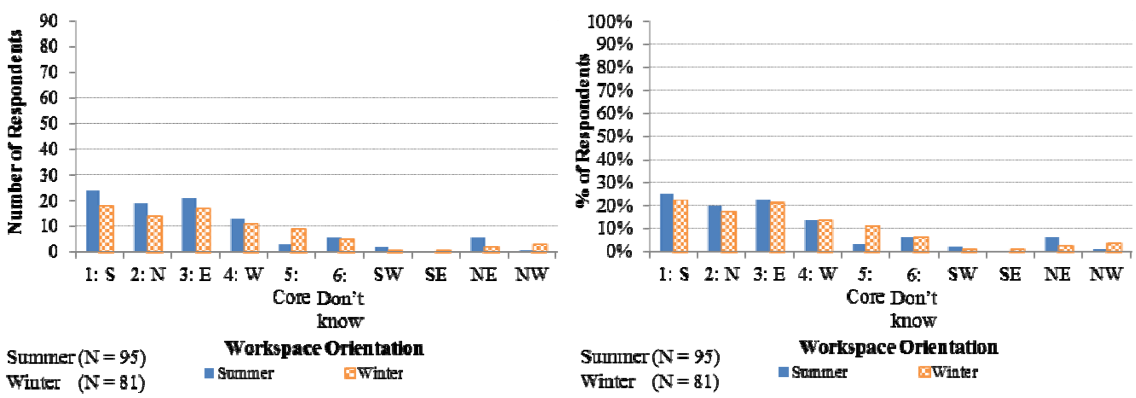


Figure 86: Respondent Workspace Information: Orientation

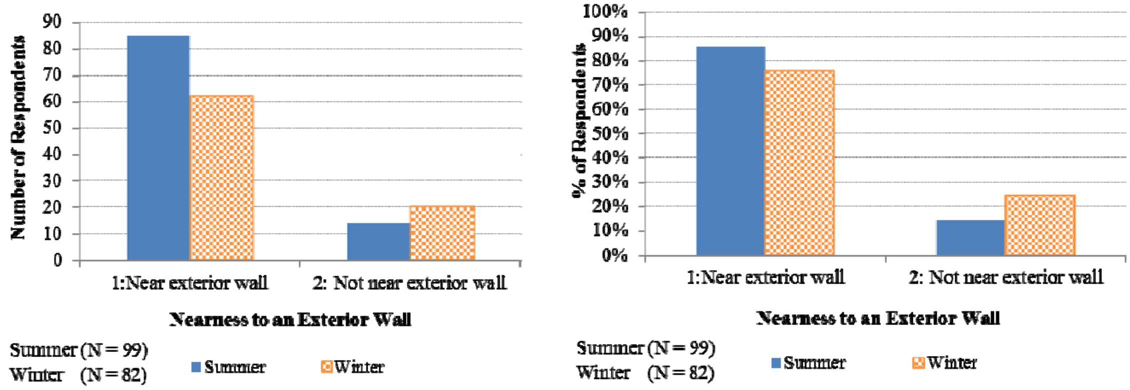


Figure 87: Respondent Workspace Information: Nearness to an Exterior Wall

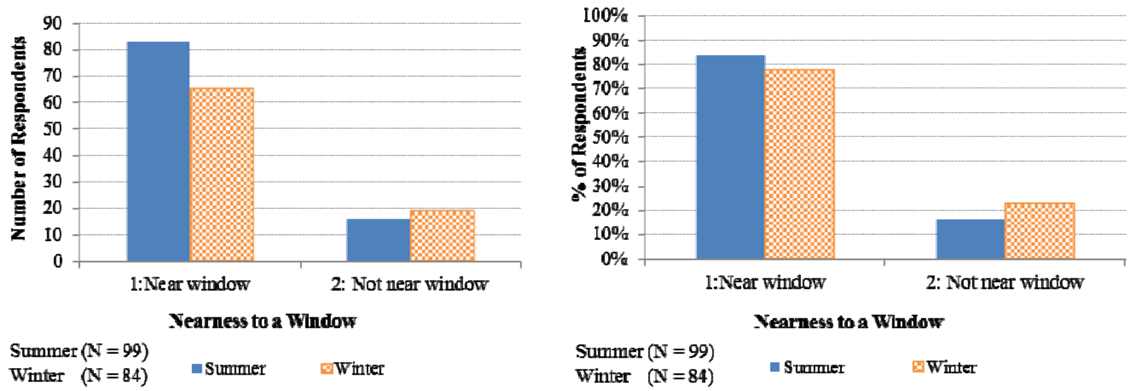


Figure 88: Respondent Workspace Information: Nearness to a Window

- Surveyed IEQ satisfaction and self-reported productivity

Table 24 shows the frequency distributions of surveyed IEQ satisfaction and self-reported productivity for summer and winter periods with the mean scores calculated based on a 7-point satisfaction and productivity scales (3: very satisfied, 0: neutral, -3: very dissatisfied; and 3: enhances, 0: neutral, -3: interferes). On average, the survey respondents were satisfied with their IEQ environments with positive mean satisfaction and productivity scores for all four areas (i.e., thermal comfort, IAQ, lighting, and acoustics). The highest mean satisfaction and productivity scores were observed in the responses for lighting (2.11 (summer) and 2.13 (winter) for lighting level satisfaction; 1.85 (summer) and 1.84 (winter) for visual comfort satisfaction; and 1.69 (summer) and 1.56 (winter) for productivity), followed by IAQ (1.28 (summer) and 1.41 (winter) for satisfaction; and 1.21 (summer) and 1.10 (winter) for productivity). The mean scores of the responses for acoustics are: 1.13 (summer) and 1.10 (winter) for noise level satisfaction; and 0.89 (summer) and 0.63 (winter) for sound privacy satisfaction; and 1.00 (summer) and 0.84 (winter) for productivity. The responses for thermal comfort yielded the lowest mean scores: 0.68 (summer) and 0.71 (winter) for satisfaction; and 0.87 (summer) and 0.80 (winter) for productivity

Frequency-wise, more than 20% of respondents were not satisfied with their thermal environments and sound privacy: 30% (summer) and 28% (winter) dissatisfied with thermal comfort; and 22% (summer) and 28% (winter) dissatisfied with sound privacy. More than 20% of respondents also reported that the perceived thermal comfort in their workspace interfered with their job performance. On the other hand, the responses for lighting level and visual comfort yielded the highest satisfaction percentages: 92% (summer) and 90% (winter) satisfied with lighting level; and 84% (summer) and 84% (winter) satisfied with visual comfort.

Table 24: Frequency Distribution of Surveyed IEQ Satisfaction and Self-Reported Productivity with Mean Scores for Summer and Winter

		Thermal Comfort				**IAQ**				**Lighting**						**Acoustics**					
		Satisfaction		Productivity		Satisfaction		Productivity		Satisfaction (Lighting Level)		Satisfaction (Visual Comfort)		Productivity		Satisfaction (Noise Level)		Satisfaction (Sound Privacy)		Productivity	
Summer (N=99)																					
-3	**Very dissatisfied (Interferes)**	6	6%	6	6%	4	4%	3	3%	1	1%	2	2%	1	1%	3	3%	8	8%	2	2%
-2		11	11%	2	2%	1	1%	1	1%	2	2%	1	1%	0	0%	6	6%	3	3%	4	4%
-1		13	13%	11	12%	11	11%	4	4%	2	2%	6	6%	5	5%	8	8%	10	11%	9	9%
0	**Neutral**	4	4%	18	19%	8	8%	26	27%	3	3%	7	7%	18	19%	13	13%	8	8%	21	22%
1		28	28%	18	19%	22	22%	14	15%	14	14%	12	12%	10	11%	21	21%	26	27%	19	20%
2		19	19%	22	23%	28	29%	27	28%	26	27%	28	28%	24	25%	22	22%	21	22%	21	22%
3	**Very satisfied (Enhances)**	18	18%	18	19%	24	24%	21	22%	50	51%	43	43%	37	39%	25	26%	19	20%	19	20%
Mean Scores		***0.68***		***0.87***		***1.28***		***1.21***		***2.11***		***1.85***		***1.69***		***1.13***		***0.89***		***1.00***	
Winter (N=83)																					
-3	**Very dissatisfied (Interferes)**	7	8%	0	0%	1	1%	0	0%	0	0%	0	0%	0	0%	3	4%	7	8%	3	4%
-2		7	8%	7	9%	5	6%	1	1%	0	0%	2	2%	2	2%	7	8%	8	10%	1	1%
-1		10	12%	12	15%	3	4%	5	6%	5	6%	9	11%	5	6%	6	7%	8	10%	11	13%
0	**Neutral**	6	7%	13	16%	13	16%	29	35%	3	4%	2	2%	12	15%	8	10%	7	8%	21	25%
1		19	22%	18	22%	12	15%	12	14%	12	14%	11	13%	16	20%	19	23%	23	28%	15	18%
2		22	26%	22	27%	23	28%	24	29%	20	24%	22	27%	20	24%	19	23%	16	19%	19	23%
3	**Very satisfied (Enhances)**	14	16%	10	12%	24	30%	13	15%	44	52%	37	45%	27	33%	21	25%	14	17%	13	16%
Mean Scores		***0.71***		***0.80***		***1.41***		***1.10***		***2.13***		***1.84***		***1.56***		***1.10***		***0.63***		***0.84***	

- Sources of discomfort

Figures 89 to 92 present the frequency distributions of the responses to the branching questions that asked the sources of discomfort for each IEQ topic area: thermal comfort, IAQ, lighting, and acoustics. The common major sources of thermal discomfort for both summer and winter include hot/cold complaints in workspace (19% and 15% of summer and winter responses, respectively), inaccessible thermostat (18% and 13% of summer and winter responses, respectively), incoming sun (11% and 11% of summer and winter responses, respectively), and thermostats adjusted by other people (10% and 11% of summer and winter responses, respectively), as shown in Figure 89. In summer, there were about 15% of responses that complained about the cooling and heating systems that did not respond quickly enough to the thermostat changes, but only 5% of responses in winter complained about it. On the other hand, about 11% of responses in winter rated drafts from vents and windows as a discomfort source, while no one complained about drafts in summer.

The major IAQ discomfort source was identified as stuffy or stale air for both summer and winter, followed by unclean air and odors, as shown in Figure 90. About 84% and 86% of summer and winter responses, respectively, perceived stuffy or stale air as major or minor IAQ problems. There were about 67% of responses for both summer and winter that complained about unclean air, and about 65% and 59% of summer and winter responses, respectively, rated odors as major or minor IAQ problems. The identified sources of odors causing discomfort varied, including carpet or furniture, cleaning products, food, photocopies, outside source, tobacco smoke, and perfume.

Few people complained about lighting quality of the case-study building, and the identified sources of lighting discomfort varied, as shown in Figure 91. For acoustics, the major three discomfort sources were related to people: people talking in neighboring areas, (23% and 21% of summer and winter responses, respectively), people overhearing my private conversations (16% and 21% of summer and winter responses, respectively), and people talking on the phone while the respondents did not want to hear them (15% and 18% of summer and winter responses, respectively), as shown in Figure 92. The other discomfort sources identified include telephones ringing, mechanical noise, echoing sounds, outdoor noise, and office equipment noise.

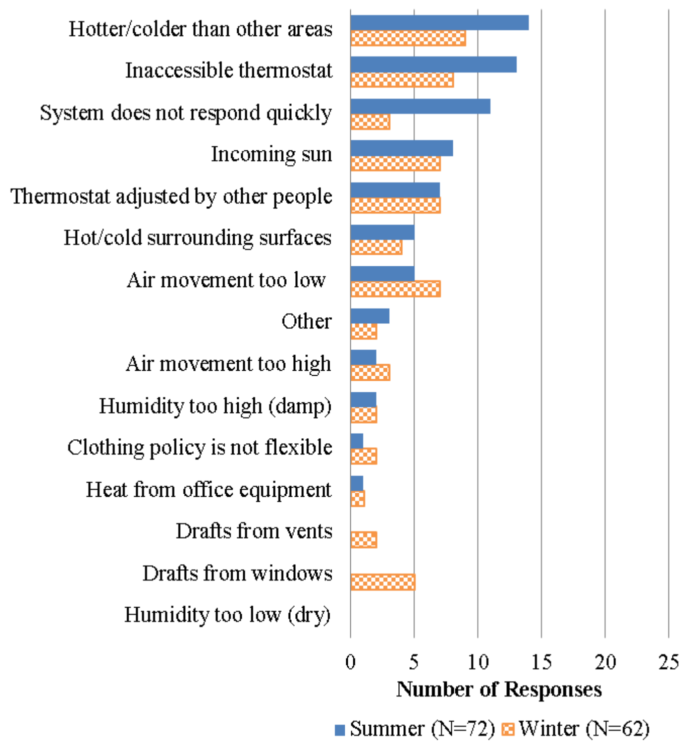


Figure 89: Source of Thermal Discomfort

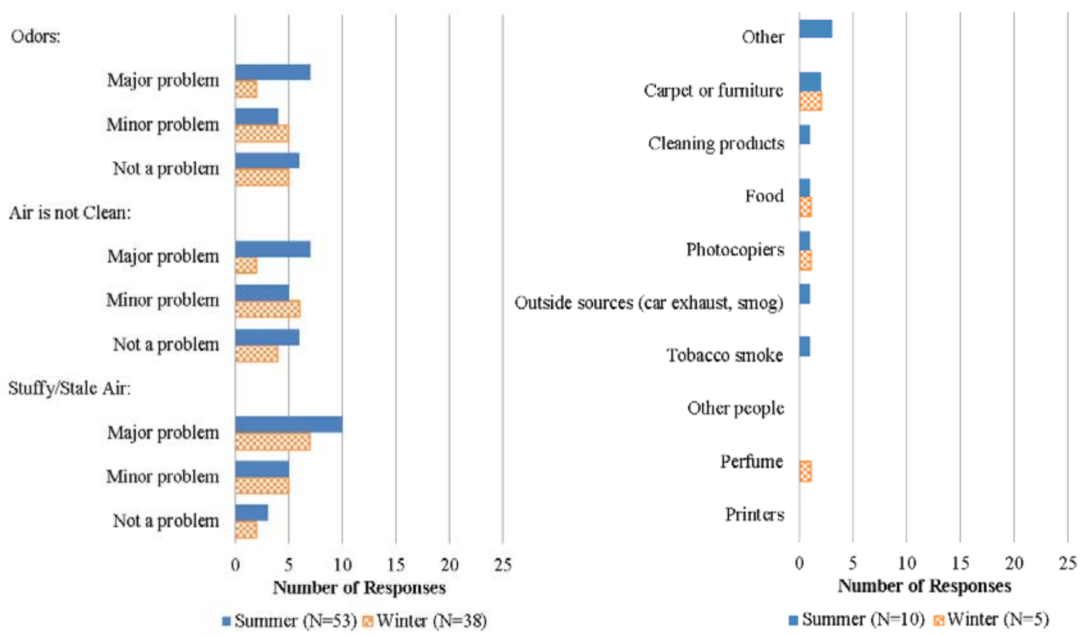


Figure 90: Sources of IAQ Discomfort

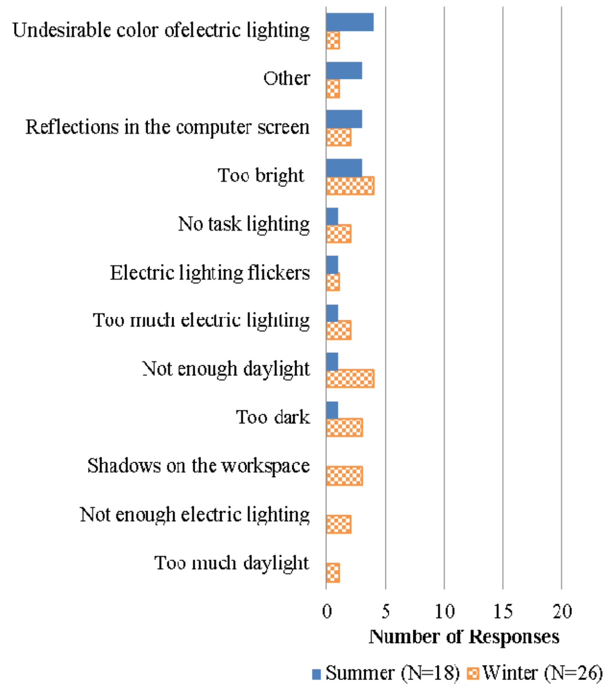


Figure 91: Source of Lighting Discomfort

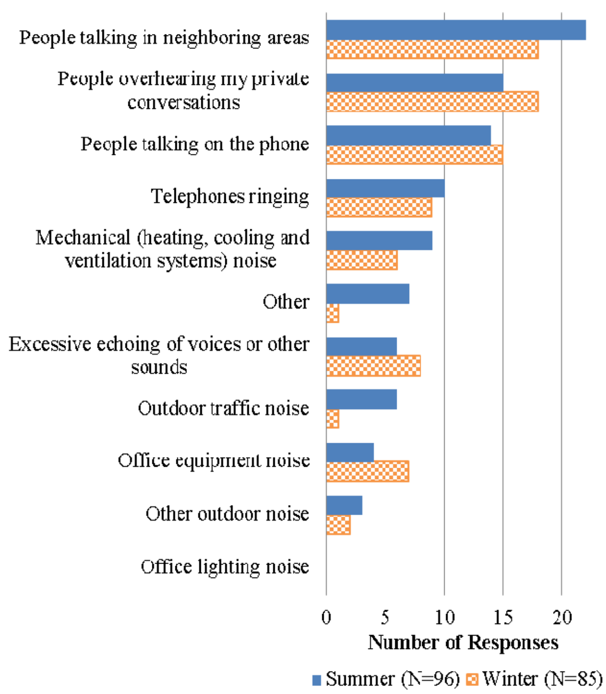


Figure 92: Sources of Acoustics Discomfort

- Comparison of IEQ Satisfaction Survey Results between Summer and Winter

Between seasons, there were few differences in mean values as well as frequency distributions of IEQ satisfaction and self-reported productivity scores. Table 25 shows the results of independent samples t-test conducted to compare the mean satisfaction and productivity scores between summer and winter[117]. In the table, the mean satisfaction and productivity scores of two groups (i.e., summer versus winter) are presented in the fourth column with the corresponding standard deviation in the fifth column. The sixth column lists the standard error of the mean, which is the standard deviation of the sampled, mean satisfaction and productivity scores relative to the true population mean. The seventh column lists *p*-values from the t-test that indicates statistical significance to determine whether the null hypothesis is true or not. The last column lists a 95% confidence interval calculated on the difference between the summer and winter survey results. If the estimated range includes zero, it means there is no significant difference in the means of the surveyed respondents between the summer and winter surveys at a 95% confidence level.

The null hypothesis was that the mean satisfaction and productivity scores of two groups (i.e., summer versus winter) are the same, which essentially states that there are no seasonal influences on the occupants' subjective IEQ assessments. For all four IEQ areas (i.e., thermal comfort, IAQ, lighting and acoustics), the null hypothesis failed to be rejected with high *p*-values over 0.10, which means that no significant differences were found between summer and winter groups.

Table 26 shows the results of paired samples t-test (i.e., dependent samples t-test) to observe seasonal changes within the same population (i.e., 23 paired data) in the same format as Table 25 above. The null hypothesis was that the mean difference of paired satisfaction and productivity scores between summer and winter is zero, which basically states no seasonal changes in the paired responses. As a result, the null hypothesis failed to be rejected with high *p*-values over 0.10 for all four IEQ areas except one: lighting level satisfaction. Summer lighting level satisfaction was lower than winter satisfaction with a marginal significance ($p = 0.10$).

[117] An independent samples t-test was performed since the surveys were conducted using random sampling.

Table 25: Summary Statistics of Comparison between Summer and Winter Mean Satisfaction and Productivity Scores Using Independent Samples T-Test

	Season	N	Mean	Std. Deviation	Std. Error Mean	p-value	95% Confidence Interval of the Difference	
							Lower	Upper
Thermal Comfort								
Satisfaction	Summer	99	0.68	1.84	0.18	0.92	-0.57	0.51
	Winter	85	0.71	1.86	0.20	*(Not significant)*		
Productivity	Summer	95	0.87	1.69	0.17	0.78	-0.41	0.55
	Winter	82	0.80	1.50	0.17	*(Not significant)*		
IAQ								
Satisfaction	Summer	98	1.28	1.58	0.16	0.58	-0.60	0.33
	Winter	81	1.41	1.55	0.17	*(Not significant)*		
Productivity	Summer	96	1.21	1.47	0.15	0.58	-0.29	0.52
	Winter	84	1.10	1.27	0.14	*(Not significant)*		
Lighting								
Satisfaction: Lighting Level	Summer	98	2.11	1.24	0.13	0.92	-0.37	0.33
	Winter	84	2.13	1.16	0.13	*(Not significant)*		
Satisfaction: Visual Comfort	Summer	99	1.85	1.43	0.14	0.98	-0.41	0.42
	Winter	83	1.84	1.43	0.16	*(Not significant)*		
Productivity	Summer	95	1.69	1.38	0.14	0.52	-0.28	0.54
	Winter	82	1.56	1.37	0.15	*(Not significant)*		
Acoustics								
Satisfaction: Noise Level	Summer	98	1.13	1.66	0.17	0.89	-0.46	0.53
	Winter	83	1.10	1.73	0.19	*(Not significant)*		
Satisfaction: Sound Privacy	Summer	95	0.89	1.78	0.18	0.33	-0.27	0.81
	Winter	83	0.63	1.86	0.20	*(Not significant)*		
Productivity	Summer	95	1.00	1.54	0.16	0.50	-0.30	0.61
	Winter	83	0.84	1.53	0.17	*(Not significant)*		

Table 26: Summary Statistics of Comparison between Summer and Winter Mean Satisfaction and Productivity Scores Using Paired Samples T-Test

	Season	N	Mean	Std. Deviation	Std. Error Mean	*p*-value	95% Confidence Interval of the Difference	
							Lower	Upper
Thermal Comfort								
Satisfaction	Summer	23	1.04	1.64	0.34	0.77	-0.70	0.52
	Winter	23	1.13	1.87	0.39	*(Not significant)*		
Productivity	Summer	23	1.13	1.71	0.36	0.77	-0.51	0.68
	Winter	23	1.04	1.22	0.26	*(Not significant)*		
IAQ								
Satisfaction	Summer	23	1.17	1.70	0.35	0.43	-0.93	0.41
	Winter	23	1.43	1.50	0.31	*(Not significant)*		
Productivity	Summer	23	0.96	1.66	0.35	0.33	-0.67	0.23
	Winter	23	1.17	1.37	0.29	*(Not significant)*		
Lighting								
Satisfaction: Lighting Level	Summer	23	1.52	1.81	0.38	0.10 (Marginally significant)	-1.24	0.11
	Winter	23	2.09	1.08	0.23			
Satisfaction: Visual Comfort	Summer	23	1.57	1.73	0.36	0.25	-0.83	0.22
	Winter	23	1.87	1.25	0.26	*(Not significant)*		
Productivity	Summer	23	1.57	1.59	0.33	0.23	-0.21	0.82
	Winter	23	1.26	1.36	0.28	*(Not significant)*		
Acoustics								
Satisfaction: Noise Level	Summer	23	1.00	1.73	0.36	0.72	-0.42	0.59
	Winter	23	0.91	1.86	0.39	*(Not significant)*		
Satisfaction: Sound Privacy	Summer	23	0.87	1.84	0.38	0.77	-0.51	0.68
	Winter	23	0.78	2.02	0.42	*(Not significant)*		
Productivity	Summer	22	0.77	1.72	0.37	0.58	-0.36	0.64
	Winter	22	0.64	1.68	0.36	*(Not significant)*		

b) Follow-Up Spot Measurements

The results of follow-up spot measurements were also analyzed to discover possible causes of the problems identified from the survey as recommended in the ASHRAE PMP. Table 27 presents the results of IEQ spot measurements performed in June 2010 for 17 offices, which was the follow up to the IEQ satisfaction survey in May 2010: ten offices where occupants were dissatisfied with their IEQ environments (i.e., thermal comfort, IAQ, lighting, or acoustics), seven additional offices where occupants were satisfied. In the table, the second through the fourth columns show a brief description of respondents' workspace information, including, space type (i.e., P: Private and S: Shared), orientation, and floor. The fifth through the tenth columns list the surveyed IEQ satisfaction scores using a 7-point satisfaction scale (3: very satisfied, 0: neutral, -3: very dissatisfied) for thermal comfort, IAQ, lighting level, visual comfort, noise level, and sound privacy. Lastly, the eleventh through twentieth columns provide the results of follow-up spot measurements, including: air temperature, relative humidity, mean radiant temperature (MRT), operative temperature, predicted mean vote (PMV), predicted percentage of dissatisfied (PPD %), CO_2, horizontal illuminance level on the work plane, vertical illuminance level on the computer monitor, and A-weighted equivalent sound pressure levels (LAeq). The shaded cells indicate the responses and spot measurement results of the dissatisfied groups for the corresponding performance area.

Table 28 shows summary statistics of spot measurement results by occupants' satisfactions which were collected in the first, summer satisfaction survey, along with the results of independent samples t-test in the same format as Tables 25 and 26 above. The tested null hypothesis was that the measured values of selected IEQ performance metrics of two groups (i.e., dissatisfied versus satisfied) are the same. The null hypothesis failed to be rejected with *p*-values larger than 0.10 (i.e., which means that no significant differences were found between dissatisfied and satisfied groups) for all IEQ performance metrics except two: PPD (%) between satisfied and dissatisfied groups with their thermal comfort; and vertical illuminance (fc) between satisfied and dissatisfied groups with their visual comfort. The mean PPD (%) of a thermally dissatisfied group was higher than that of a satisfied group with a marginal significance ($p = 0.10$). A dissatisfied group with their visual comfort had a lower vertical illuminance than a satisfied group with a *p*-value of 0.05.

Table 27: Results of Follow-Up Spot Measurements in Summer (June 2010) for 17 Offices

ID	Workspace Descriptoin			Surveyed IEQ Satisfaction						Results of Follow-Up Spot Measurements									
	Type[1]	Orientation	Floor	Thermal Comfort	IAQ	Lighting Level	Visual Comfort	Noise Level	Sound Privacy	Air Temperature (F)	Relative Humidity (%)	MRT (F)	Operative Temperature (F)	PMV	PPD (%)	CO	Horizontal Illuminance (fc)	Vertical Illuminance (fc)	LAeq (dBA)
1	P	NE	1st	1	1	1	0	-2	-1	75.5	44.4	76.0	75.7	0.00	5.00	735	41.5	26.5	44.7
2	P	N	2nd	-2	3	3	3	3	3	76.2	43.3	76.8	76.5	-0.31	7.01	703	19.6	13.7	55.7
3	P	N	2nd	-2	3	2	1	-1	3	71.8	49.1	73.9	72.9	-0.37	7.89	700	62.9	45.2	49.8
4	P	E	2nd	1	-3	-2	-1	-1	-1	73.8	49.9	74.4	74.1	-0.04	5.03	723	56.1	15.5	52.8
5	P	NE	3rd	-3	0	3	0	3	3	77.0	42.5	78.9	77.9	0.34	7.35	656	90.1	93.7	45.3
6	S	Core	3rd	1	0	-1	-1	0	-3	74.1	43.3	74.8	74.5	0.39	8.20	719	23.7	7.0	50.9
7	P	N	4th	0	0	2	2	-3	-3	75.1	51.3	75.6	75.3	-0.02	5.01	708	61.8	40.7	46.2
8	P	W	5th	-2	3	3	3	3	3	75.6	43.4	77.3	76.4	0.10	5.20	763	19.4	57.5	49.9
9	S	E	5th	-3	1	0	-1	-3	-3	76.1	40.6	76.6	76.3	0.07	5.12	746	2.4	1.3	60.6
10	P	W	6th	-2	3	3	3	-2	2	76.4	42.9	77.0	76.7	0.22	5.96	780	42.5	27.6	53.6
11	P	S	1st	1	2	2	2	3	3	75.7	44.7	76.6	76.2	0.07	5.10	683	38.3	18.4	45.9
12	P	N	2nd	3	2	3	3	1	1	74.9	46.1	75.8	75.4	-0.05	5.06	655	18.7	16.5	58.4
13	P	S	2nd	1	1	3	2	3	3	75.4	43.8	76.0	75.7	-0.01	5.00	688	45.5	29.4	50.3
14	P	S	2nd	1	2	3	2	0	0	74.0	44.9	74.6	74.3	-0.15	5.47	686	28.7	22.7	46.1
15	P	N	3rd	1	1	2	2	1	1	75.8	39.1	77.1	76.4	0.07	5.10	662	33.9	20.2	44.2
16	P	NE	4th	3	3	2	2	2	2	75.1	46.3	75.8	75.5	0.04	5.03	724	61.6	37.5	43.1
17	P	S	4th	3	3	3	3	3	3	76.4	46.4	77.0	76.7	0.24	6.19	774	50.8	23.0	46.8

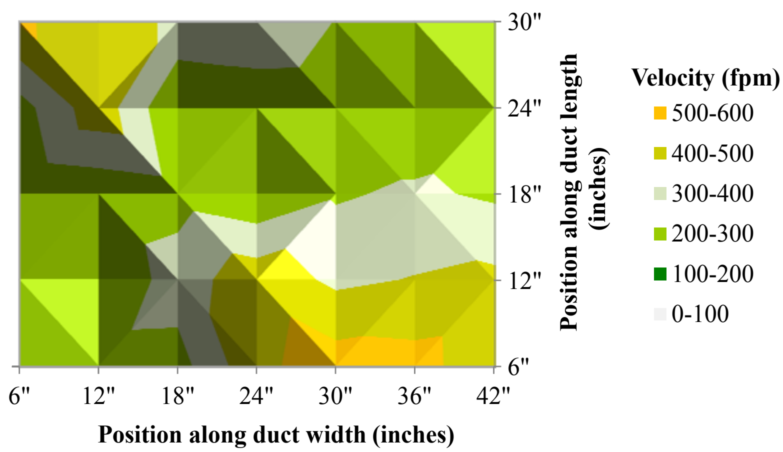
NOTES: The shaded cells indicate the responses and spot measurement results of the dissatisfied groups for the corresponding performance area.
1) P: Private, S: Shared

Table 28: Summary Statistics of IEQ Spot Measurement Comparison between Dissatisfied and Satisfied Groups Using Independent Samples T-Test

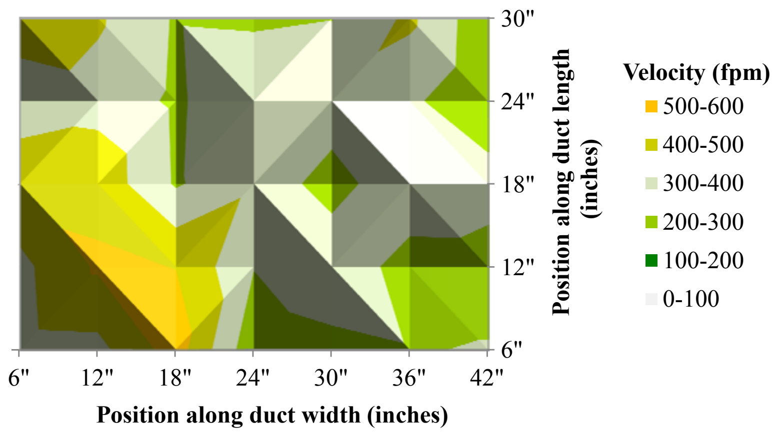
	Season	N	Mean	Std. Deviation	Std. Error Mean	*p*-value	95% Confidence Interval of the Difference	
							Lower	Upper
Thermal Comfort								
Air temp. (F)	Dissatisfied	6	75.52	1.88	0.77	0.50	-0.93	1.82
	Satisfied	11	75.07	0.82	0.25	*(Not significant)*		
RH (%)	Dissatisfied	6	43.63	2.87	1.17	0.26	-5.22	1.54
	Satisfied	11	45.47	3.25	0.98	*(Not significant)*		
MRT (F)	Dissatisfied	6	76.75	1.62	0.66	0.13	-0.33	2.25
	Satisfied	11	75.79	0.91	0.27	*(Not significant)*		
Operative temp. (F)	Dissatisfied	6	76.12	1.68	0.69	0.28	-0.61	1.97
	Satisfied	11	75.44	0.85	0.26	*(Not significant)*		
PMV	Dissatisfied	6	0.01	0.29	0.12	0.70	-0.26	0.18
	Satisfied	11	0.05	0.15	0.04	*(Not significant)*		
PPD (%)	Dissatisfied	6	6.42	1.16	0.47	0.10 (Marginally significant)	-0.17	2.07
	Satisfied	11	5.47	0.97	0.29			
IAQ								
CO_2 (ppm)	Dissatisfied	1	723.00	.	.	0.78	-76.55	99.80
	Satisfied	16	711.38	40.13	10.03	*(Not significant)*		
Lighting: Lighting Level								
Horizontal illuminance (fc)	Dissatisfied	2	39.90	22.91	16.20	0.94	-37.18	34.62
	Satisfied	15	41.18	22.34	5.77	*(Not significant)*		
Vertical illuminance (fc)	Dissatisfied	2	11.25	6.01	4.25	0.22	-54.60	13.91
	Satisfied	15	31.59	22.04	5.69	*(Not significant)*		
Lighting: Visual Comfort								
Horizontal illuminance (fc)	Dissatisfied	3	27.40	27.04	15.61	0.19	-47.29	10.30
	Satisfied	13	45.89	19.77	5.48	*(Not significant)*		
Vertical illuminance (fc)	Dissatisfied	3	7.93	7.15	4.13	0.05 (Marginally significant)	-54.62	0.32
	Satisfied	13	35.08	21.40	5.94			
Acoustics: Noise Level								
LAeq (dBA)	Dissatisfied	6	51.28	5.76	2.35	0.35	-3.08	8.08
	Satisfied	11	48.78	4.83	1.46	*(Not significant)*		
Acoustics: Sound Privacy								
LAeq (dBA)	Dissatisfied	5	51.04	6.29	2.81	0.49	-3.98	7.88
	Satisfied	12	49.09	4.78	1.38	*(Not significant)*		

c) OA Flow Rate Spot Measurements

One-time spot measurement of outdoor air (OA) flow rate was performed at intakes of the two 100% OA AHUs that operate at full speed to provide the SDVAV units with conditioned outside air. The TSI 8360 Velocicalc Plus was used in the spot measurements (Figure 23). Figure 93 presents the measured OA velocity profiles of two OA AHUs using the color-coded air velocity. The cross section of OA intakes (4ft (length) by 3ft (width)) was divided into equal areas, and the air velocity was measured at the center of each area. The average air velocity of OA AHU No.1 and No.2 was 324 fpm and 350 fpm, respectively, which corresponds to 3,891 and 4,195 cfm of OA flow rates[118].



(a) OA AHU No.1



(b) OA AHU No.2

Figure 93: OA Velocity Profiles Measured at Two OA AHUs Intakes

118 The benchmarking results are presented in Section 5.3.1.2.

5.3.1.2. *Performance Evaluation/Benchmarking*

The evaluation of the different IEQ performance metrics was performed by comparing the results to the appropriate benchmarks, including the CBE benchmarking scores for office buildings, the ASHRAE Standard 55-2004 (ASHRAE 2004) and Standard 55-2010 (ASHRAE 2010c), the ASHRAE Standard 62.1-2007 (ASHRAE 2007b) and Standard 62.1-2010 (ASHRAE 2010d), as well as the Table 3-9 and Table 3-10 in the ASHRAE PMP.

a) Results of IEQ Satisfaction Survey

The evaluation of the surveyed occupants' satisfaction scores was performed by comparing the survey results to the CBE benchmarking scores for office buildings that consist of 39,498 responses. Figures 94 and 95 present the mean satisfaction and self-reported productivity scores for summer and winter periods based on a 7-point scale (3: very satisfied, 0: neutral, -3: very dissatisfied) against the corresponding CBE benchmarking scores. The blue squares are CBE benchmarks for offices. The data points on the right side of the blue square dots means better than average while the points on the left side means worse than average. Since both summer and winter data points for satisfaction as well as productivity are located on the right side of the blue squares, on average, the case-study building's IEQ performance is better than average against the CBE benchmarks for all topic areas, including four IEQ areas.

The same results (i.e., better than average) were obtained in a frequency-wise analysis of satisfaction and self-reported productivity against the CBE benchmarks. Figures 96 and 97 present the percentage distributions of surveyed IEQ satisfaction and self-reported productivity for summer and winter along with the CBE benchmarks. In these figures, each plot is comprised of seven color-coded bars based on a 7-point satisfaction/productivity scale (i.e., very satisfied: green, neutral: yellow, dissatisfied: red) that represent the surveyed IEQ and productivity satisfaction scales, along with additional seven blue checked bars showing the CBE benchmarks. Since both summer and winter percentage bars for satisfaction as well as productivity of the case-study building are higher than the CBE benchmarks (blue checkered bars) for the satisfied side but lower than the benchmarks for the dissatisfied side, frequency-wise, the case-study building's IEQ performance is also better than average against the CBE benchmarks.

However, different results were obtained when compared against the ASHRAE Standard 55-2004 (ASHRAE 2004) and Standard 55-2010 (ASHRAE 2010c). In the comparison, more than 20% of occupants were not satisfied with their thermal environment for both summer and winter, as shown in Figure 96, which does not conform to ASHRAE Standard 55-2004 and

Standard 55-2010 that requires 80% acceptability. More than 20% of respondents also reported that the perceived thermal comfort in their workspace interfered with their job performance, as shown in Figure 97. In addition, more than 20% of the occupants were dissatisfied with their sound privacy (Figure 96).

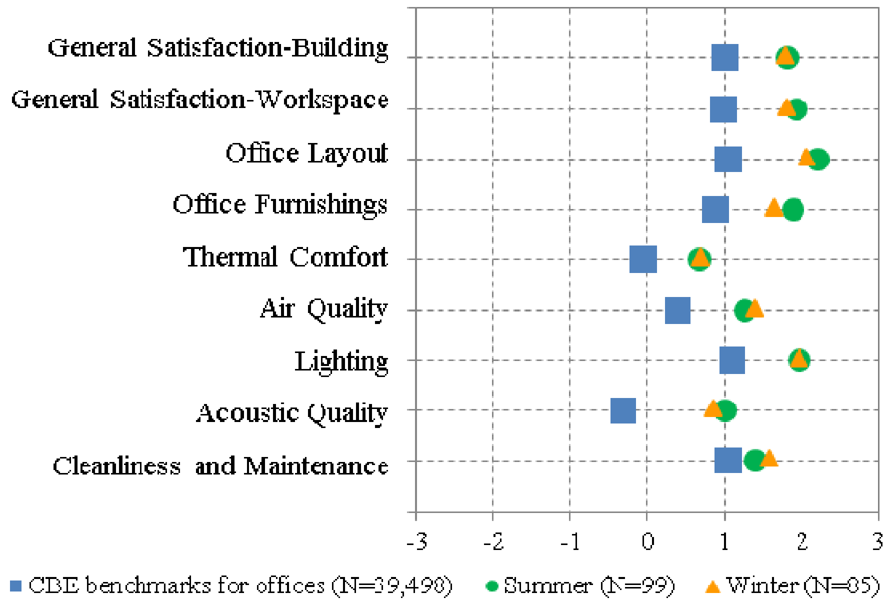


Figure 94: Mean IEQ Satisfaction Scores for Summer (N=99) and Winter (N=85) Compared to the CBE Benchmarking Scores for Offices (N=39,498)

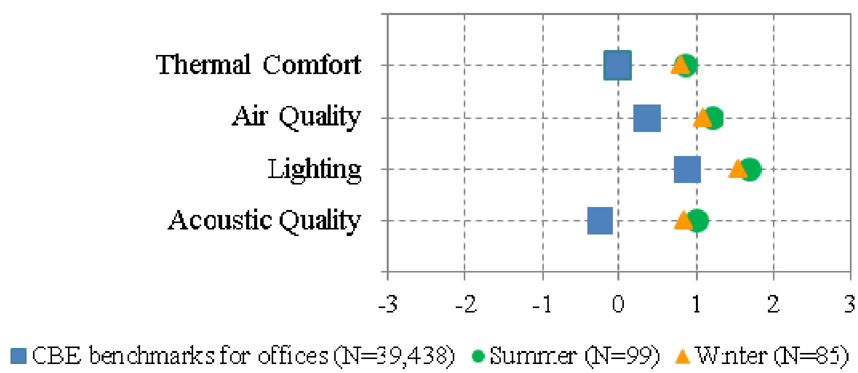
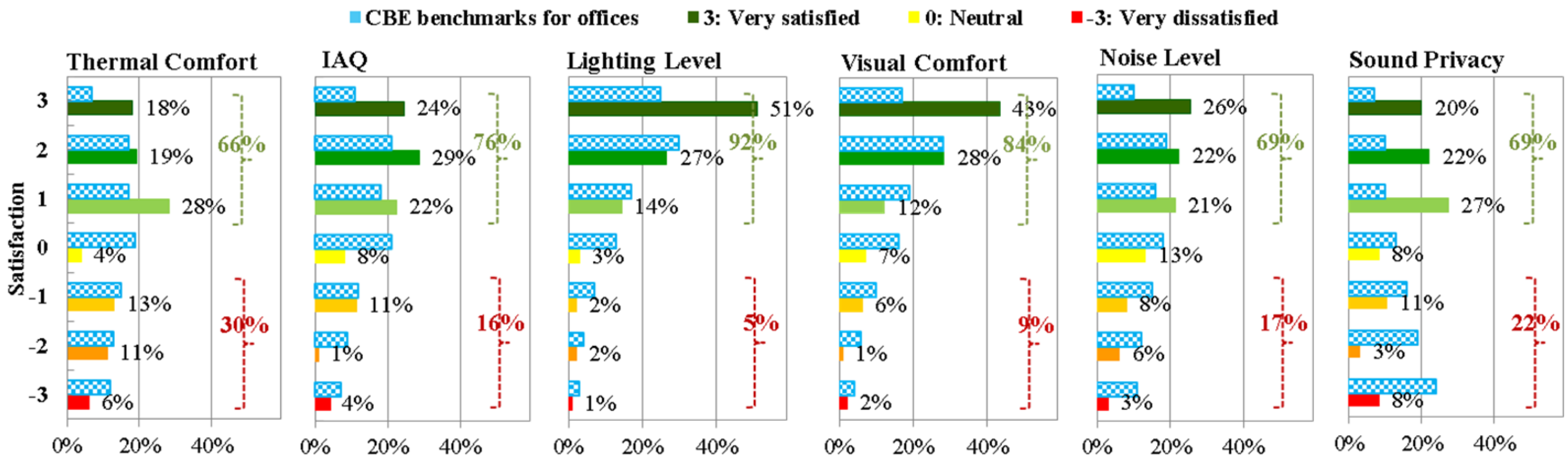
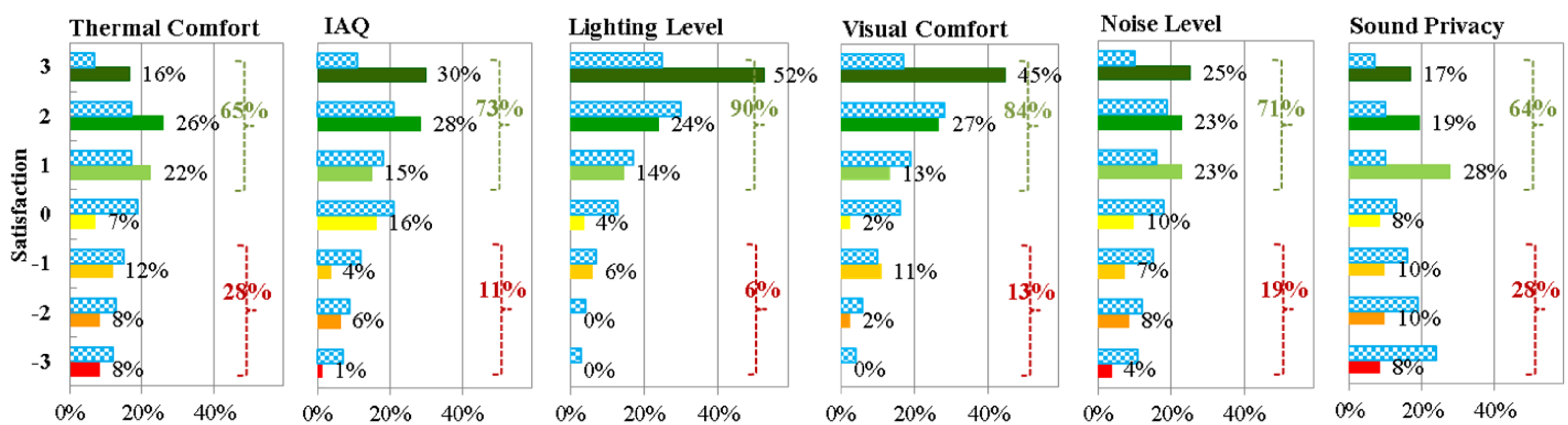


Figure 95: Mean IEQ Self-Reported Productivity Scores for Summer (N=99) and Winter (N=83) Compared to the CBE Benchmarking Scores for Offices (N=39,498)



(a) Summer Results



(b) Winter Results

Figure 96: Percentage Distributions of IEQ Satisfaction for (a) Summer and (b) Winter Compared to the CBE Benchmarking Scores for Offices (N=39,498)

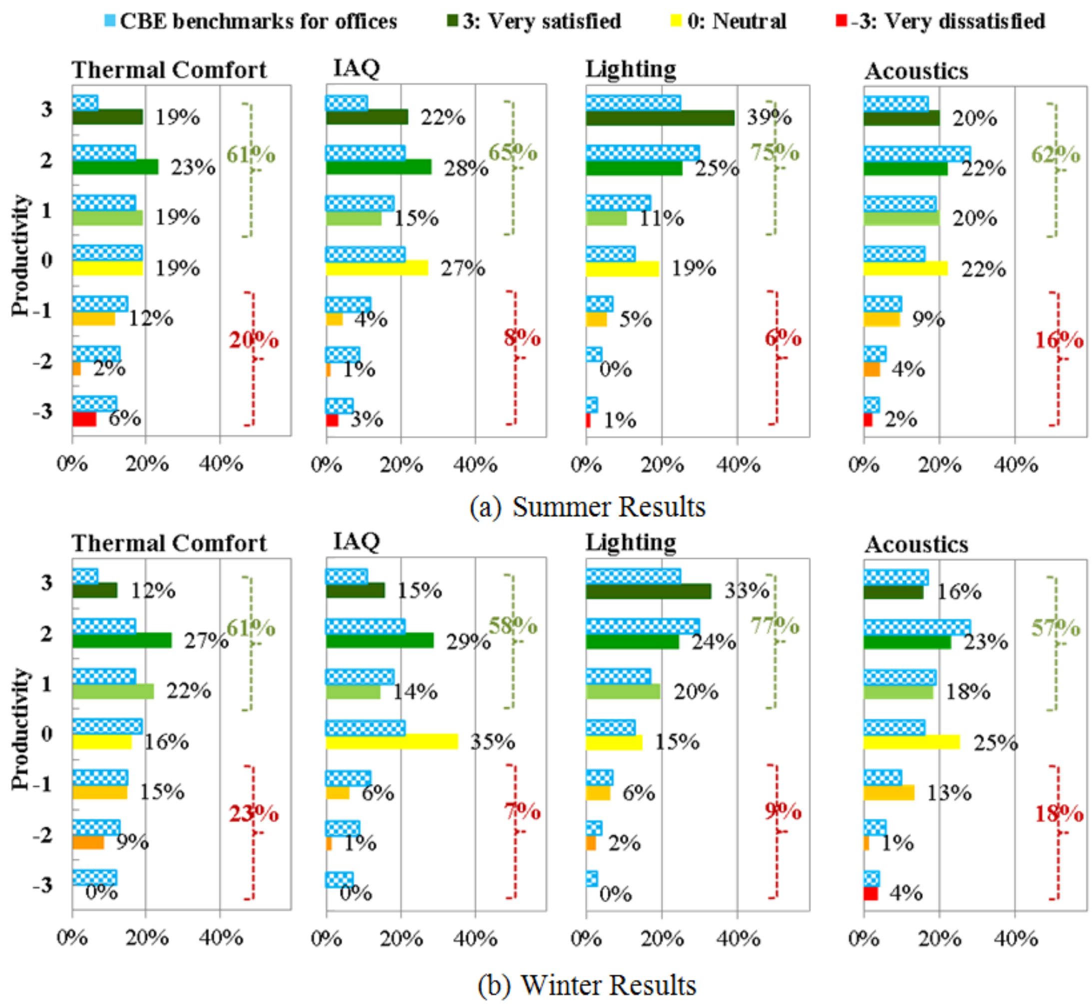


Figure 97: Percentage Distributions of IEQ Productivity for (a) Summer and (b) Winter Compared to the CBE Benchmarking Scores for Offices (N=39,498)

b) Results of Follow-Up Spot Measurements

The results of follow-up spot measurements conducted in June 2010 for 17 offices were also compared against the appropriate benchmarks in the ASHRAE PMP: ASHRAE Standard 55-2004 and Standard 55-2010 for thermal comfort; ASHRAE Standard 62.1-2007 and Standard 62.1-2010 for IAQ; ASHRAE PMP Table 3-9 for lighting; and ASHRAE PMP Table 3-10 for acoustics. Figure 98 shows indoor climate conditions of 17 offices plotted onto the ASHRAE Standard 55-2004 comfort zone[119]. Of the six thermally-dissatisfied offices, only one office (ID 3) was located in the winter comfort zone (1.0 clo), possibly indicating cold discomfort in this office. Few differences were found in the thermal environments between occupants expressing dissatisfaction (six offices) and satisfaction (eleven offices). However, of the six thermally-dissatisfied offices, the indoor climate conditions of two offices (ID 3 and 5) were located slightly outside the group. Of the other four dissatisfied offices, three maintained similar thermal

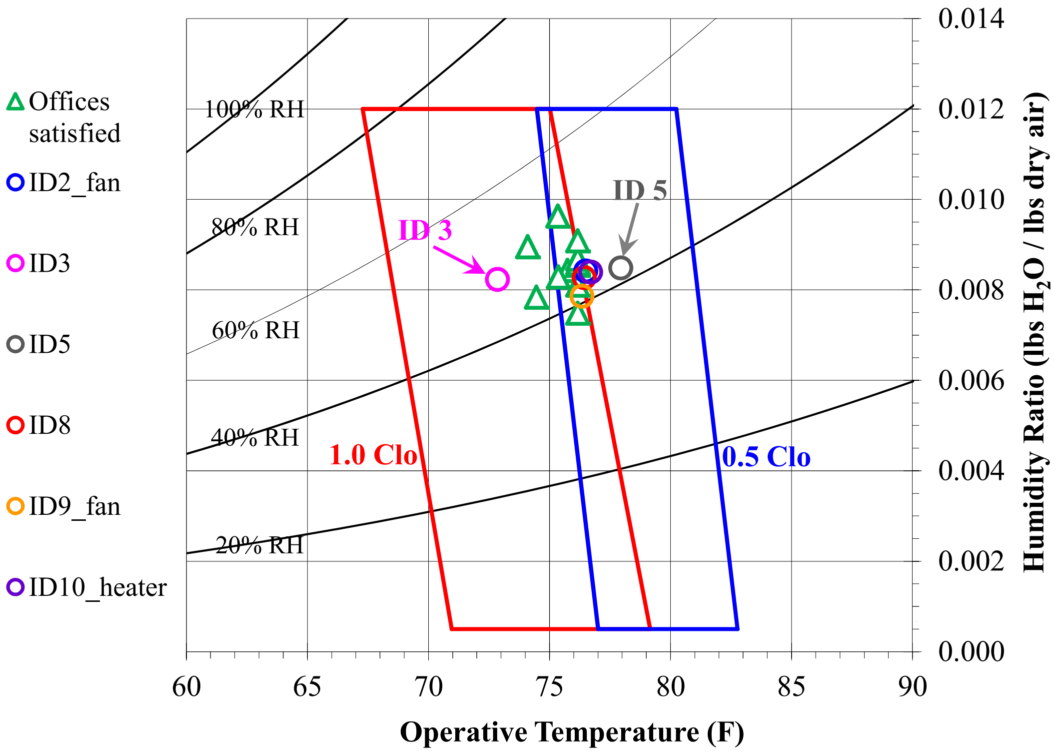


Figure 98: Measured Indoor Climate Conditions of 17 Offices on the ASHRAE Standard 55-2004 Comfort Zones: 1.0 Clo for Winter and 0.5 Clo for Summer

[119] The ASHRAE Standard 55-2004 comfort zone consists of two zones. The left zone in red is for 1.0 clo of clothing insulation which is the insulation level of clothing typically worn in winter, while the right zone in blue is for 0.5 clo of insulation which is the insulation level of clothing typically worn in summer.

environments as the satisfied offices using personal fans and a heater[120].

Figure 99 presents CO_2 concentrations measured in the 17 offices against the ASHRAE Standard 62.1-2007 and Standard 62.1-2010 benchmarks. The measured CO_2 concentrations of all 17 offices were below 950 ppm, corresponding to 8.5 L/s per person of outdoor air rate which is the minimum ventilation rate for office spaces in the ASHRAE 62.1-2010[121]. No differences were identified from the measurements of CO_2 between the offices where occupants expressing dissatisfaction (one office) versus satisfaction (sixteen offices). The use of CO_2 spot measurements did not reveal the source of IAQ dissatisfaction. This may be partly affected by the nature of spot measurements[122] since the measured CO_2 concentrations may be lower than the maximum CO_2 concentrations in the space.

Figure 100 shows horizontal and vertical illuminance measured in the 17 offices compared to the ASHRAE PMP Table 3-9. Of the two dissatisfied offices, the horizontal

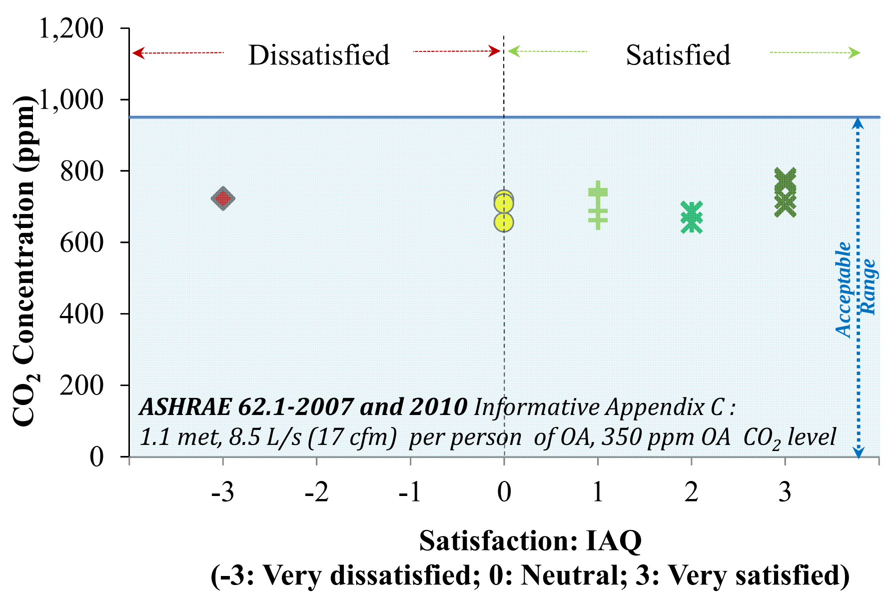
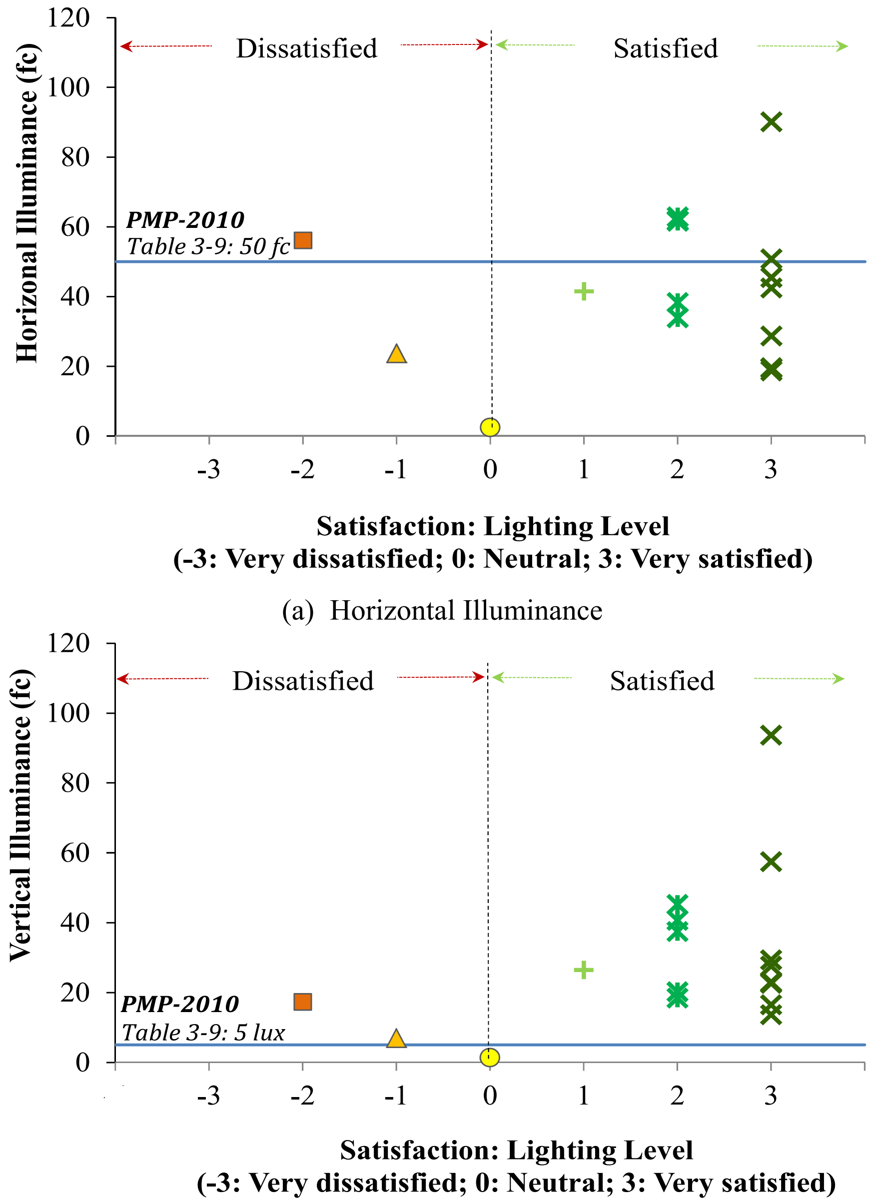


Figure 99: Measured CO_2 Concentrations of 17 Offices Against the ASHRAE Standard 62.1-2010 Benchmarks

[120] At the time of spot measurements, the fans and a heater in these three offices were operated.
[121] 950 ppm of indoor CO_2 concentration threshold limit was estimated using the Informative Appendix C of the ASHRAE 62.1-2007 and Standard 62.1-2010 with the following two assumptions: 350 ppm of outdoor CO_2 concentration and 0.0051 L/s of indoor CO_2 generation rate.
[122] Spot measurements may be helpful to discover possible causes of problems if the measurements are conducted at the right location and time when discomfort arises, and the appropriate variable can be observed.



(a) Horizontal Illuminance

(b) Vertical Illuminance

Figure 100: Measured Horizontal and Vertical Illuminance of 17 Offices Against the ASHRAE PMP Benchmarks

illuminance of one office was lower than the recommended value for task areas (50 fc), possibly indicating a visual discomfort in this office. The measured vertical illuminance of both of the two dissatisfied offices was higher than 5 fc, which is recommended in the ASHRAE PMP. No noticeable differences were found between the two dissatisfied and 15 satisfied offices.

Figure 101 shows A-weighted equivalent sound pressure levels (LAeq(dBA)) measured in the 17 offices against the ASHRAE PMP Table 3-10. The LAeq(dBA) measured in all 17 offices exceeded both the ideal and the maximum values recommended in the ASHRAE PMP: 30 and 40 dBA for private offices and 35 and 45 dBA for open plan offices. Few differences were found between the six acoustically-dissatisfied and eleven satisfied offices. The use of spot measurements did not reveal the source of dissatisfaction.

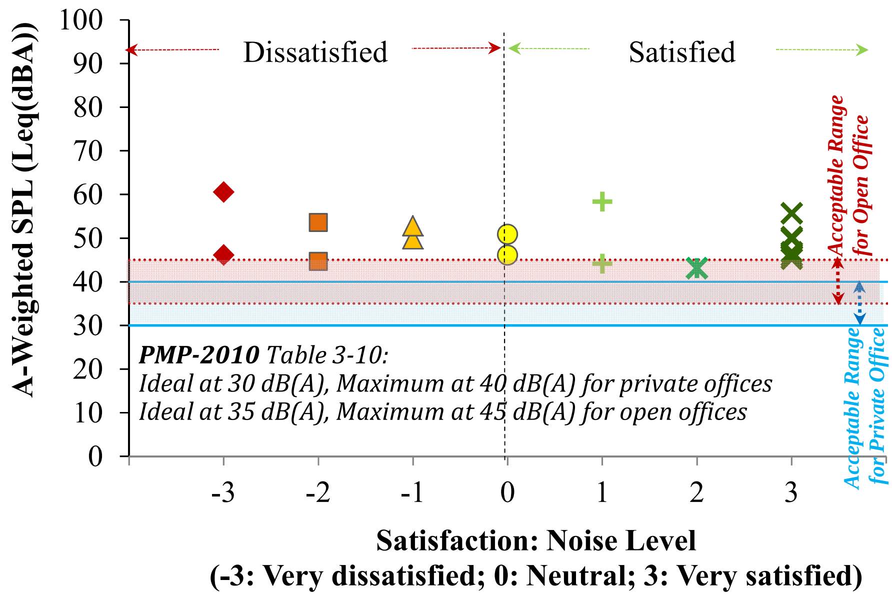


Figure 101: Measured A-Weighted Equivalent Sound Pressure Levels of 17 Offices Against the ASHRAE PMP Benchmarks

c) Results of OA Flow Rate Spot Measurements

The results of outdoor air (OA) flow rates spot measurements were compared against the appropriate benchmarks in the ASHRAE PMP: ASHRAE Standard 62.1-2007 and Standard 62.1-2010. Table 29 presents the measured OA flow rates along with the values calculated using the ASHRAE Standard 62.1-2007 and Standard 62.1-2010. The measured total OA flow rate (8,086 cfm) was about 12% lower than the value calculated using the ASHRAE Standard 62.1-2007 and Standard 62.1-2010 with the surveyed occupancy[123]. However, compared to the value calculated with default occupant density for office spaces specified in the standard[124], the measured value was almost same as the calculated rate.

Table 29: Comparison of Total OA Flow Rates between Measured versus Calculated using the ASHRAE Standard 62.1-2007 and Standard 62.1-2010

	Measured	**ASHRAE 62.1 w/ estimated density**	**ASHRAE 62.1 w/ default density**
Total OA Flow Rate (cfm)	8,086	9,053	8,057
% Difference against Measured	-	12.0%	-0.4%

[123] In Table 6-1 in the ASHRAE Standard 62.1-2007 and Standard 62.1-2010, the minimum OA flow rates for office space are 5 cfm/person and 0.06 cfm/sq.ft, which correspond to a total OA flow rate of 9,053 cfm with 323 employees and a conditioned floor area of 123,960 sq.ft.

[124] The ASHRAE Standard 62.1-2007 and Standard 62.1-2010 also provides a default value for occupant density such as 5 employees per 1,000 sq.ft for office spaces. With this default occupant density, a total OA flow rate is calculated as 8,057 cfm.

5.3.1.3. Observations

Observations from the field test of the ASHRAE PMP Basic Level IEQ protocol are as follows[125]:

- The ASHRAE PMP Basic Level IEQ protocol does not provide clear guidelines about how to display and interpret the results. For example, the ASHRAE PMP IEQ protocol does not provide any advice about how to graphically represent the surveyed IEQ satisfaction and spot measurement results across an entire building, how to compare the results against the benchmarks (i.e., mean scores versus frequency distributions)[126], or how to interpret the survey and spot measurement results of individual offices at the whole-building level.
- Different results may be obtained from different benchmarking sources. For example, in this study occupants' IEQ satisfaction was better than average against the CBE benchmarks in all areas, yet it was worse than average against the ASHRAE Standard 55-2004 and Standard 55-2010 for thermal comfort and sound privacy.
- The required metrics for the ASHRAE PMP Basic Level IEQ protocol are the results of the occupant IEQ satisfaction survey and spot measurements of several IEQ parameters. In this study, there were discrepancies between the results of the IEQ satisfaction survey and the following-up spot measurements. For example, the measured thermal environments of the occupants who expressed satisfaction in the survey were located outside the summer comfort zone in the ASHRAE Standard 55-2004 and Standard 55-2010. However, the ASHRAE PMP does not provide guidance about how to handle the discrepancies in the results between IEQ survey and spot measurements when they arise.
- The CBE survey questions consist of an evaluation of seven IEQ topics, including: office layout, office furnishings, thermal comfort, IAQ, lighting, acoustics, and cleaning/maintenance. Of these IEQ topics, three topics (i.e., office layout, office furnishing, and cleaning/maintenance) are beyond the scope of the current version of the ASHRAE PMP.
- Although the CBE benchmark is a fully satisfactory benchmark covering a wide variety of buildings in different locations over a period of years, the benchmarking database for the subjective IEQ survey needs a fully accessible public domain benchmark where all individual

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[125] A shorter observation listed in this section is repeated as an issue in Section 5.3.3.

[126] A mean satisfaction score higher than a comparable benchmark value may not indicate that the building's overall IEQ performance is acceptable.

records are available, to supplement the current CBE benchmark, which only provides summary statistics.

- A statistical comparison of the mean IEQ satisfaction and productivity scores between summer and winter using independent samples t-test revealed that there were no significant differences between summer and winter groups. In the results of paired samples t-test (i.e., dependent samples t-test) using 23 paired data, no significant differences were found between seasons for all four IEQ areas except for lighting level satisfaction. The results show that the summer lighting level satisfaction was lower than winter satisfaction with a marginal significance ($p = 0.10$). Overall, a seasonal influence on the occupants' subjective IEQ assessment was not confirmed in this study.
- IEQ spot measurements are optional for thermal comfort but required for IAQ, lighting, and acoustics regardless of the results of the IEQ satisfaction survey. Even when the majority of occupants are satisfied with their IAQ, lighting or acoustics environments, the ASHRAE PMP requires physical spot measurements.
- The current version of the ASHRAE PMP does not provide any advice about how to reproduce dissatisfaction when spot measurements are performed. IEQ spot measurements have one major limitation: it is hard to catch dynamic responses of IEQ that often get reported in a survey. In this study, of the six thermally-dissatisfied offices, three offices maintained similar thermal environments as the satisfied offices using personal fans and a small heater located under the desk. Thus, spot measurements could not confirm the complaints.
- There is a lack of specific measurement protocol that can be used for IEQ spot measurements. The lighting and acoustics protocols provide relatively detailed measurement procedures, but they give a general idea of the procedure rather than detailed step-by-step instructions. A measurement protocol based on step-by-step instructions which is standardized as much as possible will reduce a risk of misinterpretation.
- The ASHRAE PMP Basic Level presents all six performance categories in one chapter to help users navigate more easily. However, each sub-chapter repeatedly asks the same descriptive information, which could be condensed into one section.

5.3.2. *Level II and III: Intermediate and Advanced Level*

For the Intermediate and Advanced Level IEQ protocols, one field test that covered both levels was developed and applied to the case-study building since both levels require similar data collection efforts of several IEQ parameters.

5.3.2.1. <u>Performance Metrics</u>

The IEQ performance metrics required at the Intermediate Level are: data logging of temperature, humidity, mean radiant temperature (MRT), air speed with concurrent 'right-now' thermal comfort occupant survey for thermal comfort; data logging of CO_2 for IAQ; spot measurements of full grid illuminance and luminance with diagnostic lighting satisfaction occupant survey for lighting; and spot measurements of background noise and reverberation time for acoustics. At the Advanced Level, the required metrics are data logging of selected thermal comfort parameters with a more detailed spatial resolution (i.e., temperature gradients, radiation asymmetry, and air speed distribution) with a specialized local comfort occupant survey for asymmetrical or transient thermal environment for thermal comfort; data logging of CO_2, $PM_{2.5}$, and TVOCs levels for IAQ; detailed illuminance and luminance measurements using HDR photography for lighting; and measurements of speech privacy, speech communication and sound and vibration isolation for acoustic evaluations. Of the IEQ performance metrics required at the Intermediate and Advanced Levels, the metrics measured at the case-study building are[127]: data logging of four air temperatures (4, 24, 43, 66 in.), four globe temperatures (4, 24, 43, 66 in.), humidity, and air speed for thermal comfort; data logging of CO_2, and TVOCs[128] for IAQ; and detailed one-time illuminance and luminance measurements using HDR photography for lighting. For lighting and acoustics, the modified approaches were made based on the results of the Basic Level field test while also considering the significance as well as practical applicability of the measures (i.e., low availability and high cost requirements), including data logging of horizontal and vertical illuminance for lighting as well as A-weighted and C-weighted sound pressure levels (SPL) with an occupancy sensor[129]. The measurements were made over a one

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[127] The measurement selections and modified approaches were made based on the results of the Basic Level field test while also considering the significance as well as practical applicability of the measures (i.e., low availability and high cost requirements).

[128] This instrument can detect most solvent-based VOCs, including: acetone, benzene, diacetone alcohol, formaldehyde, methylene chloride, methyl ethyl ketone, perchloroethylene, toluene, and trichloroethylene.

[129] The occupancy was measured using a dual-technology occupancy sensor that employs both passive infrared and ultrasonic technologies.

week period in each of the eleven office spaces from July to September 2011 with concurrent 'right-now' thermal comfort occupant survey.

a) IEQ Continuous Measurements

Table 30 presents the results of IEQ continuous measurements performed between July and September 2011 for eleven offices: four offices where occupants were dissatisfied with their IEQ environments (i.e., thermal comfort, IAQ, lighting, or acoustics) at the Basic Level IEQ assessment survey and seven additional offices where occupants were satisfied. The shaded cells indicate the responses and measurement results of the dissatisfied group for the corresponding performance area. The 5 minute interval IEQ performance data measured in eleven office spaces of a case-study building are presented in Appendix E.

Overall, no significant differences were found in the thermal comfort performance metrics measured in eleven offices. The mean operative temperatures of eleven offices during the occupied hours over one measurement week varied between 73.9 and 76.9°F. The mean relative humidity varied between 33.7 and 42.2%. Some variations were found in the mean air speeds. Relatively high air speeds were found in two offices: 62.3 fpm for ID 4 and 48.8 fpm for ID 7. The mean air speeds of other nine offices ranged from 18.2 to 31.8 fpm. The mean PMV/PPD indices[130] ranged between −1.2 PMV (37.0% PPD) and −0.3 PMV (7.3% PPD). The highest and lowest mean PMV were found in the dissatisfied office group. One dissatisfied office (ID 1) had the highest mean PMV of −0.3 with the highest mean operative temperature of 76.9°F among the eleven offices. Another dissatisfied office (ID 4) had the lowest mean PMV of −1.2 PMV, and the occupant complained about cool discomfort due to high air movement and drafts. The mean air speed in this office (62.3 fpm) was the highest among eleven offices.

The IAQ performance metrics measured in eleven offices were very similar. The mean CO_2 concentrations of eleven offices during the occupied hours over one measurement week varied between 599 and 717 ppm. The mean TVOCs varied between 287 and 326 mV. No differences were identified between the measurement of CO_2 and TVOCs in offices where occupants expressed dissatisfaction (two offices) versus satisfaction (eight offices)[131].

Some variations were found in the lighting performance metrics measured in eleven offices. Relatively low horizontal and vertical illuminance were found in two offices: 7.3 fc horizontal illuminance and 3.6 fc vertical illuminance for ID 6; and 28.7 fc horizontal

[130] The PMV/PPD indices were calculated with the survey clothing and activity of the occupant.
[131] Additional discussions on the causes of IAQ dissatisfaction are presented in Section 5.3.3.

Table 30: Statistical Summary of IEQ One-Week Continuous Measurements for Eleven Offices: July to September 2011

ID		1	2	3	4	5	6	7	8	9	10	11	AVG
Workspace Descriptoin													
Type[1]		P	P	P	P	P	P	P	P	P	P	P	
Orientation		E	N	N	W	NE	N	S	E	W	E	S	
Floor		2nd	3rd	1st	2nd	4th	5th	2nd	7th	6th	6th	6th	
Fan[2]		Y	Y	N	N	N	N	Y	N	Y	N	N	
Personal Info.													
Age[3]		3	2	2	1	2	2	2	2	2	3	2	
Gender[4]		F	F	F	F	M	M	M	F	M	M	F	
Surveyed IEQ Satisfaction at the Basic Level													
Thermal Comfort		-2	-3	-2	-2	3	1	2	1	2	2	1	0.3
IAQ		0	-2	-1	1	3	1	3	2	2	2	2	1.2
Lighting Level		1	-1	-1	1	2	2	3	3	2	3	2	1.5
Visual Comfort		1	-1	-1	-2	2	1	2	3	2	3	2	1.1
Noise Level		0	-2	3	1	2	1	2	1	1	3	2	1.3
Sound Privacy		0	-2	1	1	2	1	2	1	1	2	2	1.0
IEQ Continuous Measurements during the Occupied Periods Measured over One Week													
Air Temp. at 66 in. (F)	Mean	77.3	75.4	74.7	74.9	75.1	74.6	75.7	74.9	76.6	76.5	74.3	75.5
	s.d.	1.3	0.3	0.7	0.3	0.4	0.2	0.6	0.6	1.8	0.6	1.0	0.7
Air Temp. at 43 in. (F)	Mean	77.2	75.8	75.0	74.9	75.5	74.8	75.8	75.1	76.8	76.6	74.4	75.6
	s.d.	1.3	0.3	0.7	0.3	0.4	0.2	0.6	0.7	1.9	0.6	1.0	0.7
Air Temp. at 24 in. (F)	Mean	77.5	75.1	74.6	75.1	75.2	74.7	75.7	74.8	76.5	76.5	74.4	75.5
	s.d.	1.5	0.3	0.7	0.3	0.4	0.2	0.7	0.6	1.5	0.6	0.9	0.7
Air Temp. at 4 in. (F)	Mean	77.5	75.5	74.8	75.1	75.5	75.0	76.0	75.1	76.5	76.7	74.4	75.6
	s.d.	1.6	0.3	0.7	0.3	0.4	0.2	0.8	0.7	1.5	0.6	0.9	0.7
Relative Humidity (%)	Mean	33.7	34.7	39.7	41.0	40.6	40.4	40.0	35.9	37.9	38.7	42.2	38.6
	s.d.	1.8	0.5	1.4	2.6	2.8	1.0	2.8	2.4	4.8	2.7	4.8	2.5
Air Speed (fpm)	Mean	19.0	25.7	19.3	62.3	23.9	31.8	48.8	30.4	18.2	24.6	28.6	30.2
	s.d.	8.0	3.4	1.6	5.6	2.0	2.7	15.5	6.9	4.0	2.1	7.5	5.4
MRT at 66 in. (F)	Mean	76.2	74.8	74.4	75.7	75.0	74.7	75.4	74.8	75.7	76.5	73.7	75.2
	s.d.	0.8	0.4	0.6	0.4	0.4	0.2	0.6	0.6	0.9	0.5	0.7	0.6
MRT at 43 in. (F)	Mean	76.4	75.0	74.5	75.6	75.1	74.8	75.5	74.9	75.7	76.6	73.7	75.3
	s.d.	1.1	0.4	0.6	0.4	0.4	0.2	0.6	0.6	1.0	0.5	0.7	0.6
MRT at 24 in. (F)	Mean	76.2	74.8	74.3	75.6	75.1	74.6	75.2	74.7	75.8	76.3	73.5	75.1
	s.d.	0.5	0.4	0.6	0.3	0.4	0.2	0.4	0.6	0.9	0.5	0.6	0.5
MRT at 4 in. (F)	Mean	76.3	74.9	74.4	75.5	75.1	74.7	75.2	74.8	75.8	76.4	73.5	75.1
	s.d.	0.5	0.4	0.6	0.3	0.4	0.2	0.4	0.5	0.9	0.5	0.6	0.5
Operative Temp. at 24 in. (F)	Mean	76.9	75.0	74.4	75.2	75.1	74.7	75.5	74.8	76.2	76.4	73.9	75.3
	s.d.	0.9	0.4	0.6	0.3	0.4	0.2	0.6	0.6	1.1	0.6	0.8	0.6
PMV	Mean	-0.3	-0.7	-0.5	-1.2	-0.5	-0.6	-0.7	-0.8	-0.5	-0.5	-1.0	-0.7
	s.d.	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.2	0.1	0.2	0.1
PPD (%)	Mean	7.3	15.8	10.6	37.0	10.7	11.9	16.8	19.5	11.2	11.3	25.4	16.1
	s.d.	2.1	2.8	2.8	4.9	1.9	1.3	3.9	5.6	5.5	2.8	8.3	3.8
CO_2 (ppm)	Mean	673	674	663	676	639	704	717	710	599	616	652	666
	s.d.	64	51	58	69	74	71	82	65	34	65	48	62
VOCs (mV)	Mean	304	287	307	325	298	305	294	306	326	321	302	307
	s.d.	7	4	5	10	10	22	5	6	13	14	16	10
Horizontal Illuminance (fc)	Mean	44.2	40.6	38.2	37.4	66.3	7.3	28.7	52.0	52.3	56.1	58.5	43.8
	s.d.	19.0	5.9	1.6	12.3	4.2	3.9	1.3	6.0	27.1	7.7	22.2	10.1
Vertical Illuminance (fc)	Mean	22.6	19.3	18.2	31.0	21.2	3.6	16.0	29.2	62.3	35.0	73.5	30.2
	s.d.	10.2	3.4	1.8	9.0	1.5	1.6	1.2	7.7	44.0	13.7	26.4	11.0
Leq (dBA)	Mean	54.1	44.9	46.1	47.2	43.0	42.5	49.3	51.6	46.0	49.8	48.2	47.5
	s.d.	3.5	4.0	1.8	1.8	3.4	2.6	3.4	3.8	2.3	2.5	2.5	2.9
Leq (dBC)	Mean	68.5	69.1	65.9	68.2	64.9	67.8	69.7	74.0	78.5	68.3	70.8	69.6
	s.d.	0.8	0.9	0.6	1.0	1.1	1.0	1.0	0.7	1.2	0.8	0.8	0.9

NOTES: The shaded cells indicate the responses and spot measurement results of the dissatisfied groups for the corresponding performance area.

1) P:Private, S:Shared

2) Y:Yes, N:No

3) 1:30 or under, 2:31-50, 3:Over 50

4) F:Female, M:Male

illuminance and 16.0 fc vertical illuminance for ID 7. In the office with the lowest mean horizontal illuminance (ID 6), the ceiling light fixtures remained turned off during the most of the measurement week, but the occupant was satisfied with his lighting environment that was maintained by daylight only. Since the task areas were closer to the window than the measurement location, the occupant was expected to be exposed to a brighter environment. The mean horizontal and vertical illuminance of other nine offices ranged from 37.4 to 66.3 fc and from 18.2 to 73.5 fc, respectively.

Some differences were found in the acoustics performance metrics measured in eleven offices. The mean A-weighted equivalent sound pressure levels (LAeq) of eleven offices during the occupied hours over one measurement week varied between 42.5 and 54.1 dBA. The mean C-weighted equivalent sound pressure levels (LCeq) varied between 64.9 and 78.5 dBC. One dissatisfied office had the third lowest LAeq of 44.9 dBA, but the mean LCeq was on the high side, the fifth highest among eleven offices.

b) 'Right-Now' Thermal Comfort Survey

Table 31 presents a statistical summary of 'right-now' survey performed during the IEQ continuous measurements[132]. The shaded cells indicate the responses and measurement results of the dissatisfied group for thermal comfort. The mean thermal sensation votes[133] of eleven occupants over one measurement week varied between −2.0 and 1.4. Only three occupants (ID 6, ID 8, and ID 11) voted more than half of the responses within the range of ±0.5. The mean thermal comfort votes[134] varied between 3.2 and 6.0. Eight occupants (ID 3 to 5 and ID 7 to 11) found their thermal environments comfortable more than half of the responses. The mean thermal acceptability votes[135] ranged from 1.3 to 2.0. Six occupants (five satisfied and one dissatisfied) found their thermal environment acceptable all the time, while another five occupants reported unacceptable conditions occasionally. The mean thermal preference votes[136] ranged from 1.0 to 2.6. Four occupants preferred no change in more than half of the responses. The mean air movement preference votes[137] ranged from 1.2 to 3.0. Six occupants preferred no change in more than half of the responses. The mean clothing levels of eleven occupants ranged

[132] The occupants were asked to repeat the survey twice a day over the measurement period.
[133] 3:Hot, 2:Warm, 1:Slightly warm, 0:Neutral, −1:Slightly cool, −2:Cool, and −3:Cold
[134] 6:Very comfortable, 5:Comfortable, 4:Just comfortable, 3:Just uncomfortable, 2:Uncomfortable, and 1:Very uncomfortable
[135] 1:Not Acceptable, 2:Acceptable
[136] 1:Cooler, 2:No change, 3:Warmer
[137] 1:Less air movement, 2:No change, 3:More air movement

Table 31: Statistical Summary of IEQ 'Right-Now' Survey for Eleven Offices

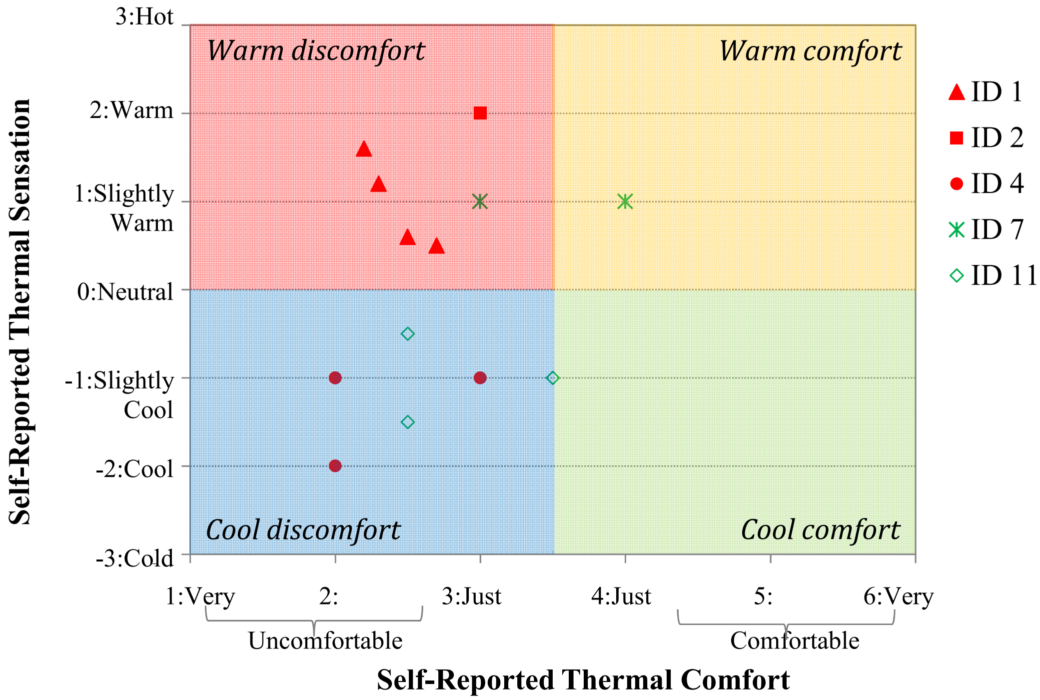
ID		1	2	3	4	5	6	7	8	9	10	11	AVG
Workspace Descriptoin													
Type[1]		P	P	P	P	P	P	P	P	P	P	P	
Orientation		E	N	N	W	NE	N	S	E	W	E	S	
Floor		2nd	3rd	1st	2nd	4th	5th	2nd	7th	6th	6th	6th	
Fan[2]		Y	Y	N	N	N	N	Y	N	Y	N	N	
Personal Info.													
Age[3]		3	2	2	1	2	2	2	2	2	3	2	
Gender[4]		F	F	F	F	M	M	M	F	M	M	F	
Subjective Responses													
Thermal Sensation[5]	Mean	0.1	1.4	-1.1	-0.8	-2.0	0.4	0.1	-0.2	0.4	-0.2	-0.3	-0.2
	% within ±0.5	29%	29%	33%	50%	0%	60%	38%	100%	25%	50%	78%	45%
Thermal Comfort[6]	Mean	3.2	3.3	4.2	3.5	6.0	3.3	4.5	4.7	4.5	4.3	3.4	4.1
	% of Comfortable	29%	29%	83%	60%	100%	40%	88%	100%	75%	89%	78%	70%
Acceptability[7]	Mean	1.4	1.3	2.0	1.6	2.0	2.0	1.8	2.0	2.0	2.0	1.7	1.8
	% of Acceptable	43%	29%	100%	60%	100%	100%	75%	100%	100%	100%	67%	79%
Thermal Preference[8]	Mean	1.0	1.0	2.0	2.6	2.1	1.2	1.4	2.3	1.6	1.9	2.3	1.8
	% of No Change	0%	0%	33%	40%	91%	20%	38%	67%	63%	50%	67%	43%
Air Movement Preference[9]	Mean	3.0	3.0	2.2	1.2	2.0	2.2	2.5	1.7	2.4	1.6	2.0	2.2
	% of No Change	0%	0%	83%	20%	100%	80%	50%	67%	63%	40%	100%	55%
Operating Fan/Blinds[10]	Mean	1.0	1.7	1.0	2.0	1.1	2.0	1.6	2.0	1.0	1.6	2.0	1.5
	% of Yes	100%	29%	100%	0%	91%	0%	38%	0%	100%	40%	0%	45%
Clothing (clo)	Mean	0.57	0.57	0.58	0.62	0.61	0.61	0.61	0.59	0.57	0.57	0.56	0.6
Activity (met)	Mean	1.04	1.09	1.10	1.16	1.08	1.10	1.04	1.07	1.09	1.18	1.13	1.1
Physical Indoor Climate Conditions Measured during the 'Right-Now' Survey													
Air Temp. at 24 in. (F)	Mean	77.8	75.3	74.8	75.0	75.0	74.7	75.7	74.8	76.9	76.4	74.5	75.5
	s.d.	1.8	0.2	0.6	0.1	0.4	0.3	1.1	0.1	2.1	0.8	0.9	0.8
Relative Humidity (%)	Mean	33.6	34.7	39.3	41.5	38.9	40.0	41.0	35.3	39.4	38.1	42.4	38.6
	s.d.	2.0	0.5	1.2	3.2	1.6	1.6	3.6	0.4	7.2	2.6	4.6	2.6
Air Speed (fpm)	Mean	16.8	28.5	18.7	63.2	23.9	31.8	44.3	31.5	16.0	26.5	31.7	30.3
	s.d.	4.7	7.0	0.8	6.1	2.9	3.6	12.1	9.3	4.6	6.1	9.3	6.0
MRT at 24 in. (F)	Mean	76.1	75.0	74.5	75.6	74.9	74.6	74.9	74.8	76.0	76.3	73.5	75.1
	s.d.	0.5	0.3	0.5	0.2	0.4	0.3	0.6	0.0	1.4	0.7	0.7	0.5
Operative Temp. at 24 in. (F)	Mean	77.0	75.2	74.6	75.2	75.0	74.6	75.4	74.8	76.4	76.3	74.0	75.3
	s.d.	1.1	0.3	0.5	0.1	0.4	0.3	0.8	0.0	1.7	0.8	0.7	0.6
PMV	Mean	-0.2	-0.6	-0.4	-0.7	-0.5	-0.6	-0.7	-0.7	-0.3	-0.4	-0.8	-0.6
	s.d.	0.2	0.3	0.1	0.6	0.3	0.1	0.1	0.4	0.5	0.5	0.6	0.3
PPD (%)	Mean	7.2	15.1	9.1	23.7	12.9	12.0	16.8	18.6	11.7	12.9	23.6	14.9
	s.d.	2.1	6.4	1.8	14.8	3.4	1.7	3.2	10.4	7.7	6.7	15.5	6.7

NOTES: The shaded cells indicate the responses and spot measurement results of the dissatisfied group for thermal comfort.
1) P:Private, S:Shared
2) Y:Yes, N:No
3) 1:30 or under, 2:31-50, 3:Over 50
4) F:Female, M:Male
5) 3:Hot, 2:Warm, 1:Slightly warm, 0:Neutral,-1:Slightly cool, -2:Cool, -3:Cold
6) 6:Very comfortable, 5:Comfortable, 4:Just comfortable, 3:Just uncomfortable, 2:Uncomfortable, 1:Very uncomfortable
7) 1:Not acceptable, 2:Acceptable
8) 1:Cooler, 2:No change, 3:Warmer
9) 1:Less air movement, 2:No change, 3:More air movement
10) 1:Yes, 2:No

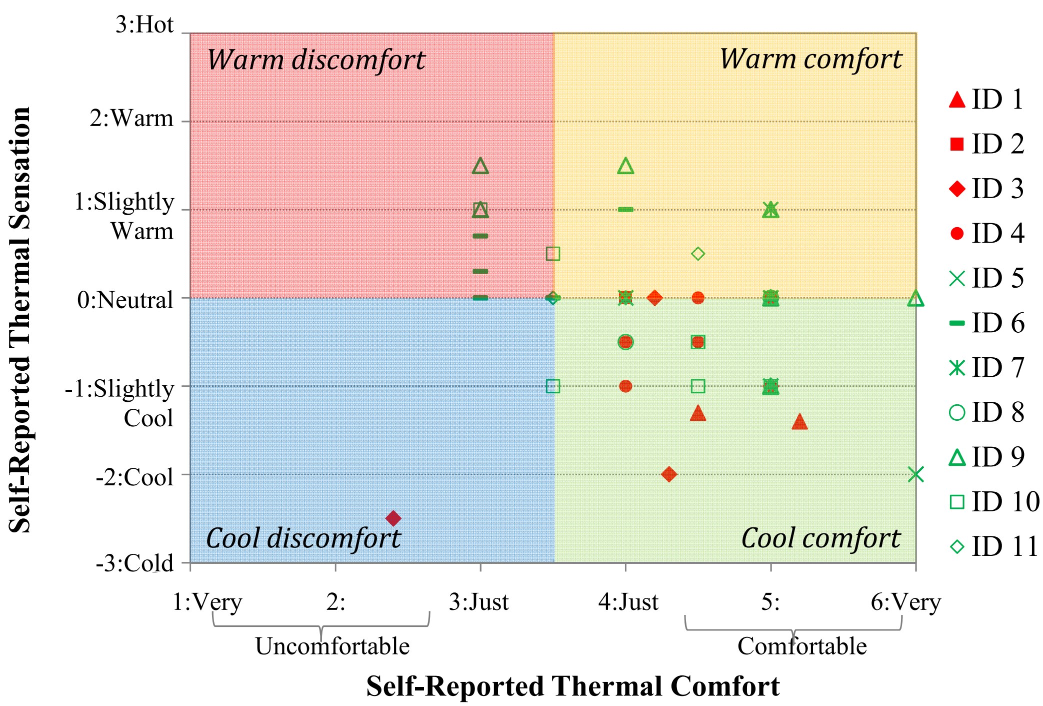
between 0.56 and 0.62 clo, which corresponds to typical summer office attire[138]. The mean metabolic rates ranged between 1.0 and 1.2 met, which corresponds to sedentary, office activities[139].

It was noted that there were person-to-person variations in the subjective responses of thermal sensation, comfort, acceptability, and preference. Figure 102 presents all the reported thermal sensation votes against thermal comfort votes by the response to the question of thermal acceptability: (a) not acceptable and (b) acceptable. Three occupants ID 1, ID 2, and ID 7 complained about warm discomfort and preferred cooler conditions when discomfort arose although their predicted mean thermal sensation votes (i.e., PMV) during the 'right-now' survey was −0.2, −0.6, and −0.7 respectively. On the other hand, there were also occupants who expressed cool discomfort: ID 4 and ID 11. These two occupants felt discomfort due to the cold and preferred warmer conditions when discomfort arose. Their mean PMVs during the survey were −0.7 and −0.8, respectively. The ID 5 occupant always reported cool thermal sensation (−2.0), but found his thermal environment acceptable as well as very comfortable (6.0). The remained five occupants found their thermal environments acceptable all the time with varying thermal sensation votes and comfort levels. For example, the reported thermal sensation and comfort votes of the ID 9 occupant varied between −1.0 and 1.5 and between 3.0 and 6.0, respectively, but he considered his thermal environment acceptable all the time.

[138] The clothing ensembles of trousers with a short-sleeve shirt have approximately 0.57 clo of insulation, and the ensembles of trousers with a long-sleeve shirt have approximately 0.61 clo of insulation per Table B1 of ASHRAE Standard 55-2004 and Standard 55-2010.
[139] A seated person is expected to have a metabolic rate of 1.0 met for reading/writing, 1.1 met for typing, and 1.2 met for filing per Table A1 of ASHRAE Standard 55-2004 and Standard 55-2010.



(a) Responses Voted 'Not Acceptable' to the Question of Thermal Acceptability



(b) Responses Voted 'Acceptable' to the Question of Thermal Acceptability

Figure 102: Self-Reported Thermal Sensations of Eleven Occupants against the Corresponding Thermal Comfort Votes

5.3.2.2. *Performance Evaluation/Benchmarking*

The evaluation of the different IEQ performance metrics was performed by comparing the measurement results to the appropriate benchmarks, including the ASHRAE Standard 55-2004 (ASHRAE 2004) and Standard 55-2010 (ASHRAE 2010c), the ASHRAE RP-884 database (de Dear 1998), the ASHRAE Standard 62.1-2007 (ASHRAE 2007b) and Standard 62.1-2010 (ASHRAE 2010d), the ISO Standard 8995:2002 (ISO 2002), the Swedish National Board of Health and Welfare (as cited in Kjellberg et al. 1997), and the Swedish Royal Board of Building (as cited in Kjellberg et al. 1997) as well as the Table 3-9 and Table 3-10 in the ASHRAE PMP.

a) IEQ Continuous Measurements

- Thermal comfort

The results of thermal comfort measurements for eleven offices were compared against the appropriate benchmarks specified in the ASHRAE PMP: ASHRAE Standard 55-2004 and Standard 55-2010. The current version of the ASHRAE PMP references the ASHRAE Standard 55-2004 for the benchmarks. However, newer editions of Standard 55 that supersede the referenced editions in the ASHRAE PMP are currently available: ASHRAE Standard 55-2010. The comparisons between two versions revealed a discrepancy in the provisions of turbulence intensity and draft risk calculation, which would influence on the benchmarking results, if applicable[140].

Figure 103 presents the statistical distributions (maximum, 95th, median, 5th, minimum) of measurement results during the occupied periods for the eleven offices (four dissatisfied and seven satisfied) with the appropriate benchmarking criteria (if applicable), including (a) operative temperature, (b) predicted mean vote (PMV), (c) predicted percentage of dissatisfied (PPD), (d) air speed, (e) relative humidity, (f) humidity ratio, (g) vertical air temperature difference between head and ankles, and (h) operative temperature drifts/ramps[141,142]. Since the ASHRAE PMP Intermediate and Advanced Level IEQ protocols do not provide clear guidelines about how to graphically represent and analysis the results of continuously measured

[140] The major revisions in the 55-2010 edition include: clarification of how to apply upper humidity limit in the standard; removal of turbulence intensity and draft risk calculations; clarification of mandatory requirements to comply with Standard 55; addition of a general satisfaction survey; and editorial changes throughout the document.

[141] Air and globe temperatures measured at the 24 in. were used to calculate operative temperature, PMV, and PPD as per Section 7.2.2 of ASHRAE Standard 55-2004 and Standard 55-2010.

[142] The 5 minute interval IEQ performance data measured in eleven office spaces of a case-study building are presented in Appendix E.

performance metrics, this study selected a statistical analysis to describe the time-varying distribution of indices. The 95^{th} and 5^{th} percentiles were chosen to characterize extreme variations based on ±5% of deviation. The median was chosen as a convenient way to describe the average of skewed distributions by a single number for a comparison between locations, while also conveying information on that variation for half the measurement period. The X-axis of the plots consists of a 7-point thermal satisfaction scale (3: very satisfied, 0: neutral, -3: very dissatisfied) surveyed at the Basic Level field test for each office.

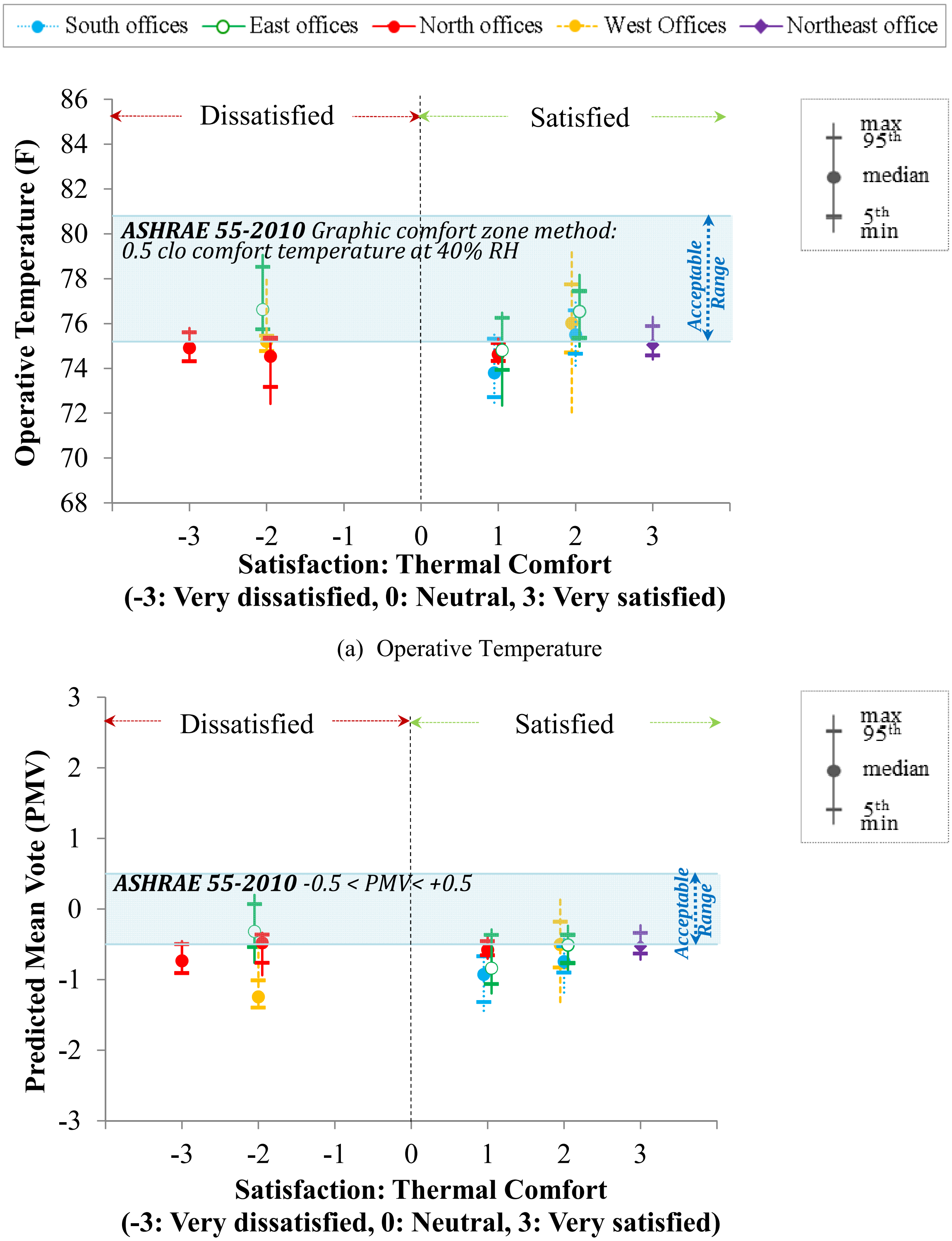
The median operative temperatures of the seven offices were lower than the lower boundary for ASHRAE Standard 55-2004 and Standard 55-2010 Section 5.2.1.1 Graphic Comfort Zone Method's summer (0.5 clo) comfort temperature. When the Computer Model Method (i.e., PMV model) in Section 5.2.1.2 of ASHRAE Standard 55-2004 and Standard 55-2010 was used, nine offices were out of the acceptable comfort range for more than 50% of occupied hours during a measurement week. The median PMVs of nine of the eleven offices were lower than −0.5, which is the lower boundary for Computer Model Method's acceptable PMV range, and the median PPDs of the same nine offices exceeded the 10% criterion, which means more than 10% of people are predicted to be dissatisfied due to local thermal discomfort in these offices. Conversely, the humidity environments of all eleven offices were maintained well below 0.012 lbs-H_2O/lbs-dry air of a humidity ratio, which is the high limit specified in the Section 5.2.2 of the ASHRAE Standard 55-2004 and Standard 55-2010. Thus the humidity environments of all eleven offices conform to ASHRAE Standard 55-2004 and Standard 55-2010.

The thermal stratification was examined using the temperature difference between head (43 in.) and ankles (4in.). For all eleven offices, the vertical temperature differences were lower than the allowable differences in Section 5.2.4.3 of ASHRAE Standard 55-2004 and Standard 55-2010, which is 5.4°F. Lastly, the temperature fluctuations with time were examined using the change in operative temperature during a 15 minute period. Although the two offices approached the limit, all eleven offices maintained the operative temperature variations less than 2.0°F, which is the limit based on Section 5.2.5 of ASHRAE Standard 55-2004 and Standard 55-2010.

When comparing the thermal conditions of the offices expressing dissatisfaction (i.e., four offices) versus the offices expressing satisfaction (i.e., seven offices), the differences were not noticeable. However, the median PMV of one dissatisfied office was −0.3 PMV, which was the highest thermal sensation among the eleven offices. The occupant in this office also expressed warm discomfort. For about 93% of occupied hours, the thermal conditions of this office were inside the comfort range specified in the ASHRAE Standard 55-2004 and Standard 55-2010 based on the PMV-PPD, but the occupant preferred lower temperatures in the 'right-now' surveys which were answered seven times during a measurement period. In a time-of-day graphical display, increasing temperatures due to solar radiation from the window were observed in the morning in this east-facing office, which also caused temperature drifts near the maximum acceptable limit of the standard (Figure 104).

The lowest median PMV (−1.2 PMV and 38% PPD) is found in one of the dissatisfied offices (third line from the left in Figure 103 (b)), and the occupant complained about cool discomfort due to high air movement and drafts. The air speed distribution in this office during a measurement week revealed higher air speeds compared to other offices, and in the results of 'right-now' survey, the occupant preferred less air movement. However, since the current version of ASHRAE Standard 55-2010 revised the provisions on draft by excluding its de facto draft limit (40 fpm) in the previous 2004 version and adding a limit (30 fpm) only for the conditions below 72.5°F operative temperature, there are no applicable air speed criteria for this office with an operative temperature higher than 22.5°C based on the ASHRAE Standard 55-2010.

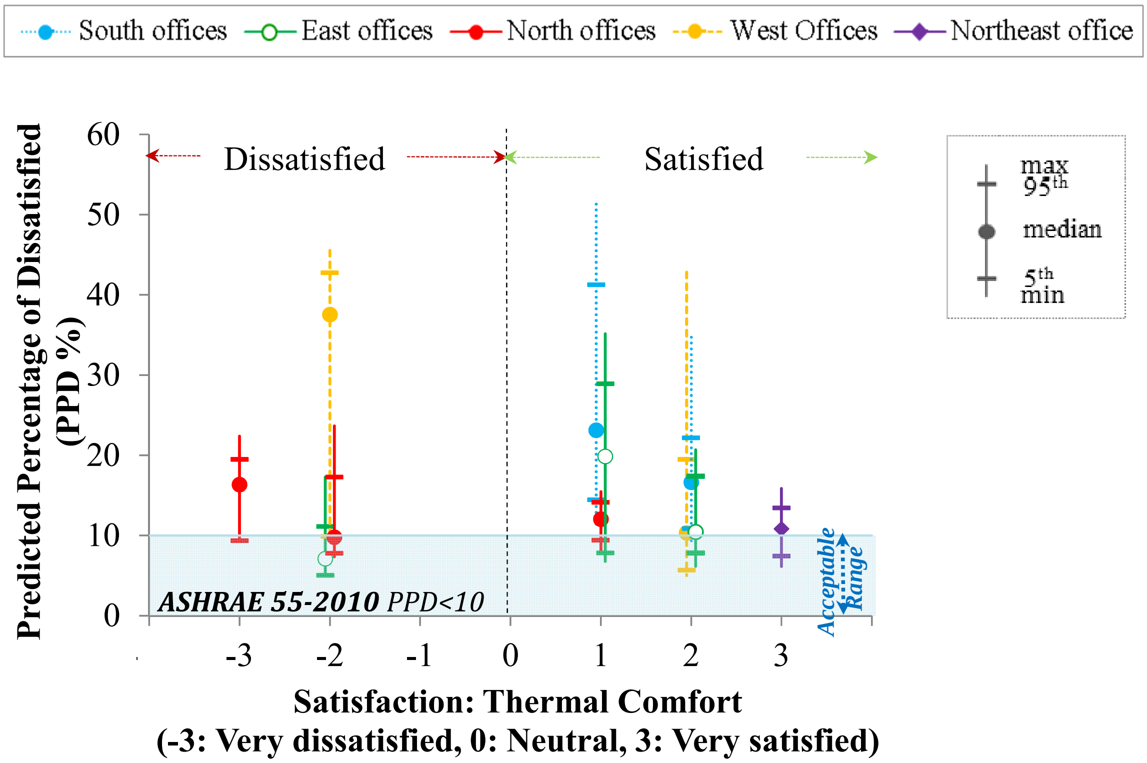
The thermal environments of two other dissatisfied offices were similar to those observed in satisfied offices. The occupant who answered "very dissatisfied" in the Basic Level IEQ survey complained about the inaccessible thermostat which was adjusted by other people in another office and preferred lower temperatures in the 'right-now' surveys. This may indicate individual differences beyond two well-known personal variables, clothing and activity. The other occupant also complained about the inaccessible thermostat and cold temperatures in winter which could not be verified in this measurement.



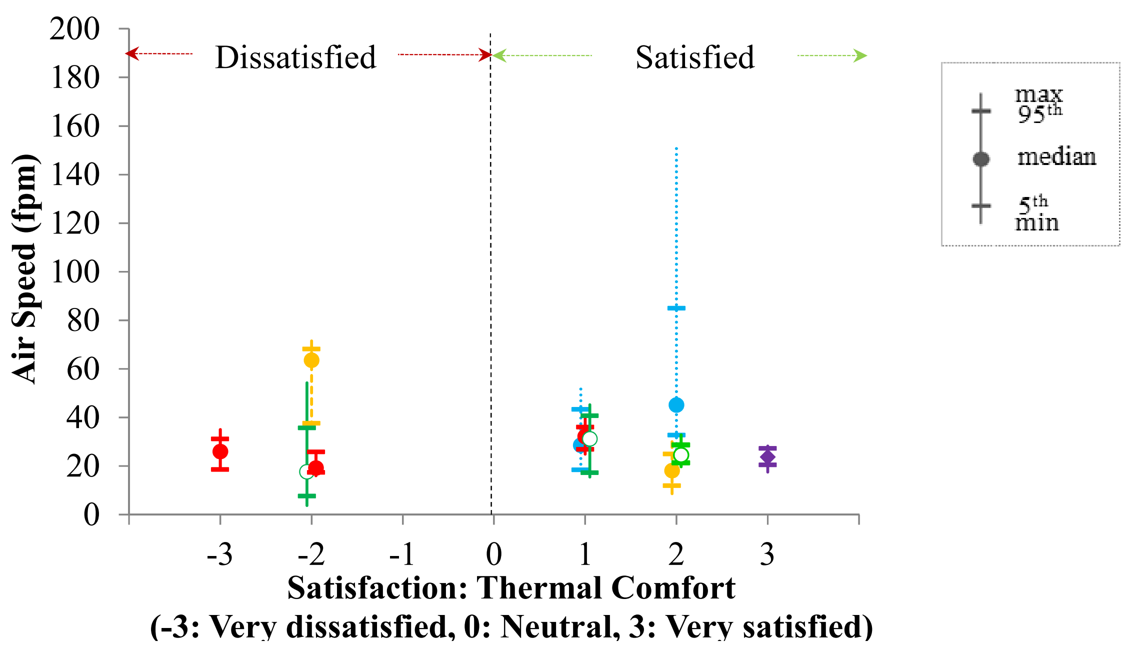
(a) Operative Temperature

(b) Predicted Mean Vote (PMV)

Figure 103: Statistical Distributions (Maximum, 95th, Median, 5th, Minimum) of Thermal Comfort Measurement Results for Eleven Offices

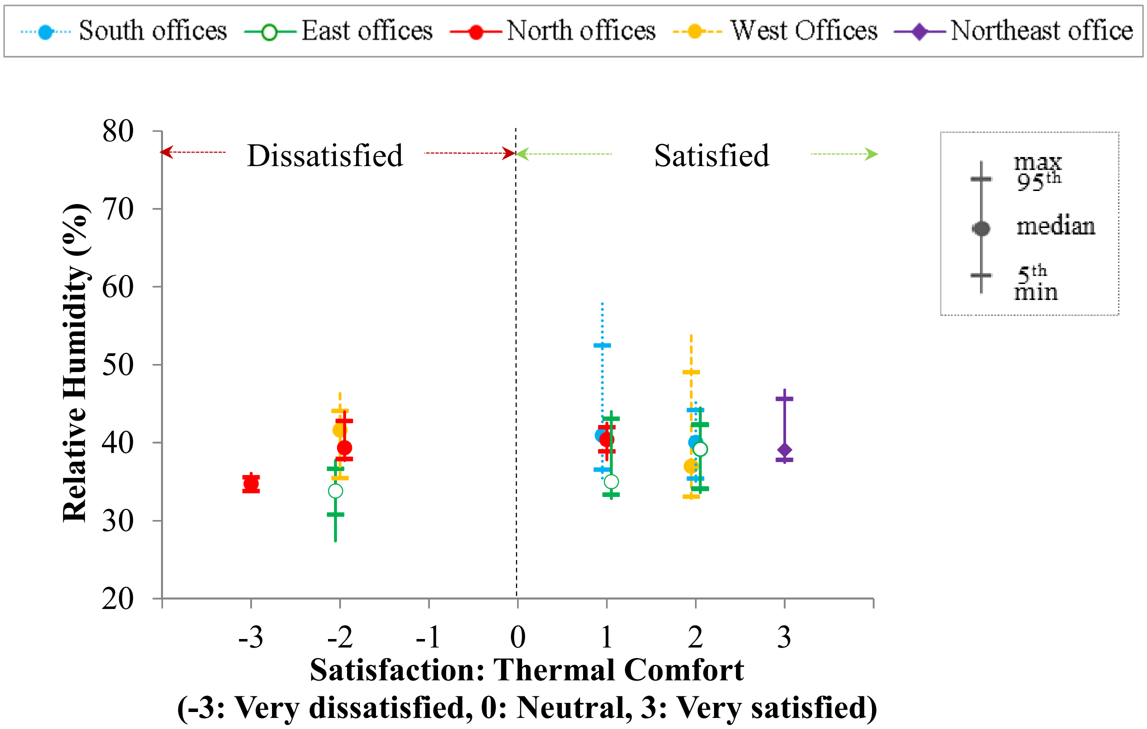


(c) Predicted Percentage of Dissatisfied (PPD %)

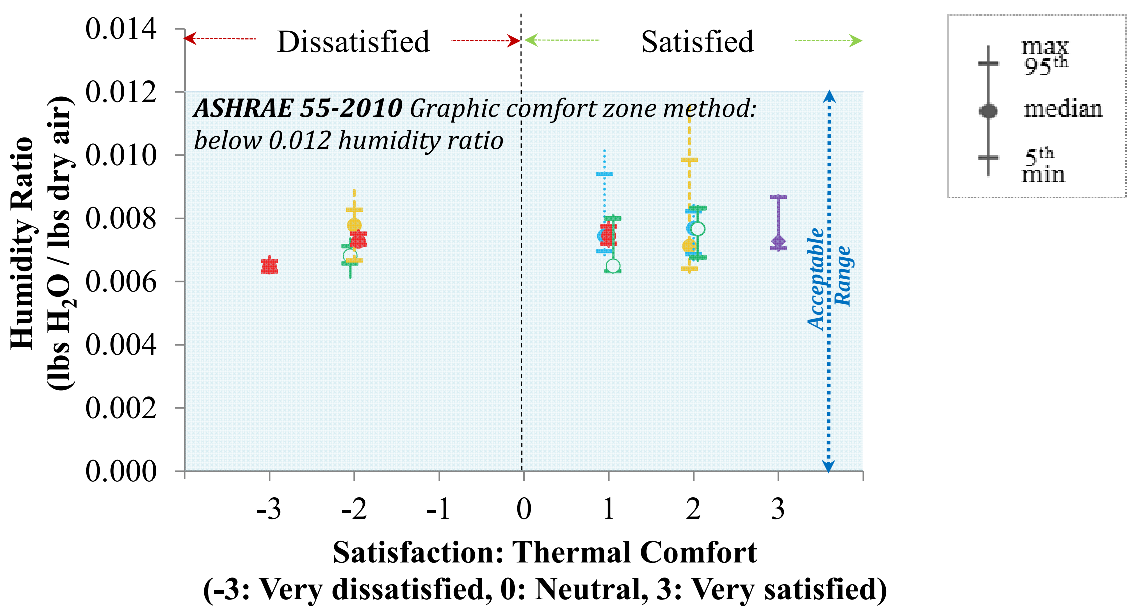


(d) Air Speed

Figure 103: Continued

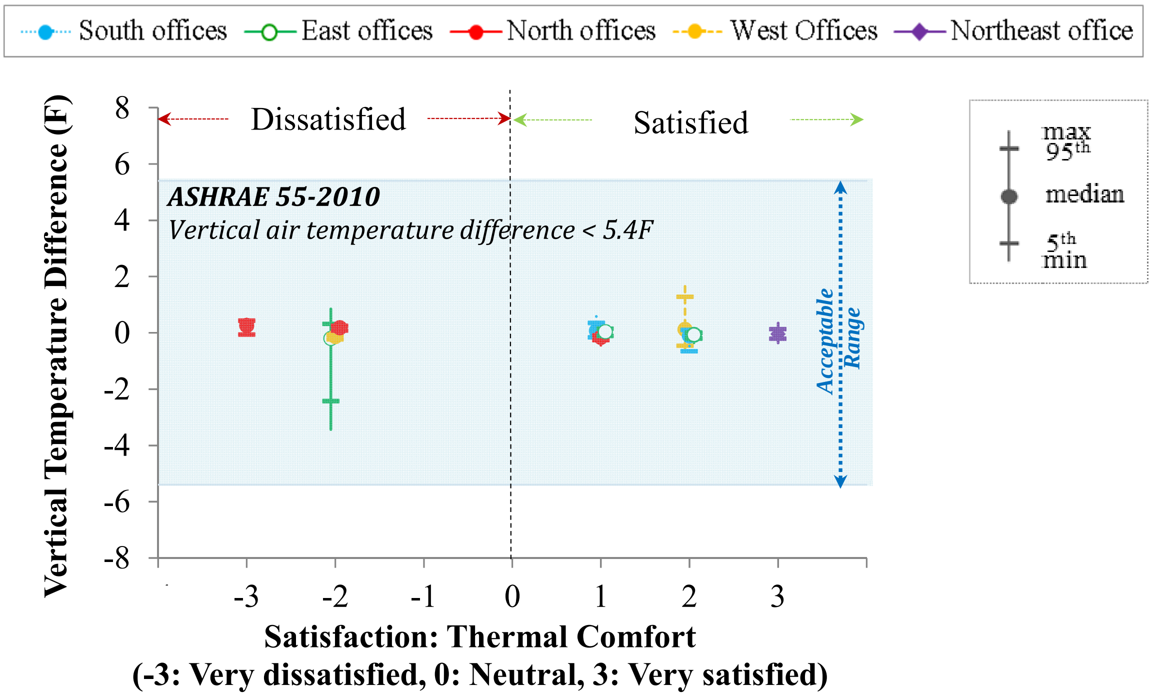


(e) Relative Humidity

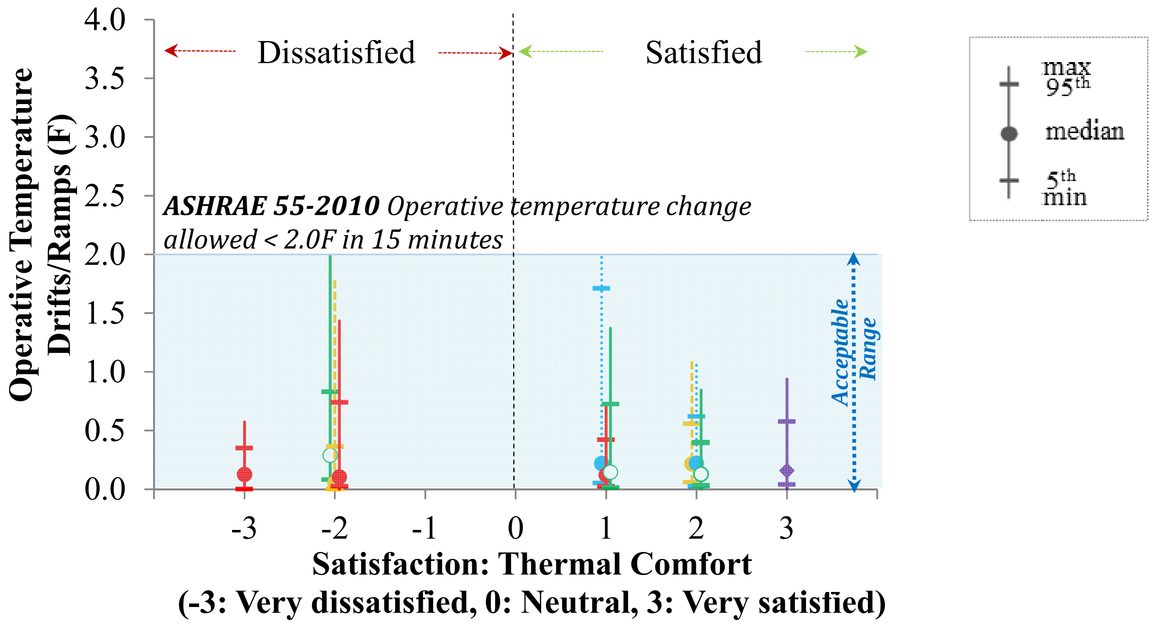


(f) Humidity Ratio

Figure 103: Continued



(g) Vertical Temperature Difference



(h) Operative Temperature Drifts/Ramps

Figure 103: Continued

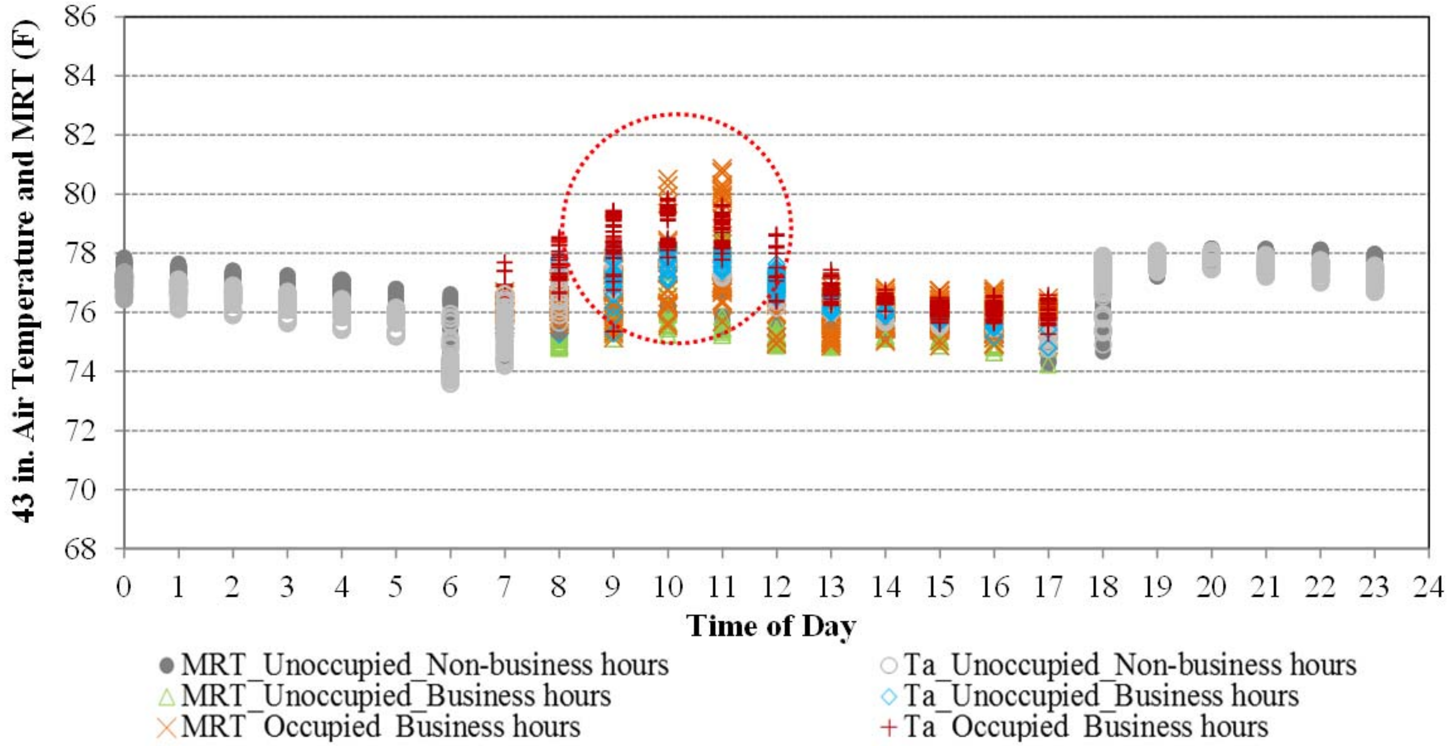


Figure 104: Hourly Profiles of Air and Mean Radiant Temperatures at the 43 in. of the ID 1 East-Facing Office (August 2 to 9, 2011)

- IAQ

The results of IAQ measurements for eleven offices were compared against the appropriate benchmarks specified in the ASHRAE PMP: ASHRAE Standard 62.1-2007 and Standard 62.1-2010. The current version of the ASHRAE PMP references to use the ASHRAE Standard 62.1-2007 for the benchmarks. However, newer editions that supersede the referenced editions in the ASHRAE PMP are currently available: the ASHRAE Standard 62.1-2010. The comparisons between two versions revealed a discrepancy in the provisions of ventilation rates for a few occupancy categories, which would influence on the benchmarking results for certain types of occupancies[143].

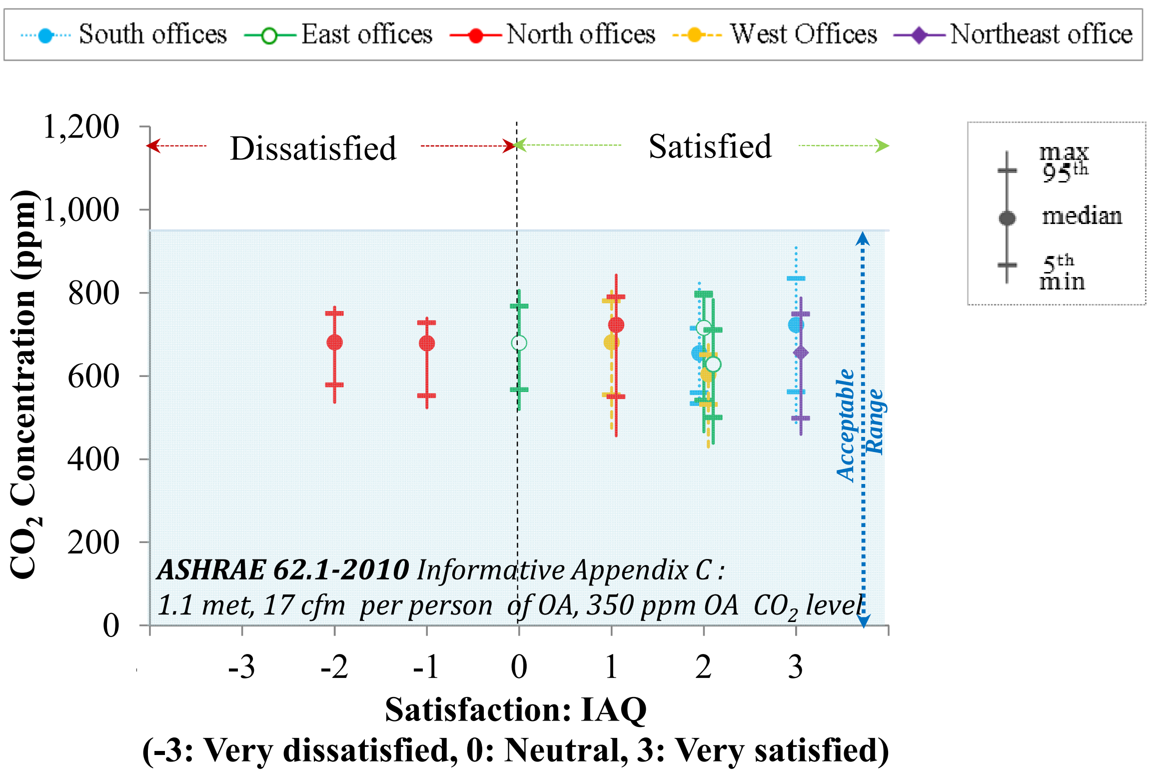
Figure 105 presents the statistical distributions of measurement results during the occupied periods for eleven offices (two dissatisfied, one neutral, and eight satisfied) with the appropriate benchmarking criteria, including (a) CO_2, (b) TVOCs, and (c) outdoor ventilation rate. The outdoor ventilation rate was estimated from the daily maximum CO_2 concentrations using equilibrium CO_2 analysis method per Section 10 of the ASTM D6245-2007 (ASTM 2007). The X-axis of the plots consists of a 7- point IAQ satisfaction scale surveyed at the Basic Level field test.

The following observations can be made regarding the results of the IAQ evaluation. The maximum CO_2 concentrations of all eleven offices were below 950 ppm, corresponding to 17 cfm per person of outdoor air rate which is the minimum ventilation rate for office spaces in the ASHRAE Standard 62.1-2007 and Standard 62.1-2010[144]. The TVOCs levels of all eleven offices were far below the cautionary threshold limit value (650 mV) specified in a manufacturer's note (Eco Sensors, Inc. 2011)[145]. In several offices, there were some events in which TVOCs levels increased, but the increase was short lived. These one-time events were likely to occur during the use of office stationery supplies or cleaning products that contain VOC

[143] The major revisions in the 2010 edition include: clarification of minimum ventilation requirements; addition of natural ventilation procedure; more robust IAQ procedure; additional requirements for the design of DCV systems; revision of ventilation rates for a few occupancy categories; and addition of new minimum filtration/air cleaning requirements.
[144] 950 ppm of indoor CO_2 concentration threshold limit was estimated using the Informative Appendix C of the ASHRAE 62.1-2007 and Standard 62.1-2010 with the following two assumptions: 350 ppm of outdoor CO_2 concentration and 0.0051 L/s (0.011 cfm) of indoor CO_2 generation rate.
[145] The TVOCs were measured using an instrument that produces a voltage signal between 0 to 2 volts, which increases as the TVOCs level increases. The manufacturer's note specifies two benchmarking criteria: cautionary at 650 mV (i.e., 25 ppm for perchloroethylene) and hazardous at 1,040 mV (i.e., 50 ppm for perchloroethylene). Hazardous conditions are the conditions near the Occupational Safety and Health Administration (OSHA) threshold limit values (TLV) of individual VOCs (Eco Sensors, Inc. 2011).

gases and vapors, including felt marker pens, hand sanitizers, and floor cleaners. The outdoor air flow rates are displayed with the uncertainty bar, and the calculated rates ranged from 23 to 36 cfm per person, which exceeded the ASHRAE's minimum ventilation rate for offices (17 cfm per person of outdoor air rate).

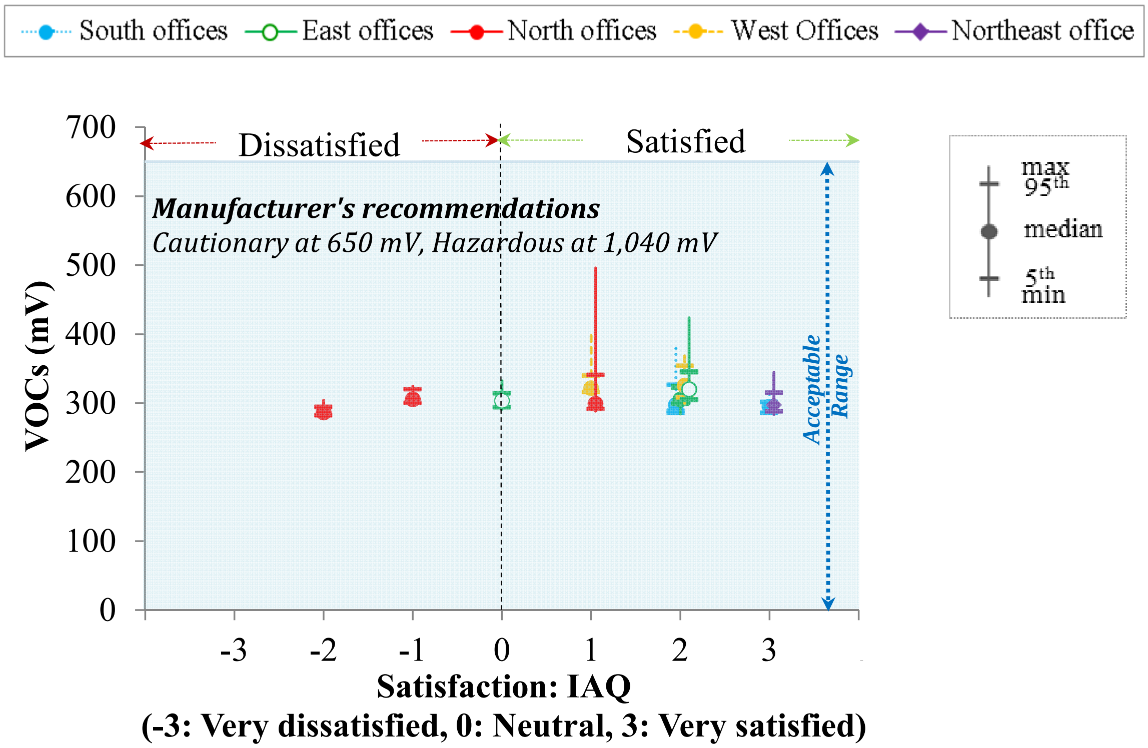
No differences were identified between the measurement of CO_2 and TVOCs in offices where occupants expressed dissatisfaction (two offices) versus satisfaction (eight offices). The two dissatisfied offices were ventilated adequately based on the CO_2 measurement results. However, the occupants complained about stuffy and stale air due to poor circulation within a room, which could not be verified from the measurements of CO_2 and TVOCs[146].



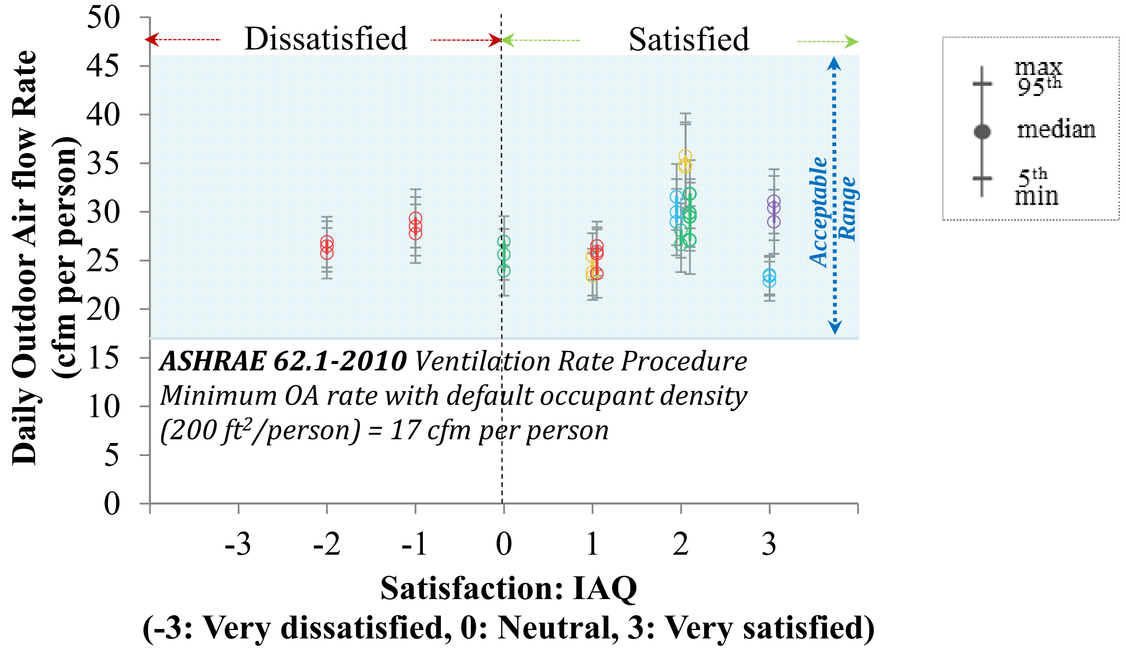
(a) CO_2 Concentration

Figure 105: Statistical Distributions (Maximum, 95th, Median, 5th, Minimum) of IAQ Measurement Results for Eleven Offices

[146] Section 6.2.3.2 discusses a new approach how to use a vertical temperature profile of a room as a simple indicator to diagnose air circulation problems in these two dissatisfied offices.



(b) TVOCs



(c) Outdoor Ventilation Rate

Figure 105: Continued

- Lighting

The results of lighting measurements for eleven offices were compared against the Table 3-9 in the ASHRAE PMP and the ISO Standard 8995:2002 (ISO 2002). Figure 106 presents the statistical distributions of measurement results during the occupied periods for the eleven offices (two dissatisfied and nine satisfied) with the appropriate benchmarking criteria, including (a) horizontal illuminance and (b) vertical illuminance. The X-axis of the plots consists of a 7-point lighting level satisfaction scale surveyed at the Basic Level field test.

The measured median horizontal illuminances of four offices were higher than the recommended value for task areas (50 fc) in both the ASHRAE PMP and ISO Standard 8995:2002. In a second comparison to the value for the immediate surrounding areas (within 20 in. from the task area) in the ISO Standard 8995:2002, ten offices complied with the provision (i.e., the median illuminance higher than 30 fc). One satisfied office showed very low horizontal illuminance with the median illuminance around 6.8 fc[147].

The median vertical illuminance of ten offices was higher than 5 fc which is recommended in the ASHRAE PMP. A large variation in vertical illuminance was found in two offices where the blinds were partially open, and in one of these offices, the computer monitors face a window, which indicates a high possibility of glare during the daytime. In an analysis of this west-facing office using HDR photography taken around noon on a typical summer weekday, the luminance ratio between the task and monitor was approximately1:56 (2.5 cd/m^2:140 cd/m^2, 0.7 fL :41 fL) which far exceeded the 1:3 limit in the ASHRAE PMP (Figure 107).

No differences were identified from the measurements of illuminance between the offices where occupants expressed dissatisfaction (i.e., two offices) and satisfaction (i.e., nine offices). One of the dissatisfied occupants complained about darkness in the task areas because of a hutch over the desk. This problem could not be verified using the instrumentation cart since it was located in the immediate surrounding areas[148]. Another dissatisfied occupant complained that the room was too bright with overhead lights but not bright enough with just a desk lamp, which may be due to different preferences on lighting levels since the measured lighting levels in this office were near the recommended values.

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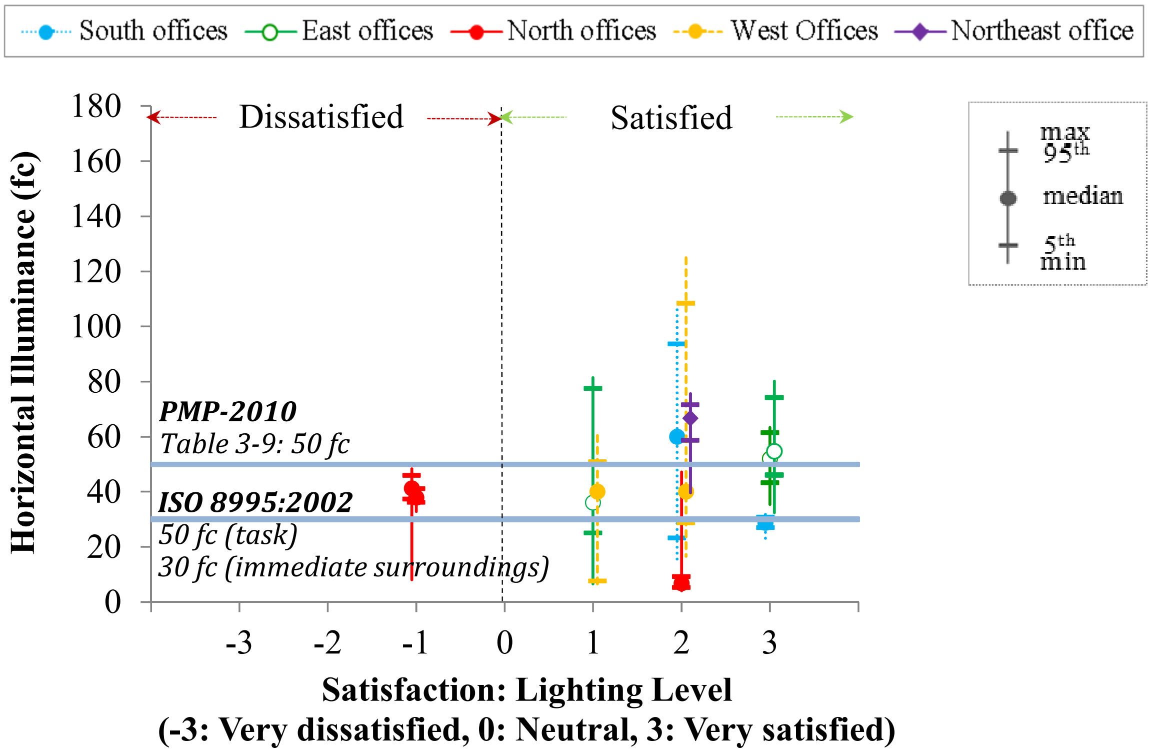
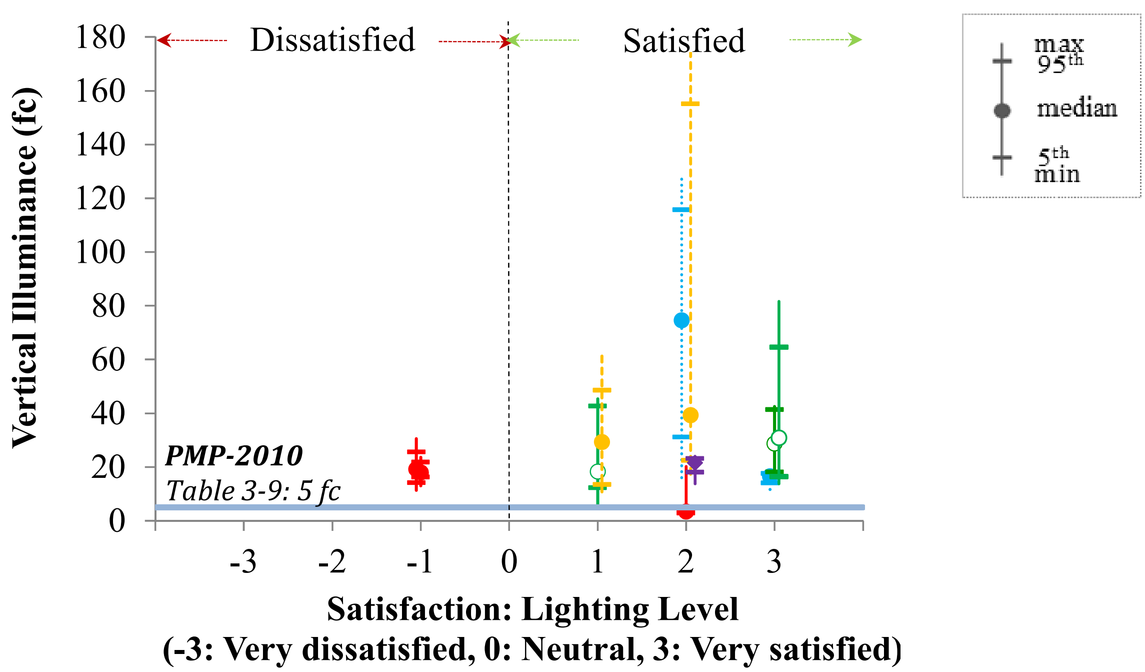
[147] The ceiling light fixtures in this office remained turned off during the most of the measurement week, but the occupant was satisfied with his lighting environment that was maintained by daylight only. Since the task areas were closer to the window than the measurement location, the occupant was expected to be exposed to a brighter environment.

[148] The cart can be improved by using detachable or remote illuminance sensors located at the task using wireless devices.

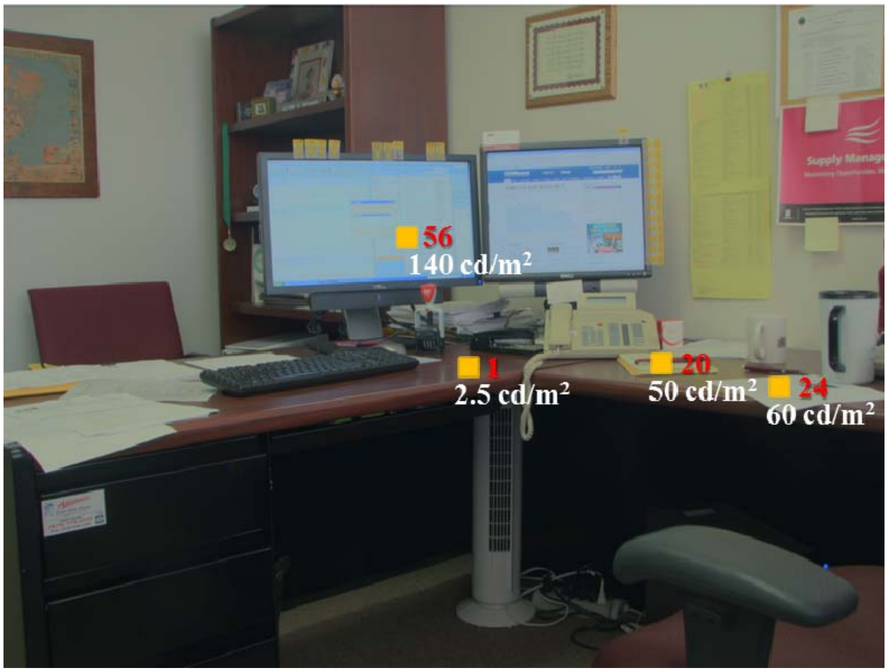


(a) Horizontal Illuminance

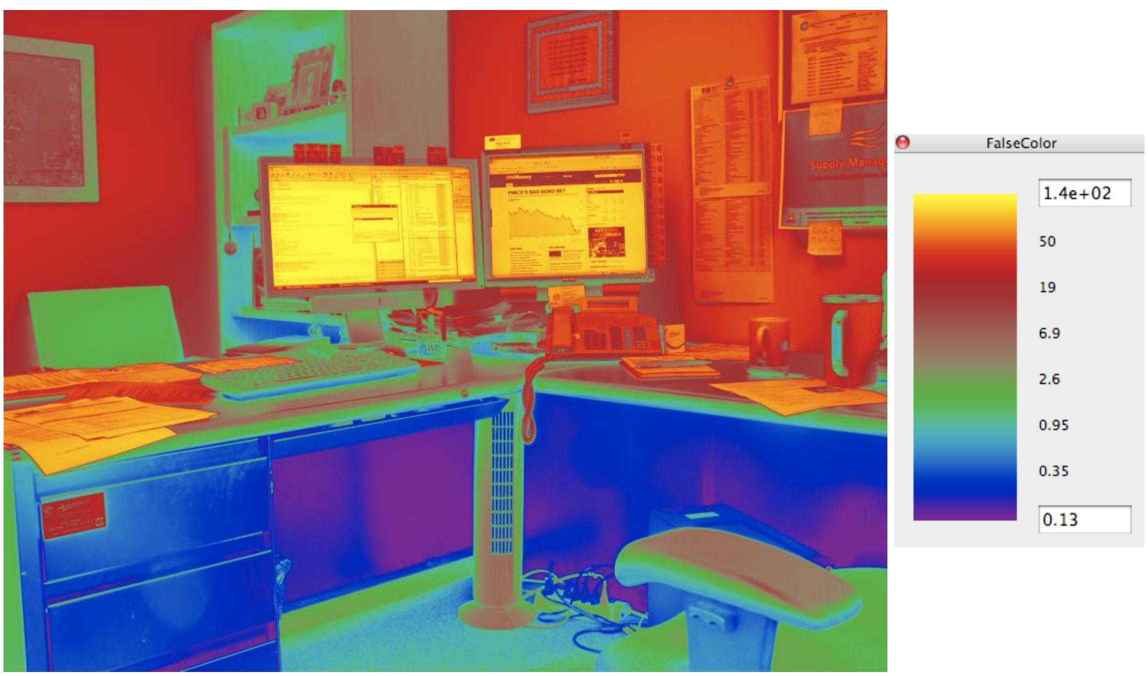


(b) Vertical Illuminance

Figure 106: Statistical Distributions (Maximum, 95th, Median, 5th, Minimum) of Lighting Measurement Results for Eleven Offices



(a) HDR Image



(b) False Color Image

Figure 107: HDR and False Color Images of the ID 9 West-Facing Office (September 6, 2011 12:30 pm)

- Acoustics

The results of acoustics performance measurements for eleven offices were compared against the Table 3-10 in the ASHRAE PMP as well as the Swedish National Board of Health and Welfare (as cited in Kjellberg et al. 1997) and the Swedish Royal Board of Building (as cited in Kjellberg et al. 1997). Figure 108 presents the statistical distributions of measurement results for eleven offices (one dissatisfied, one neutral, and nine satisfied) with the appropriate benchmarking criteria, including (a) LAeq, (b) LCeq, (c) difference between LAeq and background noise, and (d) difference between LCeq and LAeq[149]. The X-axis of the plots consists of a 7-point noise level satisfaction scale surveyed at the Basic Level field test.

Of eleven offices, three offices met the criteria for background noise specified in the ASHRAE PMP with a minimum LAeq lower than 40 dBA which corresponds to the maximum allowable background noise level (Figure 108 (a)). The median LAeq of three offices (first, second, and ninth lines from the left in Figure 108 (c)) were 5 dB or more above the background noise, which might be partly affected by the use of portable fans in these three offices. Ten offices had a median LCeq – LAeq difference higher than 15 dB, and two of them had a median difference over 25 dB (Figure 108 (d)). Using the method by the Swedish National Board of Health and Welfare and the Swedish Royal Board of Building[150], the measured noise in ten offices can be considered as low frequency noise, which likely annoyed the occupants.

When comparing the acoustics environments of offices between satisfied and dissatisfied, the dissatisfied office had a relatively high LCeq – LAeq difference. The LCeq of one dissatisfied office was higher than LAeq by 24 dB or more for more than 50% of occupied hours during a measurement week, which indicates a possibility of annoyance related to low frequency. In the subjective IEQ survey, the occupant in this office complained about noise made by people in neighboring areas and rooms. The measured background sound level of this office was the third lowest level with a minimum LAeq of 39 dBA, which complies with the criteria for background noise levels in the ASHRAE PMP. However, due to individual differences, there is

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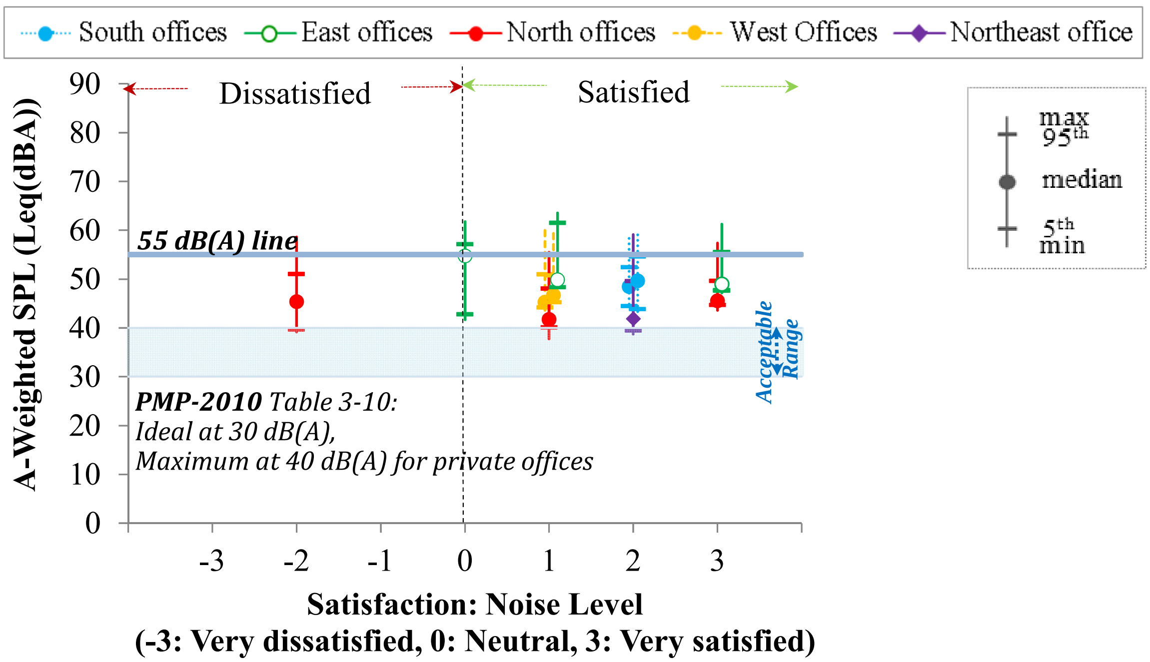
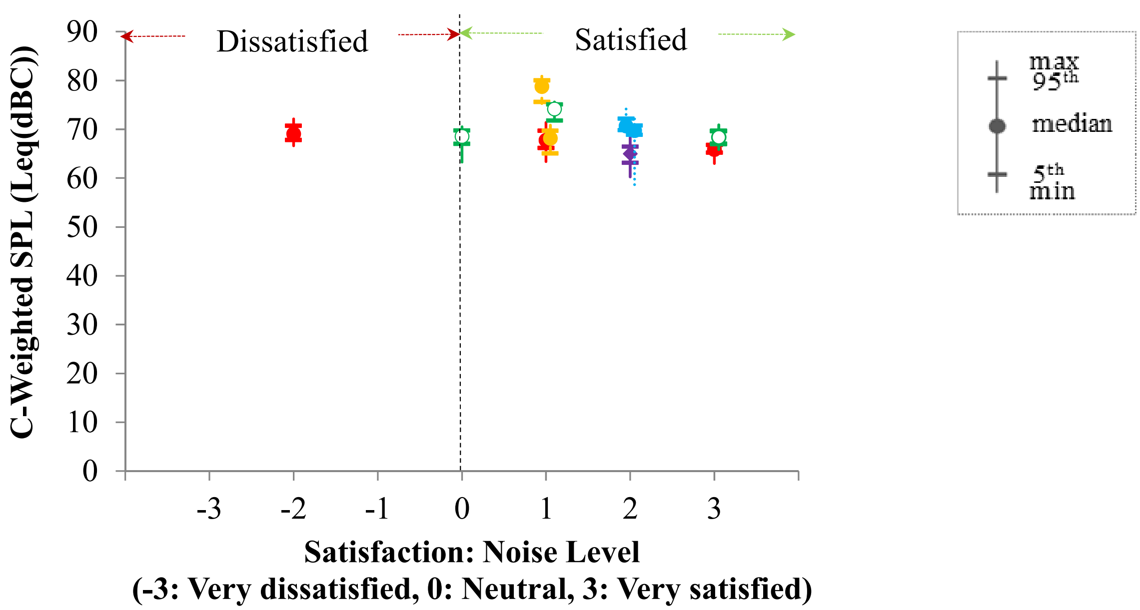
[149] To identify low frequency noise components in the measured noise, the difference between C- and A-weighted SPL were calculated instead of octave band measurements. The LCeq – LAeq difference has been previously regarded as a simple indicator to estimate low frequency noise annoyance (Berglund et al. 1999).

[150] Based on some Swedish recommendations (Swedish National Board of Health and Welfare, as cited in Kjellberg et al. 1997; Swedish Royal Board of Building, as cited in Kjellberg et al. 1997), the measured noise can be regarded as low frequency if the LCeq – LAeq difference exceeds 15-20 dB, and if the difference is greater than 25 dB, there is a chance of serious low frequency noise annoyance.

still likelihood that the background sound was not enough to mask intruding noise for the occupant in this office.

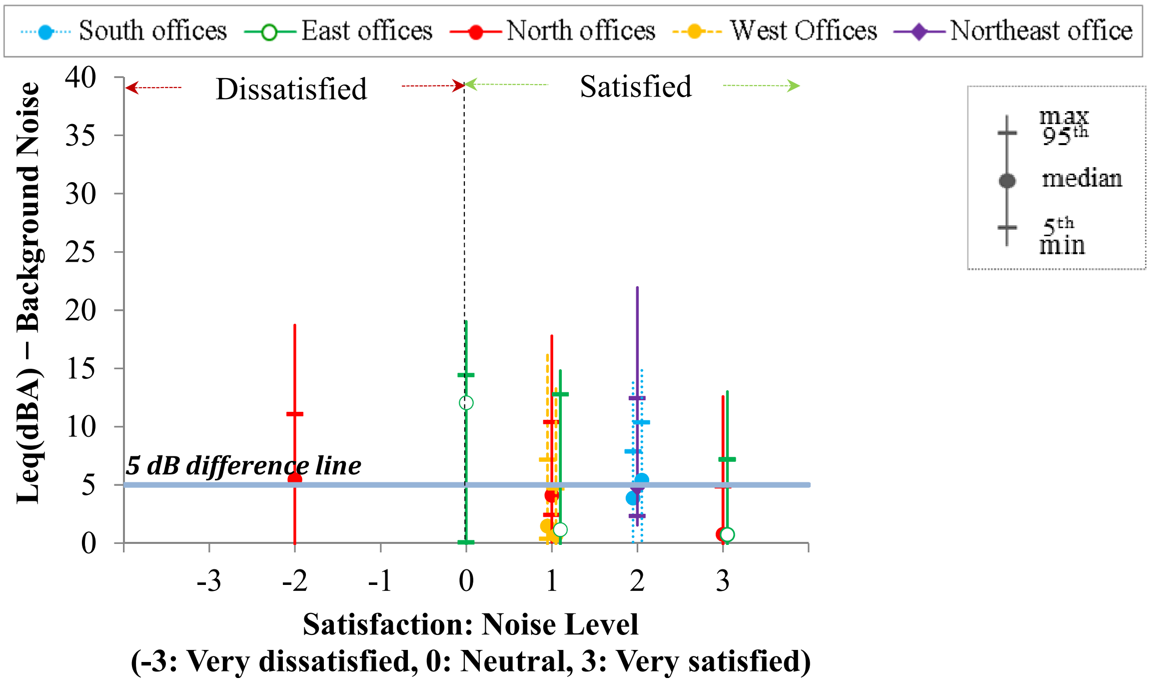


(a) A-Weighted SPL

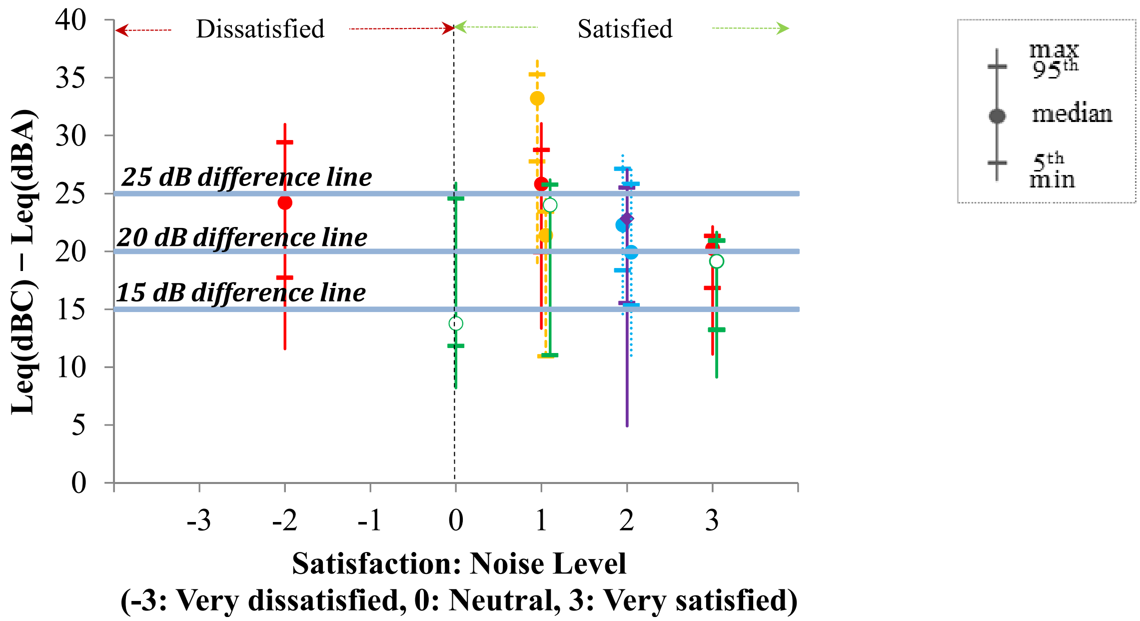


(b) C-Weighted SPL

Figure 108: Statistical Distributions (Maximum, 95th, Median, 5th, Minimum) of Acoustics Measurement Results for Eleven Offices



(c) Leq(dBA) – Background Noise



(d) Leq (dBC) – Leq (dBA)

Figure 108: Continued

b) 'Right-Now' Thermal Comfort Survey

The results of 'right-now' thermal comfort survey were compared against the extensive world-wide ASHRAE RP-884 database (de Dear 1998; 2004)[151]. Of the 52 data sets, eight data sets that were collected in air-conditioned office buildings during the hot summer season were selected for a fair comparison (Table 32). The selected data sets were collected between 1982 and 1997 in eight buildings in California, USA; twelve buildings in Montreal, Canada; and 43 buildings in five cities, Australia such as Brisbane, Darwin, Melbourne, Townsville, and Kalgoorlie-Boulder.

Table 33 provides a comparison of the case-study building's survey results against the selected RP-884 data sets. Figures 109 to 114 graphically represent the results using the percentage distributions of responses, including, thermal sensation, PMV, thermal comfort, thermal acceptability, thermal preference, and air movement preference[152]. The mean thermal sensation vote of the case-study building was about −0.3, which was lower than the mean votes of the selected RP-884 data sets for the USA (0.2) and Australia (0.0), and about the same as the Canadian mean vote (−0.3). The percentage of responses voting within ±0.5 thermal sensation

Table 32: Eight RP-884 Data Sets Selected for an Analysis

RP-884 Database ID	Location	Building Type	A/C Type	Season	Survey Year	Number of Buildings	Sample Size (n)
32	San Francisco Bay Area, CA, USA	Office	HVAC	Summer	1987	7	673
44	San Ramon, CA, USA	Office	HVAC	Summer	1993	1	96
USA Total						**8**	**769**
9	Montreal, Canada.	Office	HVAC	Summer	1994	12	443
Canada Total						**12**	**443**
11	Brisbane, Australia	Office	HVAC	Summer	1983-84	5	564
14	Darwin, Australia	Office	HVAC	Wet Summer	1982	7	555
15	Melbourne, Australia	Office	HVAC	Summer	1982-83	4	512
37	Townsville, Australia	Office	HVAC	Wet Summer	1993	11	606
48	Kalgoorlie-Boulder, Australia	Office	HVAC	Summer	1997	16	589
Australia Total						**43**	**2,826**

[151] The RP-884 database consists of 52 data sets collected from 28 cities all over the world. Most data sets were collected in office buildings, including air-conditioned and naturally-ventilated buildings.
[152] In the Figures, the thermal sensation and comfort vote were binned into 0.5 and 1.0 vote intervals, respectively, since these two votes were surveyed based on a continuous scale. The calculated PMVs were binned into 0.5 vote intervals.

was about 40% in the case-study building, which was about 8% and 2% less than the average of the USA and Australia, respectively, but higher than the Canadian average by 16%. In the percentage distribution of the thermal sensation votes binned into 0.5 vote intervals, the case-study building's distribution was similar to the Australian average except a higher percentage of votes on −2.0 (Cool) rather than 1.0 (Warm). Overall, the self-reported thermal sensation votes collected in the case-study building were slightly cooler compared to the selected RP-884 benchmarks.

The cooler, self-reported thermal sensation votes observed in the case-study building was also confirmed in a comparison of the calculated PMVs between data sets. The mean PMV of the case-study building was about −0.23, which was the lowest compared to the selected RP-884 data sets for the USA (−0.20), Canada (−0.02), and Australia (−0.03). In the percentage distribution of the PMVs binned into 0.5 vote intervals, the case-study building's distribution was negatively skewed with a peak at −0.50. On the other hand, the peak points of the selected RP-884 data sets were observed at 0.00 (neutral). No significant differences were found in the mean clothing levels and metabolic rates surveyed in the case-study building compared to the selected RP-884 data sets.

The mean thermal comfort vote of the case-study building was about 4.1, which was lower than the selected RP-884 data sets by 0.3 to 0.6. The percentage of responses voting on the comfortable side was about 71% in the case-study building. This is about 3% less than the average of the RP-884 data sets for the USA as well as Canada; and 13% less than the Australian average. In the percentage distribution of the thermal comfort votes binned into 1.0 vote intervals, the case-study building had the lowest percentage distribution for 5.0 (Comfortable) and 6.0 (Very comfortable) while the highest percentage was observed for 3.0 (Just uncomfortable) and 4.0 (Just comfortable). Overall, the self-reported thermal comfort votes collected in the case-study building were toward the less comfortable side compared to the selected RP-884 benchmarks.

For thermal acceptability, the mean vote of the case-study building was about 1.8, which was similar to the mean vote of the selected RP-884 data sets of Canada and Australia[153]. The percentage of responses voting acceptable was about 79% in the case-study building, which was less than the averages of Canada and Australia by 5 to 6%. Overall, the self-reported thermal

[153] Thermal acceptability votes are not available for the USA data sets.

acceptability votes collected in the case-study building were less acceptable compared to the selected RP-884 benchmarks.

The mean thermal preference vote of the case-study building was about 1.8, which was the same as the mean votes of the selected RP-884 data sets. The percentage of responses voting no change was about 45% in the case-study building, which was 9 to 11% less than the averages of the selected RP-884 data sets. On the other hand, higher percentages of responses were observed for both cooler and warmer. Overall, the self-reported thermal preference votes collected in the case-study building more favored cooler or warmer environments compared to the selected RP-884 benchmarks.

The mean air movement preference vote of the case-study building was about 2.1, which was slightly higher than the mean votes of Canada and Australia[154] by 0.3 to 0.4. The percentages of responses voting less air movement or no change were higher than Canada and Australia by 5 to 12% and by 11 to 23%, respectively. On the other hand, much lower percentage of responses was observed for more air movement. Overall, the self-reported air movement preference votes collected in the case-study building more often favored no change or less air movement environment compared to the selected RP-884 benchmarks.

[154] Air movement preference votes are not available for the USA data sets.

Table 33: Comparison of 'Right-Now' Survey Results against the Selected RP-884 Data Sets

		Case-Study Building	RP-884 Data Sets (Summer, A/C Buildings)										
			USA			Canada		Australia					
			ID 32	ID 44	**AVG**	ID 9	**AVG**	ID 11	ID 14	ID 15	ID 37	ID 48	**AVG**
Sample Size (n)		**84**	673	96	**769**	443	**443**	564	555	512	606	589	**2,826**
Personal Info.													
Age[1]		31-50	NA	NA	NA	41.2	41.2	30.8	33.5	32.5	32.9	35.6	33.1
Gender[2]		0.5	0.6	0.5	0.6	0.5	0.5	0.5	0.5	0.3	0.6	1.5	0.7
Subjective Responses													
Thermal Sensation[3]													
	Mean	-0.3	0.3	0.1	0.2	-0.3	-0.3	0.0	-0.2	0.3	-0.3	0.1	0.0
	% within ±0.5	40%	46%	64%	48%	24%	24%	46%	39%	49%	35%	43%	42%
Thermal Comfort[4]													
	Mean	4.1	4.4	4.8	4.5	4.4	4.4	NA	NA	NA	4.6	4.7	4.7
	% of Comfortable	71%	73%	83%	74%	74%	74%	NA	NA	NA	84%	85%	84%
Acceptability[5]													
	Mean	1.8	NA	NA	NA	1.9	1.9	NA	NA	NA	1.8	1.9	1.8
	% of Acceptable	79%	NA	NA	NA	85%	85%	NA	NA	NA	79%	89%	84%
Thermal Preference[6]													
	Mean	1.8	1.8	2.3	1.8	1.8	1.8	1.9	1.9	1.8	1.8	1.8	1.8
	% of No Change	45%	53%	66%	54%	54%	54%	51%	56%	54%	55%	63%	56%
Air Movement Preference[7]													
	Mean	2.1	NA	NA	NA	2.4	2.4	NA	NA	NA	2.5	2.4	2.5
	% of No Change	55%	NA	NA	NA	32%	32%	NA	NA	NA	42%	47%	44%
Clothing (clo)	Mean	0.59	0.61	0.59	0.61	0.58	0.58	0.56	0.51	0.65	0.44	0.49	0.53
Activity (met)	Mean	1.10	1.13	1.09	1.12	1.22	1.22	1.18	1.17	1.16	1.32	1.33	1.24
Physical Indoor Climate Conditions Measured during the 'Right-Now' Survey													
Air Temp.	Mean	75.6	73.2	73.0	73.2	75.4	75.4	74.8	74.6	74.2	74.6	74.2	74.5
at 24 in. (F)	s.d.	1.4	1.9	1.0	1.8	2.3	2.3	2.1	2.7	2.6	1.7	2.5	2.4
Globe Temp.	Mean	75.2	73.7	73.2	73.6	74.3	74.3	75.1	75.3	74.7	74.8	74.7	74.9
at 24 in. (F)	s.d.	1.0	1.7	1.0	1.7	2.2	2.2	2.2	2.9	2.7	1.8	2.5	2.4
Relative	Mean	38.9	61.9	50.1	60.4	45.1	45.1	53.2	56.4	43.9	56.3	41.5	50.4
Humidity (%)	s.d.	4.2	5.1	2.8	6.3	7.6	7.6	5.0	5.5	6.5	6.3	8.8	9.1
Air Speed (fpm)	Mean	31.1	19.5	18.5	19.4	20.4	20.4	29.8	27.4	20.9	26.3	41.8	33.9
	s.d.	15.5	10.5	5.9	10.1	5.4	5.4	18.9	25.0	10.1	11.1	24.5	20.1
Operative Temp.	Mean	75.4	73.7	73.1	73.6	74.5	74.5	75.1	75.4	74.7	74.8	74.6	74.9
at 24 in. (F)	s.d.	1.1	1.8	0.9	1.7	2.2	2.2	2.2	3.0	2.8	1.8	2.4	2.5
PMV[8]	Mean	-0.23	-0.17	-0.41	-0.20	-0.02	-0.02	-0.04	-0.02	0.04	0.01	-0.16	-0.03
	s.d.	0.37	0.56	0.40	0.55	0.55	0.55	0.55	0.51	0.51	0.51	0.61	0.54
PPD (%)	Mean	8.96	11.96	11.81	11.94	11.12	11.12	11.09	10.50	10.37	10.36	12.77	11.04
	s.d.	4.81	10.98	7.25	10.58	9.58	9.58	11.60	7.93	7.76	7.88	12.96	9.96

NOTES: NA = Not Available

1) Since the survey participants in the case-study building were asked to indicate their age group (1:30 or under, 2:31-50, or 3:Over 50) instead of an actual age, the most common age group was presented in this Table.

2) 0:Male, 1:Female

3) 3:Hot, 2:Warm, 1:Slightly warm, 0:Neutral,-1:Slightly cool, -2:Cool, -3:Cold

4) 6:Very comfortable, 5:Comfortable, 4:Just comfortable, 3:Just uncomfortable, 2:Uncomfortable, 1:Very uncomfortable

5) 1:Not acceptable, 2:Acceptable

6) 1:Cooler, 2:No change, 3:Warmer

7) 1:Less air movement, 2:No change, 3:More air movement

8) To calculate PMV for this comparison, upholstery insulation of about 0.15 clo was added to the surveyed clothing ensemble insulation.

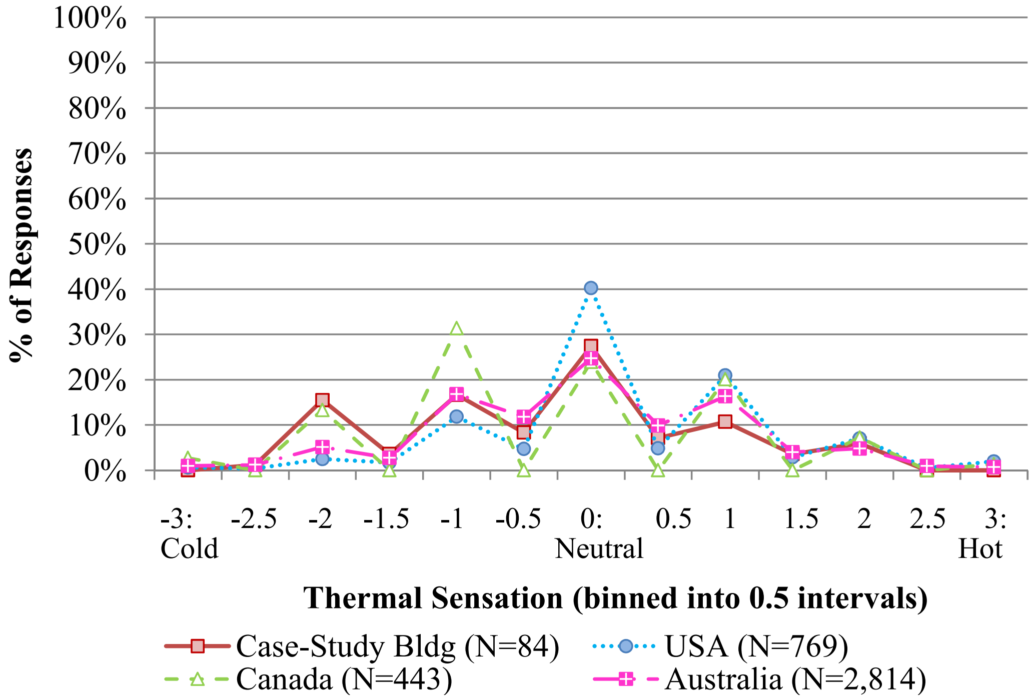


Figure 109: Percentage Distribution of the Self-Reported Thermal Sensation Votes Binned into 0.5 Vote Intervals for the Case-Study Building and the Selected RP-884 Data Sets

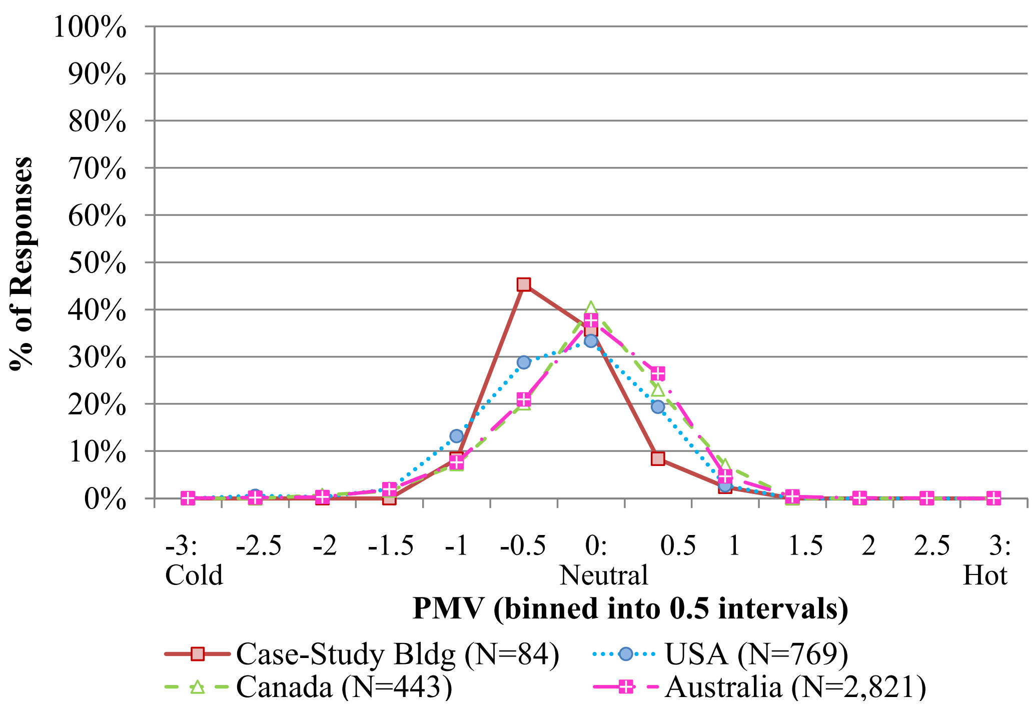


Figure 110: Percentage Distribution of the Calculated PMVs Binned into 0.5 Vote Intervals for the Case-Study Building and the Selected RP-884 Data Sets

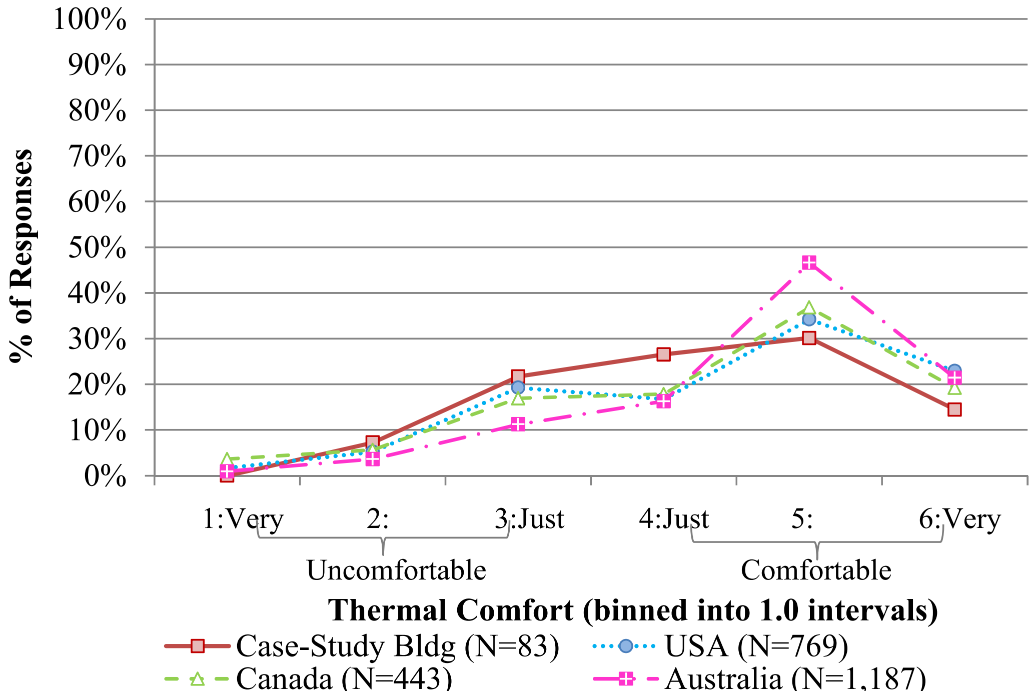


Figure 111: Percentage Distribution of the Self-Reported Thermal Comfort Votes Binned into 1.0 Vote Intervals for the Case-Study Building and the Selected RP-884 Data Sets

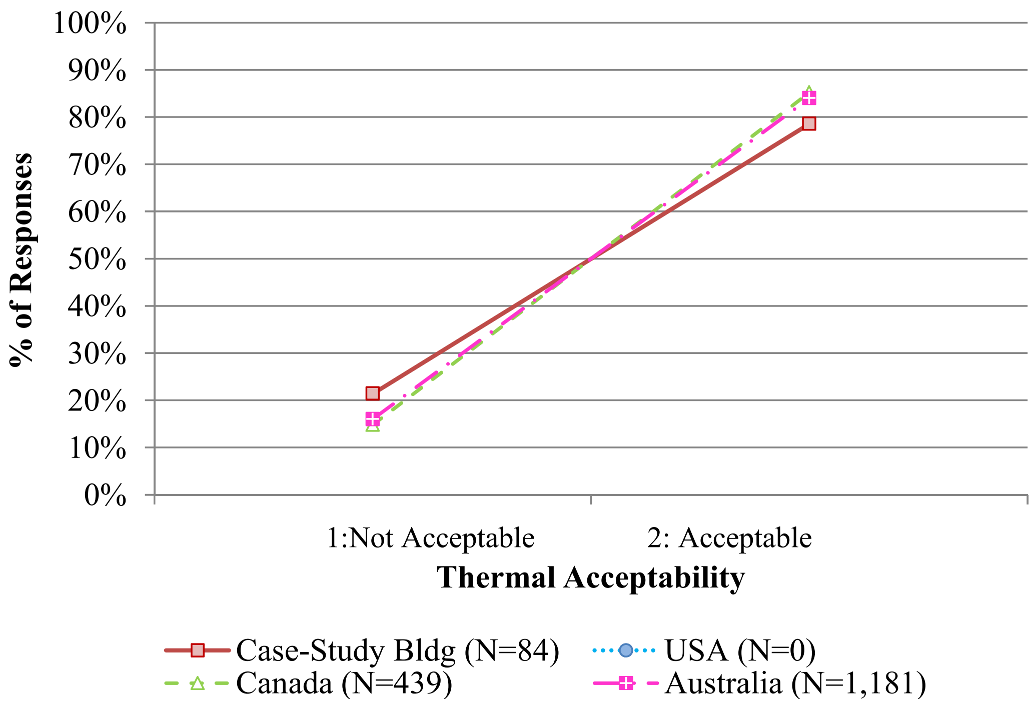


Figure 112: Percentage Distribution of the Thermal Acceptability Votes for the Case-Study Building and the Selected RP-884 Data Sets

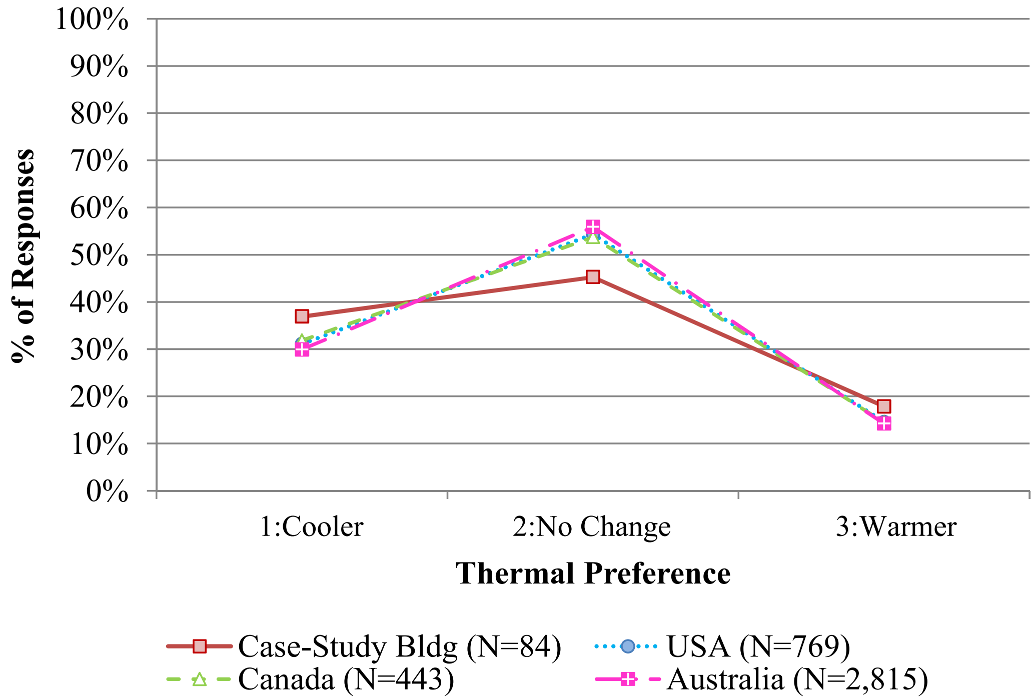


Figure 113: Percentage Distribution of the Thermal Preference Votes for the Case-Study Building and the Selected RP-884 Data Sets

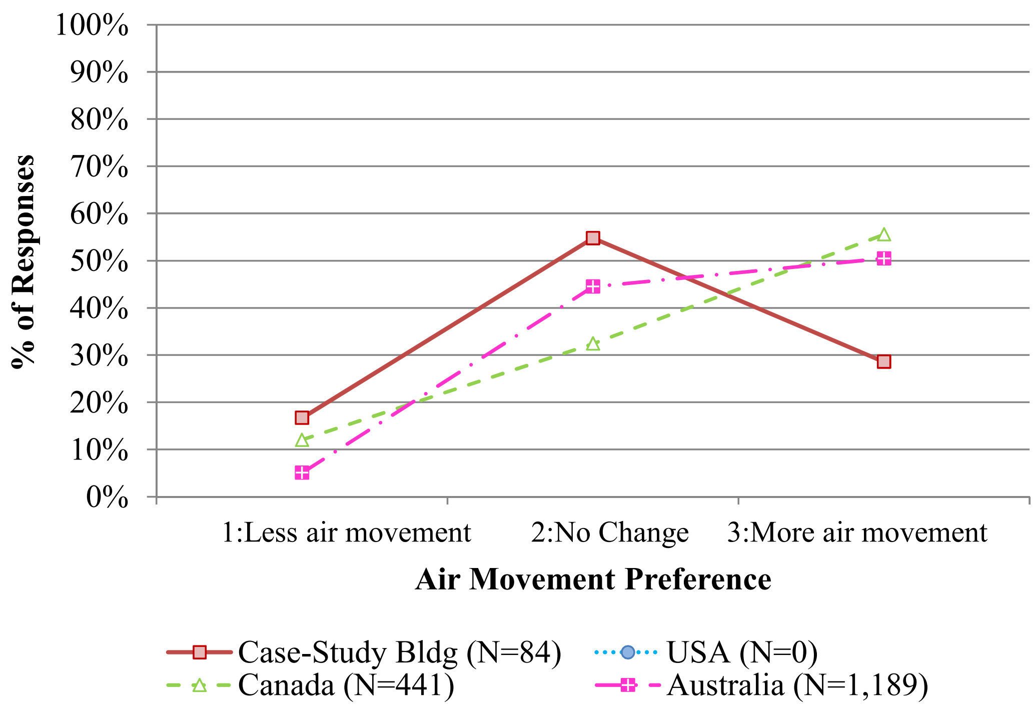


Figure 114: Percentage Distribution of the Air Movement Preference Votes for the Case-Study Building and the Selected RP-884 Data Sets

5.3.2.3. Observations

Observations from the field test of the ASHRAE PMP Intermediate and Advanced Level IEQ protocol are as follows[155]:

- The current version of the ASHRAE PMP Intermediate and Advanced Level IEQ protocols is not a stand-alone document because it relies on multiple external standards and protocols. As currently written, it does not provide enough details that are sufficient for the users to perform the measurements and to compare the results against the benchmarks without referencing other external documents, including: ASHRAE Standard 55-2004 (ASHRAE 2004) and Standard 55-2010 (ASHRAE 2010c), ASHRAE RP-884 database (de Dear 1998), and ASHRAE Standard 62.1-2007 (ASHRAE 2007b) and Standard 62.1-2010 (ASHRAE 2010d)[156].
- The current version of the ASHRAE PMP Intermediate and Advanced Level IEQ protocols references several external standards for benchmarks, including the ASHRAE Standard 55-2004 for thermal comfort and the ASHRAE Standard 62.1-2007 for IAQ. However, newer editions of these standards that supersede the referenced editions in the ASHRAE PMP are currently available, including the ASHRAE Standard 55-2010 and ASHRAE Standard 62.1-2010. Comparisons between the two versions revealed a discrepancy in several provisions between the two versions, which may influence the benchmarking results[157].
- One of the main benchmarks to evaluate thermal comfort performance in the ASHRAE PMP is the ASHRAE Standard 55 compliance provisions. Unfortunately, ASHRAE Standard 55-2004 and Standard 55-2010 do not have criteria on lower humidity limits although non-thermal comfort issues (i.e., skin drying, eye dryness) are recognized in these standards. Low humidity has been reported as one of the contributors to sick building syndrome (SBS) symptoms (Mendell 1993 and Menzies and Bourbeau 1997), and therefore, future edition of the ASHRAE PMP should address it.
- The main benchmarks referenced to evaluate lighting performance in the ASHRAE PMP are Table 3-9 of the ASHRAE PMP and the ISO Standard 8995:2002. Unfortunately, both

155 A shorter observation listed in this section is repeated as an issue in Section 5.3.3.

156 Although the current version of the ASHRAE PMP provides some examples, neither standard procedures nor report formats were established, which does not comply with the objective of the ASHRAE PMP.

157 This includes a removal of turbulence intensity and draft risk calculations in the ASHRAE Standard 55-2010 and a revision of ventilation rates for a few occupancy categories in the ASHRAE Standard 62.1-2010.

benchmarks do not have any criteria on high illuminance limits although complaints were observed in the subjective survey about indoor lighting environments that are too bright.

- The two dissatisfied offices were ventilated adequately based on the CO_2 measurement results. However, the occupants complained about stuffy and stale air due to poor circulation within their room, which could not be verified from the measurements of CO_2 and TVOCs, as recommended by the ASHRAE PMP.
- There were several IEQ issues that could not be verified using the instrumentation cart. Several occupants expressed dissatisfaction although their physical IEQ environments met the criteria specified in the ASHRAE PMP. This may indicate individual differences in subjective IEQ preferences, which could not be quantified using the detailed measurement cart. However, the ASHRAE PMP IEQ protocols do not provide guidelines how to consider or interpret person-to-person variations in the evaluations.
- IEQ spot measurements are helpful to discover possible causes of problems if the measurements are conducted at the same time when the discomfort arises, which is not easy to accomplish. Unfortunately, the ASHRAE PMP Intermediate and Advanced Level lighting and acoustics protocols do not require a continuous measurement while it is required in thermal comfort and IAQ protocols. In this study, large time-of-day variations in the continuously measured lighting and acoustics performance metrics were observed. For example, as expected, the measured illuminance level was highest in the afternoon in west-facing office, while the peak level was observed in the morning in east-facing office.
- To discover possible causes of problems, the IEQ measurements should be conducted at the same location where a specific discomfort arises, which is not easy to accomplish. The ASHRAE PMP Advanced Level thermal comfort protocol suggests replacing the occupant's chair with the measurement cart and collecting data for several minutes. However, this suggestion is not always feasible for continuous measurements when the office is occupied and in use. Meanwhile, the ASHRAE PMP Intermediate and Advanced Level IAQ protocols suggest measurements in representative spaces, which is open to self-interpretation as to exactly what a representative space is.
- The LCeq – LAeq difference can be regarded as a simple indicator to estimate low frequency noise annoyance when a full, octave band frequency analysis is not available due to the practical applicability of octave band measurements, (i.e., very few manufacturers who make the equipment and high equipment costs).

- The ASHRAE PMP Intermediate and Advanced Level IEQ protocols do not provide clear guidelines about how to graphically represent and analysis the results of continuously measured performance metrics, although continuous measurements are required for thermal comfort and IAQ protocols. This study determined a statistical analysis to describe the time-varying distribution of indices: maximum, 95^{th}, median, 5^{th}, and minimum. The 95^{th} and 5^{th} percentiles were chosen to characterize extreme variations based on a ±5% deviation. The median was chosen as a convenient way to describe the average of skewed distributions using a single number for a comparison between locations, while also conveying information about that variation for half the measurement period.
- The ASHRAE PMP Intermediate Level IEQ protocols do not provide clear guidelines how to display and interpret the results of a 'right-now' survey. For example, the ASHRAE PMP IEQ protocols do not provide advice about how to select the appropriate data sets from the extensive ASHRAE RP-884 database, how to compare the results against the selected benchmarks (mean scores versus frequency distributions), or how to interpret the subjective responses with the concurrently measured physical indoor climate conditions.
- Although the ASHRAE RP-884 benchmark database is a satisfactory benchmark covering a wide variety of locations and climate zones from 28 cities all over the world, the database is based on relatively old data sets that had been collected during the 1990's. In addition, most data sets were collected in office buildings in several countries. Of the total 52 data sets, thirteen data sets were from Australia, thirteen were from the USA, and ten were from Pakistan, which are three countries with very different cultures and possibly thermal comfort needs.

5.3.3. *Summary of IEQ Protocol Field-Testing Results*

The IEQ performance metrics required at the ASHRAE PMP Basic, Intermediate, and Advanced Levels energy protocol were calculated and compared against the benchmarks specified in the ASHRAE PMP using a case-study building. Twenty-two issues were noted from the field test and summarized in this section[158]. The recommendations for each identified issue are provided in Section 6.1.1.3. For the selected issues, new or modified approaches are discussed in Section 6.2.3.

- **Issue IEQ-1**: The ASHRAE PMP Basic Level IEQ protocol does not provide clear guidelines about how to display and interpret the results[159].
- **Issue IEQ-2**: Different results may be obtained from different benchmarking sources. For example, in this study occupants' IEQ satisfaction was better than average against the CBE benchmarks in all areas, yet it was worse than average against the ASHRAE Standard 55-2004 and Standard 55-2010 for thermal comfort and sound privacy. However, in the ASHRAE PMP, there is no information on prevailing benchmarks.
- **Issue IEQ-3**: The required metrics for the ASHRAE PMP Basic Level IEQ protocol are the results of the occupant IEQ satisfaction survey and spot measurements of several IEQ parameters. In this study, there were discrepancies between the results of the IEQ satisfaction survey and the following-up spot measurements[160]. However, the ASHRAE PMP does not provide guidance about how to handle the discrepancies in the results between IEQ survey and spot measurements of the same space when they arise.
- **Issue IEQ-4:** The CBE survey questions consist of an evaluation of seven IEQ topics, including: office layout, office furnishings, thermal comfort, IAQ, lighting, acoustics, and cleaning/maintenance. Of these IEQ topics, three topics (i.e., office layout, office furnishing, and cleaning/maintenance) are beyond the scope of the current version of the ASHRAE PMP. Furthermore, the ASHRAE PMP does not provide guidance about what to do with this information.

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[158] A shorter observation listed in Sections 5.3.1.3 and 5.3.2.3 is repeated as an issue in this section.

[159] For example, the ASHRAE PMP IEQ protocol does not provide any advice about how to graphically represent the surveyed IEQ satisfaction and spot measurement results across an entire building; how to compare the results against the benchmarks (i.e., mean scores versus frequency distributions); or how to interpret the survey and spot measurement results of individual offices at the whole-building level.

[160] For example, the measured thermal environments of the occupants who expressed satisfaction in the survey were located outside the summer comfort zone in the ASHRAE Standard 55-2004 and Standard 55-2010.

- **Issue IEQ-5:** Although the CBE benchmark is fully satisfactory benchmarks covering a wide variety of buildings in different locations over a period of years, the benchmarking database for the subjective IEQ survey needs a fully accessible public domain benchmark database where all individual records are available for analysis, to supplement the current CBE benchmark, which only provides summary statistics.
- **Issue IEQ-6:** The ASHRAE PMP Basic Level IEQ protocol does not discuss the seasonal influence on an occupants' subjective IEQ assessment. Although no significant differences were revealed in the surveyed IEQ satisfaction and productivity scores between summer and winter, some differences may result when the building has significantly different operating mode by season[161].
- **Issue IEQ-7:** The ASHRAE PMP Basic Level IEQ protocol does not apply a uniform set of rules on the use of spot measurements. IEQ spot measurements are optional for thermal comfort but required for IAQ, lighting, and acoustics regardless of the results of the IEQ satisfaction survey. Even when the majority of occupants are satisfied with their IAQ, lighting or acoustics environments, the ASHRAE PMP requires physical spot measurements.
- **Issue IEQ-8:** The current version of the ASHRAE PMP does not provide any advice about how to reproduce dissatisfaction when spot measurements are performed. IEQ spot measurements have one major limitation: it is hard to catch dynamic responses of IEQ that often get repeated in a survey. In this study, of the six thermally-dissatisfied offices, three offices maintained similar thermal environments as the satisfied offices using personal fans and a small heater located under the desk. Thus, spot measurements could not confirm the complaints.
- **Issue IEQ-9:** The ASHRAE PMP has no specific measurement protocol that can be used for IEQ spot measurements. Although the lighting and acoustics protocols provide a relatively detailed measurement procedure, they only give a general idea of the procedure rather than detailed step-by-step instructions. A measurement protocol based on step-by-step instructions, which is standardized as much as possible, will reduce the risk of misinterpretation.

[161] A statistical comparison of the mean IEQ satisfaction and productivity scores between summer and winter using independent samples t-test revealed that there were no significant differences between summer and winter groups (Table 25). In the results of paired samples t-test (i.e., dependent samples t-test) using 23 paired data, no significant differences were found between seasons for all four IEQ areas except for lighting level satisfaction (Table 26). The results show that the summer lighting level satisfaction was lower than winter satisfaction with a marginal significance (p = 0.10). Overall, a seasonal influence on the occupants' subjective IEQ assessment was not confirmed in this study.

- **<u>Issue IEQ-10:</u>** The ASHRAE PMP Basic Level presents all six performance categories in one chapter to help users navigate more easily. However, each sub-chapter repeatedly asks the same descriptive information, which could be condensed into one section.
- **<u>Issue IEQ-11:</u>** The current version of the ASHRAE PMP Intermediate and Advanced Level IEQ protocols is not a stand-alone document because it relies on multiple external standards and protocols. As currently written, it does not provide enough details that are sufficient for the users to perform the measurements and compare the results against benchmarks without referencing other external documents, including: ASHRAE Standard 55-2004 (ASHRAE 2004) and Standard 55-2010 (ASHRAE 2010c), ASHRAE RP-884 database (de Dear 1998), and ASHRAE Standard 62.1-2007 (ASHRAE 2007b) and Standard 62.1-2010 (ASHRAE 2010d)[162].
- **<u>Issue IEQ-12:</u>** The current version of the ASHRAE PMP Intermediate and Advanced Level IEQ protocols references several external standards for benchmarks, including the ASHRAE Standard 55-2004 for thermal comfort and the ASHRAE Standard 62.1-2007 for IAQ. However, newer editions of these standards that supersede the referenced editions in the ASHRAE PMP are currently available, including the ASHRAE Standard 55-2010 and ASHRAE Standard 62.1-2010. Comparisons between the different versions revealed a discrepancy in several of the referenced provisions between the two versions, which may influence the benchmarking results. This includes a removal of turbulence intensity and draft risk calculations in the ASHRAE Standard 55-2010 and a revision of ventilation rates for a few occupancy categories in the ASHRAE Standard 62.1-2010.
- **<u>Issue IEQ-13:</u>** One of the main benchmarks to evaluate thermal comfort performance in the ASHRAE PMP is the ASHRAE Standard 55 compliance provisions. Unfortunately, ASHRAE Standard 55-2004 and Standard 55-2010 do not have criteria on lower humidity limits although non-thermal comfort issues (i.e., skin drying, eye dryness) are recognized in these standards. Low humidity has been reported as one of the contributors to sick building syndrome (SBS) symptoms (Mendell 1993 and Menzies and Bourbeau 1997), and therefore, future edition of the ASHRAE PMP should address it.

[162] Although the current version of the ASHRAE PMP provides some examples, neither standard procedures nor report formats were established, which does not comply with the objective of the ASHRAE PMP.

- **Issue IEQ-14:** The main benchmarks referenced to evaluate lighting performance in the ASHRAE PMP are Table 3-9 of the ASHRAE PMP and the ISO Standard 8995:2002. Unfortunately, both benchmarks do not have any criteria on high illuminance limits although complaints were observed in the subjective survey about indoor lighting environments that are too bright.
- **Issue IEQ-15:** The two dissatisfied offices were ventilated adequately based on the CO_2 measurement results. However, the occupants complained about stuffy and stale air due to poor circulation within their room, which could not be verified from the measurements of CO_2 and TVOCs, as recommended by the ASHRAE PMP.
- **Issue IEQ-16:** There were some IEQ issues that could not be verified using the time-series measurements from the instrumentation cart. Several occupants expressed dissatisfaction although their physical IEQ environments met the criteria specified in the ASHRAE PMP. This most likely indicates individual differences in subjective IEQ preferences, which could not be quantified using the detailed measurement cart. However, the ASHRAE PMP IEQ protocols do not provide guidelines how to consider or interpret person-to-person variations in the evaluations.
- **Issue IEQ-17:** IEQ spot measurements are helpful to discover possible causes of problems if the measurements are conducted at the same time when the discomfort arises, which is not easy to accomplish. Unfortunately, the ASHRAE PMP Intermediate and Advanced Level lighting and acoustics protocols do not require continuous measurements while it is required in thermal comfort and IAQ protocols. In this study, large time-of-day variations in time-series measurements of lighting and acoustics performance metrics were observed. For example, as expected, the measured illuminance level was highest in the afternoon in west-facing office, while the peak level was observed in the morning in east-facing office.
- **Issue IEQ-18:** To discover possible causes of problems, the IEQ measurements should be conducted at the same location where a specific discomfort arises, which is not easy to accomplish. The ASHRAE PMP Advanced Level thermal comfort protocol suggests replacing the occupant's chair with the measurement cart and collecting data for several minutes. However, this suggestion is not always feasible for continuous measurements when the office is occupied and in use. In addition, the ASHRAE PMP Intermediate and Advanced Level IAQ protocols suggest measurements in representative spaces, which is open to self-interpretation as to exactly what a representative space is.

- **<u>Issue IEQ-19:</u>** The LCeq – LAeq difference can be regarded as a simple indicator to estimate low frequency noise annoyance when a full, octave band frequency analysis is not available due to the practical applicability of octave band measurements, (i.e., there are very few manufacturers who make the equipment, and the equipment has a high cost).
- **<u>Issue IEQ-20:</u>** The ASHRAE PMP Intermediate and Advanced Level IEQ protocols do not provide clear guidelines about how to analyze the results of continuous, time-series measurements for benchmarking, although continuous measurements are required for thermal comfort and IAQ protocols. This study determined a statistical analysis to describe the time-varying distribution of indices: maximum, 95th, median, 5th, and minimum. The 95th and 5th percentiles were chosen to characterize extreme variations based on a ±5% deviation. The median was chosen as a convenient way to describe the average of skewed distributions using a single number for a comparison between locations, while also conveying information about that variation for half the measurement period.
- **<u>Issue IEQ-21:</u>** The ASHRAE PMP Intermediate Level IEQ protocols do not provide clear guidelines about how to display and interpret the results of a 'right-now' survey. For example, the ASHRAE PMP IEQ protocols do not provide advice about how to select the appropriate data sets from the extensive ASHRAE RP-884 database, how to compare the results against the selected benchmarks (mean scores versus frequency distributions), or how to interpret the subjective responses with the concurrently measured physical indoor climate conditions.
- **<u>Issue IEQ-22:</u>** Although the ASHRAE RP-884 benchmark database is a satisfactory benchmark covering a wide variety of locations and climate zones from 28 cities all over the world, the database is based on relatively old data sets that were collected during the 1990's. In addition, most data sets were collected in office buildings in several different countries. Of the total 52 data sets, thirteen data sets were from Australia, thirteen were from the USA, and ten were from Pakistan, which are three countries with very different cultures and possibly thermal comfort needs.

CHAPTER VI

NEW OR MODIFIED APPROACHES TO IMPROVE THE ASHRAE PMP*

This chapter presents the results of Phase II: Proposed new or modified approaches to improve the ASHRAE PMP. Section 6.1 provides an overall summary of findings from the field test for each performance area, including: energy use, water use, and IEQ (i.e., thermal comfort, IAQ, lighting, and acoustics) with the recommendations for each issue identified. In addition, the applicability of the three levels of measurement approaches in the ASHRAE PMP was examined in terms of validity, reliability and practicality. Section 6.2 presents new or modified approaches to the twelve high-priority issues to improve the current version of the ASHRAE PMP, including five for energy use, two for water use, and six for IEQ protocols.

6.1. Evaluation of the ASHRAE PMP

6.1.1. *Summary of Findings and Recommendations*

6.1.1.1. Energy Use

The energy performance metrics required at the ASHRAE PMP Basic, Intermediate, and Advanced Levels energy protocol were calculated and compared against the benchmarks (either self or external reference) provided in the ASHRAE PMP using a case-study building. Thirteen issues were noted from the field test and summarized in this section with the corresponding recommendations.

- **Issue E-1**: The perceived energy performance of the case-study building is highly dependent on which benchmark the user utilizes. However, different benchmarking sources yield very different results: i.e., worse than average performance against the ASHRAE benchmarks versus average performance against the ENERGY STAR Portfolio Manager benchmarks.
  Recommendation for Issue E-1: The ASHRAE PMP should provide users with a priority ranking of the different benchmarks and should provide advice to the user to help resolve the differences when different results arise from different benchmarks.

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- **<u>Issue E-2</u>**: The energy performance metrics required at the ASHRAE PMP Basic Level are the annual whole-building EUI as well as ECI. However, since the ECI is calculated using unit costs of energy, which were not fixed costs over time. Therefore, there may be time-dependent differences in trends derived between the two indices (i.e., EUI and ECI).
  <u>Recommendation for Issue E-2:</u> The ASHRAE PMP should provide advice to the user to help resolve the differences between two indices when different results arise.

- **<u>Issue E-3:</u>** The energy performance metrics required at the ASHRAE PMP Basic Level are indices at the whole-building level, which are the sum of all energy used in the building. Unfortunately, when the building consumes different energy from two or more sources**,** the metrics calculated separately for each energy source may provide additional insights compared to the combined metrics at the whole-building level without any extra data collection efforts since the data were collected separately for each energy source.
  <u>Recommendation for Issue E-3</u>: It is recommended that calculations of energy performance metrics for each energy source be discussed in the ASHRAE PMP when the building consumes energy from two or more different energy sources. Section 6.2.1.1 of this thesis provides details on this modified approach.

- **<u>Issue E-4</u>**: The ASHRAE PMP suggests two different EUI calculation procedures that are based on different adjustment methods[163]. In this study, for the case-study building, no significant differences were revealed in the EUIs calculated using these two procedures: resulting in a percentage error between -0.39% and 0.69%.
  <u>Recommendation for Issue E-4:</u> Although no significant differences were revealed in the EUIs calculated using these two procedures in this study, some differences could be expected when the billing month is significantly different from the calendar month. Thus, it would be better for the ASHRAE PMP to mention the different adjustment methods (i.e., calendar month versus billing month) for the two EUI calculation methods summarized in Section 5.1.1.1.

[163] In one method, the ENERGY STAR Portfolio Manager adjusted the consumption to fit the calendar month, while in the other method, the ASHRAE Standard 105-2007 selects the analysis period based on the billing period of the energy type with the largest total used to minimize errors associated with the adjustments.

- **<u>Issue E-5</u>**: The ASHRAE PMP Intermediate Level energy protocol requires calculating the inverse energy use models that relate energy use to the appropriate independent variables (i.e., outdoor temperature) for a self-reference comparison. However, the current version of the ASHRAE PMP Intermediate Level energy protocol does not provide any advice about how to ensure a fair level of confidence in the calculated model as well as performance changes (i.e., savings). In this study, the Whole-Building Performance Path of the ASHRAE Guideline 14-2002 (ASHRAE 2002) was referenced in the entire calculation procedure, although the compliance with the ASHRAE Guideline 14-2002 is not required in the current version of the ASHRAE PMP.

  <u>Recommendation for Issue E-5:</u> The ASHRAE PMP should provide advice to the user as to how to ensure a fair level of confidence that the calculated model represents the candidate building and adequately tracks performance changes (i.e., savings). In this study, the Whole-Building Performance Path of the ASHRAE Guideline 14-2002 (ASHRAE 2002) was referenced in the entire calculation procedure to calculate the uncertainty of the regression models used in the self-benchmarking results.

- **<u>Issue E-6</u>**: The ASHRAE PMP does not provide any advice about how to calculate a suitable outdoor temperature index for different types of energy use (i.e., electricity, peak demand, and natural gas use). Although it should be noted that different climate conditions can yield different results, in this study, almost identical results were obtained for the WBE use models from the use of either monthly average of daily minimum and maximum temperatures (T_{minmax}) or monthly average of hourly temperatures (T_{hourly}). However, for cooling demand models, slightly different results were obtained by using monthly maximum outdoor temperature in a billing period ($T_{max\_monthly}$) compared to the other two indices (i.e., maximum of daily min-max average outdoor temperature (T_{max_minmax}); or maximum of daily 24-hour average outdoor temperature (T_{max_24hour})), although the differences were within the range of uncertainties [164]. For natural gas models, the savings calculated with the T_{min} model were slightly higher than the savings with the T_{minmax} model by 40 to 47 MCF/yr per year. However, the difference was within the range of uncertainties.

[164] About 66 to 150 kW/yr higher savings were estimated using $T_{max\_monthly}$ due to a larger temperature deviation between $T_{max\_monthly}$ and the other two indices from 2008 to 2011 compared to 2007.

Recommendation for Issue E-6: The ASHRAE PMP should provide advice to the user as to how to calculate a suitable outdoor temperature index to calculate the ASHRAE IMT models for different types of energy use (i.e., electricity, demand, or natural gas). Section 5.1.2.2 provides a comparison of several outdoor temperature indices for whole-building electricity, demand, and natural gas use models.

- **Issue E-7**: In the calculated savings at the Intermediate Level (Figure 45), consistently lower (or negative) savings were observed in February of each year. This may indicate an under-prediction of the base-load consumption using the base year 2007 model due to holiday periods in December and January when energy use was less. When the building has a different operating mode for holidays, the monthly 3-P cooling model is likely to under-predict the base-load consumption due to holidays in December and January. At the annual-level calculation, a lower savings in February may be offset by an over-predicted savings in December and January. However, the accuracy of such a model is limited. Not surprisingly, the computed net determination biases of the baseline models were higher than the acceptable level required in the ASHRAE Guideline 14-2002, which indicates a high level of uncertainty in the baseline models based on the 3-P cooling change-point models with a single independent variable (i.e., outdoor temperature). Therefore, an issue was found that the instructions in the current version of the ASHRAE PMP are not enough about the building that has a different operating mode for holidays.

  Recommendation for Issue E-7: It is recommended that the ASHRAE PMP provide a modeling method that can be used when the building has a different operating mode for holidays with a better accuracy. Thus, a modified approach proposed in Section 6.2.1.2 of this thesis would fix the issue with the under-predicted base-load consumption of 3-P model due to holidays as well as the issue with high net determination biases of the baseline models.

- **Issue E-8**: The ASHRAE PMP does not describe how to deal with outliers for the inverse regression models when they are present in the dataset. In this study, several data points of peak demand were found to be inconsistent with other data, and therefore, the models calculated with these outlying data points did not represent the dataset well (i.e., a low R^2 and a high CV-RMSE[165]). However, the models without outliers were better determined with a higher R^2 between 0.61 and 0.91 as well as a lower CV-RMSE between 1.9% and 6.5%. In addition, it was found that the monthly outliers can provide useful information that may be helpful to detect some operational problems in the building.

Recommendation for Issue E-8: The ASHRAE PMP should provide advice to the user how to deal with outliers for the IMT models when they are present in the dataset as well as how to interpret the outliers to detect some operational problems in the building. Section 5.1.2.2 of this thesis provides a new method tested in this study to identify potential outliers[166] as well as one example of using outliers to find out some operational problems in the building. In this study, it was found that the use of ±1.5 CV-RMSE criteria of the calculated IMT 3-P cooling models was useful to detect suspected outliers for 3-P cooling models.

- **Issue E-9**: One of the energy performance metrics required at the Intermediate Level is the measurement of major end-use energy use, which requires a high level of data collection, data management and analysis. However, the ASHRAE PMP does not provide any advice about end-use benchmarks or how to benchmark the calculated energy use indices from the end-use data against a reliable, external reference.

  Recommendation for Issue E-9: It is recommended that the ASHRAE PMP provide reliable, external reference that can be used to benchmark the calculated major end-use energy use indices for a broad range of commercial buildings.

- **Issue E-10**: The energy performance metrics required at the Advanced Level used daily or hourly energy use for the whole building and major end-uses. However, the ASHRAE PMP does not provide detailed techniques or data analysis procedures that show how to interpret and analyze data at the daily or hourly level.

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165 The models with outliers had a R^2 between 0.11 and 0.81 as well as CV-RMSE between 5.2% and 16.0%.

166 To identify potential outliers, this study compared two different methods. The first method used a box and whisker plot. The data points beyond 25th and 75th quartiles by one and a half times the interquartile range (IQR = 75th quartile – 25th quartile) were considered potential outliers, which is commonly used in statistics (Emerson and Strenio 1983). The second method used the IMT 3-P cooling models that were initially calculated with all data points. The data points beyond ±1.5 CV-RMSE of the calculated IMT 3-P cooling models were considered suspected outliers. As a result, the box and whisker plot method was found effective to detect extreme outliers. However, it failed to account for a seasonal variation in peak demand. Thus the outliers that were identified using the second method were excluded in the final IMT models.

Recommendation for Issue E-10: The ASHRAE PMP should provide detailed techniques or procedures about how to interpret and analyze these high resolution data and references to related work. In this study, it was found that the use of three-dimensional, hourly electricity usage profiles for the whole-building and the major end-uses was useful in revealing several interesting features that were not identified using time-series plots. Details on this new method are provided in Section 5.1.3.1 of this thesis.

- **Issue E-11**: The current version of the ASHRAE PMP Advanced Level energy protocol relies on external standards and protocols, which prevents the ASHRAE PMP from being a stand-alone document. Currently, it does not provide details that are sufficient enough for the users to install and calibrate the equipment to take the measurements of daily or hourly energy use without referring to external documents, including the ASHRAE Guideline 14 (ASHRAE 2002) and CIBSE TM39 (CIBSE 2006b).
  Recommendation for Issue E-11: The ASHRAE PMP should provide details that are sufficient enough for the users to perform the measurements without referencing other external documents to become more of a stand-alone document.

- **Issue E-12**: The ASHRAE PMP does not provide discussions about how to use chiller operation data to investigate a building's energy performance as well as how to evaluate the chiller performance data against external benchmarks. It was found that sub-hourly chiller electricity use data was helpful in diagnosing the causes of the observed abnormally high peak demand. In this study, an inspection of additional chiller operation data (i.e., supply and return temperature and water flow) along with the 15 minute chiller electricity use data revealed that several abnormally high peaks occurred during the erroneous simultaneous operation of the two chillers or during periods of the startup of a chiller after a short-term shutdown.
  Recommendation for Issue E-12: It is recommended that the ASHRAE PMP includes a method about how to use hourly or sub-hourly chiller operation data to diagnose abnormal energy use behavior due to improper chiller operation. Since chillers are one of the largest energy consumers in a building in a cooling dominated climate, it would be also advisable for the ASHRAE PMP to include procedures about how to evaluate measured chiller performance data against external benchmarks. Section 6.2.1.3 of this thesis provides this new

approach of how to use chiller operation data to investigate a building's energy performance as well as how to benchmark it against external reference.

- **Issue E-13**: Different levels of the ASHRAE PMP procedures yield different performance evaluations of the same building. For example, slightly lower savings were indicated with the Advanced Level electric demand analysis using the maximum 90th percentile of the diversity factor compared to the electric demand savings calculated at the Intermediate Level based on monthly billed electric demand.
  Recommendation for Issue E-13: The ASHRAE PMP should provide advice to the user to help resolve the differences when different performance ratings arise from the application of different performance evaluation PMP levels to the same building.

6.1.1.2. Water Use

The water performance metrics required at the ASHRAE PMP Basic and Intermediate Levels water protocol were calculated and compared against the benchmarks provided in the ASHRAE PMP using a case-study building. Five issues were noted from the field test and summarized in this section with the corresponding recommendations.

- **Issue W-1**: The observed water performance of the case-study building is highly dependent on the benchmark the user utilizes. However, there were no benchmarks provided for buildings that have atypical spaces (i.e., office building with gymnasium shower facilities). Furthermore, different benchmarking sources may yield different performance ratings.
  Recommendation for Issue W-1: The ASHRAE PMP should provide users with advice about how to adjust the benchmarks for buildings that have atypical spaces (i.e., office building with gymnasium shower facilities) as well as advice about how to help resolve the differences when different performance ratings arise from different benchmarks (i.e., a priority ranking of the different referenced benchmarks).

- **Issue W-2:** The water performance metric required at the ASHRAE PMP Basic Level is the annual total site WUI, including water consumption of a building as well as landscape. However, the ASHRAE PMP benchmark data sets are provided separately for a building and landscape. Therefore, the water performance metric required at the ASHRAE PMP Basic Level cannot be directly compared to the benchmark references provided in the PMP.

Recommendation for Issue W-2: The ASHRAE PMP Basic Level water protocol should provide users with combined benchmarks that can be directly comparable to the required performance metrics without requiring sub-metering of end-uses.

- **Issue W-3:** The ASHRAE PMP Basic Level water protocol requires users to normalize water consumption of the building by the number of occupants or landscape areas. However, there are no clear guidelines about how to estimate and track the number of occupants and/or irrigated landscape areas associated with a building.
  Recommendation for Issue W-3: The ASHRAE PMP should provide clear guidelines how to estimate occupants and/or irrigated landscape areas.

- **Issue W-4:** The water performance metrics required at the ASHRAE PMP Intermediate Level are the annual and monthly water use index (WUI) separately for a total building, landscape, and wastewater. Unfortunately, the current version of the ASHRAE PMP does not provide any external-reference benchmarking data for these metrics. However, there are separate benchmarks for the annual index that can be directly comparable to the required Intermediate Level water performance metrics based on the findings in Section 5.2.1.3.
  Recommendation for Issue W-4: The ASHRAE PMP should provide users with external-reference benchmarks for the annual WUI that are currently provided in the Basic Level water protocol in addition to self-reference comparisons.

- **Issue W-5:** There are few detailed analysis techniques or modeling methods to analyze and evaluate a building's water performance beyond a log of the calculated WUIs[167]. In the current version of the ASHRAE PMP in the Section on Performance Evaluation/Benchmarking, several water savings strategies are discussed instead of evaluation/benchmarking methods. Although these savings strategies are helpful information for the users, they do not provide information about any benchmarks.
  Recommendation for Issue W-5: The ASHRAE PMP should provide detailed analysis techniques or modeling methods to analyze and evaluate water performance rather than water

[167] For example, the ASHRAE PMP water protocol does not require normalizing water use data for weather, it is hard to confirm whether this high increase was affected by changing weather conditions or other operation and maintenance (O&M) issues.

savings strategies. For example, the combination 3-P, multi-variable regression model that was developed in this study using outdoor temperature and precipitation amount/occurrence as independent variables has been shown to be useful. Section 6.2.2.1 of this thesis provides details on this new method.

6.1.1.3. IEQ (Thermal Comfort, IAQ, Lighting, and Acoustics)

The IEQ performance metrics required at the ASHRAE PMP Basic, Intermediate, and Advanced Levels energy protocol were calculated and compared against the benchmarks specified in the ASHRAE PMP using a case-study building. Twenty-two issues were noted from the field test and summarized in this section.

- **Issue IEQ-1**: The ASHRAE PMP Basic Level IEQ protocol does not provide clear guidelines about how to display and interpret the results[168].

  Recommendation for Issue IEQ-1: The ASHRAE PMP Basic Level IEQ protocol should provide users with clear guidelines about how to display and interpret the results, including: a graphical index that synthesizes the collected information across an entire building and a numerical ranking of the different indices (i.e., mean scores versus frequency distributions). In this study, a graphical index for displaying the surveyed IEQ satisfaction votes was developed. Section 6.2.3.1 of this thesis provides details on this new approach.

- **Issue IEQ-2**: Different results may be obtained from different benchmarking sources. For example, in this study occupants' IEQ satisfaction was better than average against the CBE benchmarks in all areas, yet it was worse than average against the ASHRAE Standard 55-2004 and Standard 55-2010 for thermal comfort and sound privacy. However, in the ASHRAE PMP, there is no information on prevailing benchmarks.

  Recommendation for Issue IEQ-2: The ASHRAE PMP Basic Level IEQ protocol should provide users with a priority ranking of the different guidelines and should provide advice to the user to help resolve the differences when different results arise from the different benchmarks.

[168] For example, the ASHRAE PMP IEQ protocol does not provide any advice about how to graphically represent the IEQ survey results and spot measurement results across an entire building; how to compare the results against the benchmarks (i.e., mean scores versus frequency distributions); or how to interpret the survey and spot measurement results of individual offices at the whole-building level.

- **Issue IEQ-3**: The required metrics for the ASHRAE PMP Basic Level IEQ protocol are the results of the occupant IEQ satisfaction survey and spot measurements of several IEQ parameters. In this study, there were discrepancies between the results of the IEQ satisfaction survey and the following-up spot measurements[169]. However, the ASHRAE PMP does not provide guidance about how to handle the discrepancies in the results between IEQ survey and spot measurements of the same space when they arise.

  Recommendation for Issue IEQ-3: The ASHRAE PMP Basic Level IEQ protocol should provide advice to the user about how to interpret the results when different results arise between subjective and instrumented measurements of the same space.

- **Issue IEQ-4:** The CBE survey questions consist of an evaluation of seven IEQ topics, including: office layout, office furnishings, thermal comfort, IAQ, lighting, acoustics, and cleaning/maintenance. Of these IEQ topics, three topics (i.e., office layout, office furnishing, and cleaning/maintenance) are beyond the scope of the current version of the ASHRAE PMP. Furthermore, the ASHRAE PMP does not provide guidance about what to do with this information.

  Recommendation for Issue IEQ-4: It is recommended for the ASHRAE PMP Basic Level IEQ protocol to determine the appropriateness of using a full set of the CBE survey questions as one of the required performance metrics in the ASHRAE PMP.

- **Issue IEQ-5:** Although the CBE benchmark is fully satisfactory benchmarks covering a wide variety of buildings in different locations over a period of years, the benchmarking database for the subjective IEQ survey needs a fully accessible public domain benchmark database where all individual records are available for analysis, to supplement the current CBE benchmark, which only provides summary statistics.

  Recommendation for Issue IEQ-5: The ASHRAE PMP Basic Level IEQ protocol should provide a fully accessible public domain benchmark database to supplement the current CBE benchmarks.

[169] For example, the measured thermal environments of the occupants who expressed satisfaction in the survey were located outside the summer comfort zone in the ASHRAE Standard 55-2004 and Standard 55-2010.

- **Issue IEQ-6:** The ASHRAE PMP Basic Level IEQ protocol does not discuss the seasonal influence on an occupants' subjective IEQ assessment. Although no significant differences were revealed in the surveyed IEQ satisfaction and productivity scores between summer and winter, some differences may result when a building has significantly different operating modes by season[170].
  Recommendation for Issue IEQ-6: It would be an improvement for the ASHRAE PMP Basic Level IEQ protocol to provide information about the seasonal influence on an occupants' subjective IEQ assessment and to provide advice about how to sample seasonality.

- **Issue IEQ-7:** The ASHRAE PMP Basic Level IEQ protocol does not apply a uniform set of rules on the use of spot measurements. IEQ spot measurements are optional for thermal comfort but required for IAQ, lighting, and acoustics regardless of the results of the IEQ satisfaction survey. Even when the majority of occupants are satisfied with their IAQ, lighting or acoustics environments, the ASHRAE PMP requires physical spot measurements.
  Recommendation for Issue IEQ-7: The ASHRAE PMP Basic Level IEQ protocol should provide a uniform set of rules to all four IEQ areas to be more consistent.

- **Issue IEQ-8:** The current version of the ASHRAE PMP does not provide any advice about how to reproduce dissatisfaction when spot measurements are performed. IEQ spot measurements have one major limitation: it is hard to catch dynamic responses of IEQ that often get repeated in a survey. In this study, of the six thermally-dissatisfied offices, three offices maintained similar thermal environments as the satisfied offices using personal fans and a small heater located under the desk. Thus, spot measurements could not confirm the complaints because there was no protocol to determine how the presence of portable heating/cooling equipment was to be accounted for.
  Recommendation for Issue IEQ-8: The ASHRAE PMP Basic Level IEQ protocol should consider providing advice about how to reproduce dissatisfaction reported in a survey when

[170] A statistical comparison of the mean IEQ satisfaction and productivity scores between summer and winter using independent samples t-test revealed that there were no significant differences between summer and winter groups (Table 25). In the results of paired samples t-test (i.e., dependent samples t-test) using 23 paired data, no significant differences were found between seasons for all four IEQ areas except for lighting level satisfaction (Table 26). The results show that the summer lighting level satisfaction was lower than winter satisfaction with a marginal significance ($p = 0.10$). Overall, a seasonal influence on the occupants' subjective IEQ assessment was not confirmed in this study.

Basic Level spot measurements are used, or provide advice about how to collect and analyze dynamic measurements in light of rapidly evolving field instruments and data loggers.

- **Issue IEQ-9:** The ASHRAE PMP has no specific measurement protocol that can be used for IEQ spot measurements. Although the lighting and acoustics protocols provide some recommendations for spot measurements, they are general guidelines rather than detailed step-by-step instructions. A measurement protocol based on step-by-step instructions, which is standardized as much as possible, will reduce the risk of misinterpretation.
  Recommendation for Issue IEQ-9: It is recommended for the ASHRAE PMP Basic Level IEQ protocol provides a specific step-by-step measurement protocol that can be applied to overall IEQ spot measurements. In this study, to accomplish uniformity, a specific IEQ spot measurement protocol for office spaces was developed and used with the corresponding data collection form presented in the Appendix A. The proposed protocol is presented in Section 4.1.4.1 of this thesis.

- **Issue IEQ-10:** The ASHRAE PMP Basic Level presents all six performance categories in one chapter to help users navigate more easily. However, each sub-chapter repeatedly asks the same descriptive information, which could be condensed into one section.
  Recommendation for Issue IEQ-10: It would be more efficient to use the ASHRAE PMP Basic Level protocol if it provided a combined set of questions related to the basic building and system characteristics that could be used by all six categories of the ASHRAE PMP and then referenced the set of questions in other section as needed.

- **Issue IEQ-11:** The current version of the ASHRAE PMP Intermediate and Advanced Level IEQ protocols is not a stand-alone document because it relies on multiple external standards and protocols. As currently written, it does not provide enough details that are sufficient for the users to perform the measurements and compare the results against benchmarks without referencing other external documents, including: ASHRAE Standard 55-2004 (ASHRAE 2004) and Standard 55-2010 (ASHRAE 2010c), ASHRAE RP-884 database (de Dear 1998), and ASHRAE Standard 62.1-2007 (ASHRAE 2007b) and Standard 62.1-2010 (ASHRAE 2010d)[171].

Recommendation for Issue IEQ-11: The ASHRAE PMP Intermediate and Advanced Level IEQ protocols need to become more than a combination of several standards for each performance category. The ASHRAE PMP also needs to provide details that are sufficient enough for the users to perform the measurements without having to reference other external documents.

- **Issue IEQ-12:** The current version of the ASHRAE PMP Intermediate and Advanced Level IEQ protocols references several external standards for benchmarks, including the ASHRAE Standard 55-2004 for thermal comfort and the ASHRAE Standard 62.1-2007 for IAQ. However, newer editions of these standards that supersede the referenced editions in the ASHRAE PMP are currently available, including the ASHRAE Standard 55-2010 and ASHRAE Standard 62.1-2010. Comparisons between the different versions revealed a discrepancy in several of the referenced provisions between the two versions, which may influence the benchmarking results[172].

  Recommendation for Issue IEQ-12: It is recommended that the ASHRAE PMP Intermediate and Advanced Level IEQ protocols clarify which versions of benchmarking standards to be used when a new edition becomes available. If more than one version is required, then the ASHRAE PMP should state why and prioritize the different version, if needed.

- **Issue IEQ-13:** One of the main benchmarks to evaluate thermal comfort performance in the ASHRAE PMP is the ASHRAE Standard 55 compliance provisions. Unfortunately, ASHRAE Standard 55-2004 and Standard 55-2010 do not have criteria on lower humidity limits although non-thermal comfort issues (i.e., skin drying, eye dryness) are recognized in these standards. Low humidity has been reported as one of the contributors to sick building

[171] Although the current version of the ASHRAE PMP provides some examples, neither standard procedures nor report format were not established, which does not comply with the objective of the ASHRAE PMP.

[172] This includes a removal of turbulence intensity and draft risk calculations in the ASHRAE Standard 55-2010 and a revision of ventilation rates for a few occupancy categories in the ASHRAE Standard 62.1-2010.

syndrome (SBS) symptoms (Mendell 1993 and Menzies and Bourbeau 1997), and therefore, future edition of the ASHRAE PMP should address it.

Recommendation for Issue IEQ-13: The ASHRAE PMP IEQ protocols should consider providing reliable benchmarks for acceptable low humidity limits.

- **Issue IEQ-14:** The main benchmarks referenced to evaluate lighting performance in the ASHRAE PMP are Table 3-9 of the ASHRAE PMP and the ISO Standard 8995:2002. Unfortunately, both benchmarks do not have any criteria on high illuminance limits although complaints were observed in the subjective survey about indoor lighting environments that are too bright.

  Recommendation for Issue IEQ-14: The ASHRAE PMP IEQ protocols should consider providing reliable benchmarks for acceptable high illuminance limits.

- **Issue IEQ-15:** The two dissatisfied offices were ventilated adequately based on the CO_2 measurement results. However, the occupants complained about stuffy and stale air due to poor circulation within their room, which could not be verified from the measurements of CO_2 and TVOCs, as recommended by the ASHRAE PMP.

  Recommendation for Issue IEQ-15: It is recommended that the ASHRAE PMP Intermediate and Advanced Level IAQ protocols discuss how to use a vertical temperature profile of a room as a simple indicator to evaluate room air circulation. Section 6.2.3.2 of this thesis provides details on this new approach, which was used to diagnose air circulation problems in these two dissatisfied offices.

- **Issue IEQ-16:** There were some IEQ issues that could not be verified using the time-series measurements from the instrumentation cart. Several occupants expressed dissatisfaction although their physical IEQ environments met the criteria specified in the ASHRAE PMP. This most likely indicates individual differences in subjective IEQ preferences, which could not be quantified using the detailed measurement cart. However, the ASHRAE PMP IEQ protocols do not provide guidelines how to consider or interpret person-to-person variations in the evaluations.

Recommendation for Issue IEQ-16: The ASHRAE PMP IEQ protocols should provide advice to the users how to interpret person-to-person variations in the evaluations when different results arise between subjective and instrumented measurements in the same space.

- **Issue IEQ-17:** IEQ spot measurements are helpful to discover possible causes of problems if the measurements are conducted at the same time when the discomfort arises, which is not easy to accomplish. Unfortunately, the ASHRAE PMP Intermediate and Advanced Level lighting and acoustics protocols do not require continuous measurements while it is required in thermal comfort and IAQ protocols. In this study, large time-of-day variations in time-series measurements of lighting and acoustics performance metrics were observed. For example, as expected, the measured illuminance level was highest in the afternoon in west-facing office, while the peak level was observed in the morning in east-facing office.
Recommendation for Issue IEQ-17: The ASHRAE PMP Intermediate and Advanced Level IEQ protocols should consider providing advice about how to collect and analyze dynamic or time-series measurements, or should adequately explain the limitation of spot measurements (i.e., for example that it is hard to catch dynamic responses) with advice about how to interpret the results when continuous measurements are not available. Section 6.2.3.3 of this thesis provides a new method about how to collect and analyze dynamic measurements.

- **Issue IEQ-18:** To discover possible causes of problems, the IEQ measurements should be conducted at the same location where a specific discomfort arises, which is not easy to accomplish. The ASHRAE PMP Advanced Level thermal comfort protocol suggests replacing the occupant's chair with the measurement cart and collecting data for several minutes. However, this suggestion is not always feasible for continuous measurements when the office is occupied and in use. In addition, the ASHRAE PMP Intermediate and Advanced Level IAQ protocols suggest measurements in representative spaces, which is open to self-interpretation as to exactly what a representative space is.
Recommendation for Issue IEQ-18: The ASHRAE PMP Intermediate and Advanced Level IEQ protocols should provide detailed continuous measurement protocols, including the location where to perform the measurements and advice about how to address asymmetric issues with the field measurements.

- **<u>Issue IEQ-19:</u>** The LCeq – LAeq difference can be regarded as a simple indicator to estimate low frequency noise annoyance when a full, octave band frequency analysis is not available due to the practical applicability of octave band measurements, (i.e., there are very few manufacturers who make the equipment, and the equipment has a high cost).
  <u>Recommendation for Issue IEQ-19</u>: It is recommended that the ASHRAE PMP Intermediate and Advanced Level acoustics protocols include the cost-effective method, proposed in this thesis to evaluate low frequency noise annoyance in the room as a low-cost alternative to the octave band frequency analysis. Section 5.3.2.2 of this thesis provides details on how to apply this new method to diagnose low frequency noise annoyance in the case-study building.

- **<u>Issue IEQ-20:</u>** The ASHRAE PMP Intermediate and Advanced Level IEQ protocols do not provide clear guidelines about how to analyze the results of continuous, time-series measurements for benchmarking, although continuous measurements are required for thermal comfort and IAQ protocols. This study determined a statistical analysis to describe the time-varying distribution of indices: maximum, 95^{th}, median, 5^{th}, and minimum. The 95^{th} and 5^{th} percentiles were chosen to characterize extreme variations based on a ±5% deviation. The median was chosen as a convenient way to describe the average of skewed distributions using a single number for a comparison between locations, while also conveying information about that variation for half the measurement period.
  <u>Recommendation for Issue IEQ-20</u>: It is recommended that the ASHRAE PMP Intermediate and Advanced Level IEQ protocols include clear guidelines about how to analyze the results of continuous, time-series measurements for benchmarking. Section 5.3.2.2 of this thesis provides details on a new method used in this study that describes the time-varying distribution of indices using statistical and graphical analysis.

- **<u>Issue IEQ-21:</u>** The ASHRAE PMP Intermediate Level IEQ protocols do not provide clear guidelines about how to display and interpret the results of a 'right-now' survey. For example, the ASHRAE PMP IEQ protocols do not provide advice about how to select the appropriate data sets from the extensive ASHRAE RP-884 database, how to compare the results against the selected benchmarks (mean scores versus frequency distributions), or how to interpret the subjective responses with the concurrently measured physical indoor climate conditions.

Recommendation for Issue IEQ-21: The ASHRAE PMP Intermediate Level IEQ protocols should provide users with clear guidelines about how to display and interpret the results of a 'right-now' survey, including: a method about how to synthesize appropriate benchmarks; a ranking of the different indices (i.e., mean scores versus frequency distributions); and a method about how to analyze subjective responses with instrumented measurement results.

- **Issue IEQ-22:** Although the ASHRAE RP-884 benchmark database is a satisfactory benchmark covering a wide variety of locations and climate zones from 28 cities all over the world, the database is based on relatively old data sets that were collected in the 1990's. In addition, most data sets were collected in office buildings in several different countries. Of the total 52 data sets, thirteen data sets were from Australia, thirteen were from the USA, and ten were from Pakistan.

Recommendation for Issue IEQ-22: The ASHRAE PMP should note the limitations of the existing ASHRAE RP-884 database and should provide advice to the user to help resolve the issues when the appropriate benchmarks are not available.

6.1.2. *Applicability Evaluations*

The applicability of the three levels of measurement approaches in the ASHRAE PMP was examined in terms of validity, reliability and practicality of each level of the protocols based on a scale from 1 (very bad) to 5 (very good). Evaluation criteria were developed in three domains: validity, reliability and practicality, which were built upon the framework originally suggested by the Malmqvist and Glaumann (2006). For each domain, two questions were addressed to evaluate the validity, reliability and practicality of each level of the protocols, as shown in Tables 34 to 36. Although this procedure is based on a subjective evaluation, the intent is to clarify the problems and issues associated with the current version of the ASHRAE PMP as well as to allow a systematic comparison of the current methods against the proposed new or modified approaches.

6.1.2.1. Energy Use

Table 34 presents the scores assigned to each evaluation question for the Basic, Intermediate and Advanced Level of the ASHRAE PMP energy protocols that were field tested under this study with related issues discussed in Section 6.1.1.1.

a) Level I: Basic Level

For the case-study building, the average assigned score of the Basic Level energy protocol was 4.2. The required metrics (i.e., annual whole-building energy use index (EUI) and an energy cost index (ECI)) were regarded as valid indicators that provided a quick characterization of a building's energy performance against reliable benchmarks. However, one area for improvement was identified regarding the calculation of separate metrics for each energy source (Issue E-3). Several reliability issues were also found with the current version of the ASHRAE PMP, including different results obtained from the use of different benchmarks (Issue E-1), different metrics (Issue E-2), and different procedures (Issue E-4). The costs required to perform the measurement were seen as very reasonable since the procedure only required utility bills and a modest amount of personnel time. Once routines were developed, the calculation procedures were fairly simple and quick. In addition, public domain software was freely available to use: ENERGY STAR Portfolio Manager (EPA 2010b), which helped with the Basic Level evaluations.

b) Level II: Intermediate Level

The average assigned score of the Intermediate Level energy protocol was 2.9. The required metrics (i.e., monthly energy use and demand as well as major end-use energy use) were regarded as valid indicators that provided an enhanced level of evaluation of a building's energy performance. However, the ASHRAE PMP failed to provide reliable, external benchmarks (Issue E-9), which does not satisfy the objective of the ASHRAE PMP. Several reliability issues were also found, including no guidelines about how to ensure reliability of the computed self-benchmarking results (Issue E-5). no guidelines about how to calculate a suitable outdoor temperature index for the inverse regression models (Issue E-6), under-predicted base load of the monthly 3-P cooling models when the building has a different operating mode for holidays (Issue E-7), and no guidelines about how to deal with outliers for the inverse models (Issue E-8). The cost requirements were different for the different metrics. For monthly energy use and demand, the costs were seen as very reasonable since the procedure only required utility bills and a limited amount of personnel time. However, for major end-use assessment, a much higher level of data collection efforts were required for a sub-metering in addition to more frequent technical support.

Table 34: Applicability Evaluation of ASHRAE PMP Energy Use Protocols

		Basic (Indicative)		Intermediate (Diagonostic)		Advanced (Investigative)	
		Assigned Scores[1]	Related Issues	Assigned Scores[1]	Related Issues	Assigned Scores[1]	Related Issues
Validity							
1	Content Validity: to what extent do the metrics measure the intended aspect of performance?	4.0	E-3	4.0		4.0	E-12
2	Criterion Validity: do comparable external benchmarks exist?	4.0		1.0	E-9	1.0	
Reliability							
1	Accuracy: to what extent do the procedures (methods) yield accurate results?	3.0	E-1,2	2.0	E-5,6,7,8	3.0	E-5,13
2	Repeatability: to what extent do the procedures (methods) yield repeatable results?	4.0	E-4	3.0	E-5,6,8	3.0	E-5,10
Practicality							
1	Cost: how costly is it to perform the intended measurements?	5.0		3.5		2.0	
2	Ease-of-Measurement: how easy is it to accomplish the intended measurements?	5.0		4.0		3.0	E-11
Average		**4.2**		**2.9**		**2.7**	

NOTES:
1) 1: Very bad; 3: Average; 5: Very good

c) Level III: Advanced Level

The average assigned score of the Advanced Level energy protocol was 2.7. The required metrics (i.e., daily or hourly energy use for the whole building and major end-uses) were regarded as valid indicators that provided a comprehensive evaluation of a building's energy performance. However, several areas for improvement of validity were also identified such as how to use chiller operation data (Issue E-12). In terms of criterion validity, the ASHRAE PMP failed to provide reliable, external benchmarks, which does not comply with the objective of the ASHRAE PMP. Several reliability issues were also found, including that no guidelines were provided about how to ensure reliability of the computed self-benchmarking results (Issue E-5); different results were obtained from different methods (Issue E-13); and no guidelines were provided about how to interpret and analyze the high resolution data (Issue E-10). Not surprisingly, the costs required to perform the measurement were high for collecting sub-hourly data by end-use. The data collection procedure also required high-level and frequent technical support for installation, operation, maintenance, and data quality assurance. In addition, to initiate the measurements, multiple external standards and protocols needed to be referenced since the current version of the ASHRAE PMP did not provide details that were sufficient enough to perform the measurements (Issue E-11).

6.1.2.2. Water Use

Table 35 presents the scores assigned to each evaluation question for the Basic and Intermediate Level of the water protocols that were field tested under this study with related issues discussed in Section 6.1.1.2.

a) Level I: Basic Level

The average assigned score of the Basic Level water protocol was 3.8. The required metrics (i.e., annual total site water use index (WUI) and water cost index (WCI)) were regarded as valid indicators that provided a quick characterization of a building's water performance against reliable benchmarks. However, one area for improvement of criterion validity was also identified; the provided benchmarks could not be directly comparable to the required metrics (Issue W-2). Several reliability issues were also found, including that different performance ratings were yielded by different benchmarks (Issue W-1) and no guidelines were provided about how to estimate the number of occupants and landscape areas (Issue W-3). The costs required to perform the measurement were seen as very good since the procedure only requires utility bills and personnel time. However, since the water consumption of the building needed to be normalized by the number of occupants (Issue W-3), additional efforts were needed to track the number of occupants.

b) Level II: Intermediate Level

The average assigned score of the Intermediate Level energy protocol was 3.3. The required metrics (i.e., annual water use index (WUI) separately for a total building, landscape, and wastewater) were regarded as valid indicators that provided an enhanced level of evaluation of a building's water performance. However, the ASHRAE PMP failed to provide detailed

Table 35: Applicability Evaluation of ASHRAE PMP Water Use Protocols

		Basic (Indicative)		Intermediate (Diagonostic)	
		Assigned Scores[1]	Related Issues	Assigned Scores[1]	Related Issues
Validity					
1	*Content Validity:* to what extent do the metrics measure the intended aspect of performance?	4.0		3.0	W-5
2	*Criterion Validity:* do comparable external benchmarks exist?	3.0	W-2	1.0	W-4
Reliability					
1	*Accuracy:* to what extent do the procedures (methods) yield accurate results?	3.0	W-1,3	3.0	W-1,3
2	*Repeatability:* to what extent do the procedures (methods) yield repeatable results?	4.0	W-3	4.0	W-3
Practicality					
1	*Cost:* how costly is it to perform the intended measurements?	5.0		5.0	
2	*Ease-of-Measurement:* how easy is it to accomplish the intended measurements?	4.0	W-3	4.0	W-3
Average		**3.8**		**3.3**	

NOTES:
1) 1: Very bad; 3: Average; 5: Very good

analysis techniques or modeling methods to analyze and evaluate water performance (Issue W-5) as well as reliable, external benchmarks (Issue W-4), which did not comply with the objective of the ASHRAE PMP. For the criteria of reliability and practicality, the same issues that were identified in the Basic Level were found to still exist in this Intermediate Level water protocol, and the same scores were assigned.

6.1.2.3. IEQ (Thermal Comfort, IAQ, Lighting, and Acoustics)

Table 36 presents the scores assigned to each evaluation question for the Basic, Intermediate and Advanced Level of the IEQ protocols that were field tested under this study with related issues discussed in Section 6.1.1.3.

a) Level I: Basic Level

The average assigned score of the Basic Level IEQ protocol was 3.0 for thermal comfort, 3.2 for IAQ, 3.3 for lighting, and 3.3 for acoustics. The required metrics (i.e., the results of the occupant IEQ satisfaction survey and spot measurements of several IEQ parameters) were regarded as valid indicators that provided a quick characterization of a building's IEQ performance against reliable benchmarks. However, several areas for improvement were also identified, including: clarification of using a full set of the CBE survey form (Issue IEQ-4); clarification of different requirements of spot measurements across four areas (i.e., optional for thermal comfort versus mandatory for other areas) (Issue IEQ-7); and the need for a fully

Table 36: Applicability Evaluation of ASHRAE PMP IEQ Protocols

		Basic (Indicative)					Intermediate (Diagonostic)					Advanced (Investigative)				
		Assigned Scores[1,2]				Related Issues	Assigned Scores[1,2]				Related Issues	Assigned Scores[1,2]				Related Issues
		TC	IAQ	L	A		TC	IAQ	L	A		TC	IAQ	L	A	
Validity																
1	*Content Validity:* to what extent do the metrics measure the intended aspect of performance?	3.0	4.0	4.0	4.0	IEQ-4,7	4.0	3.5	4.0	4.0	IEQ-15	4.0	3.5	4.0	4.0	IEQ-15
2	*Criterion Validity:* do comparable external benchmarks exist?	3.0	3.0	3.0	3.0	IEQ-5	3.5	4.0	3.5	4.0	IEQ-13,14, 22	3.5	4.0	3.5	4.0	IEQ-13,14
Reliability																
1	*Accuracy:* to what extent do the procedures (methods) yield accurate results?	3.0	3.0	3.0	3.0	IEQ-2,3,6,8	3.0	3.0	3.0	3.0	IEQ-12,16, 17,18	3.0	3.0	3.0	3.0	IEQ-12,16, 17,18
2	*Repeatability:* to what extent do the procedures (methods) yield repeatable results?	3.0	3.0	3.0	3.0	IEQ-6,8,9	3.5	3.5	3.0	3.0	IEQ-17,18, 20,21	3.5	3.5	3.0	3.0	IEQ-17,18, 20
Practicality																
1	*Cost:* how costly is it to perform the intended measurements?	3.0	3.0	3.5	3.5		3.0	3.0	2.0	2.0	IEQ-19	3.0	2.0	4.0	2.0	
2	*Ease-of-Measurement:* how easy is it to accomplish the intended measurements?	3.0	3.0	3.0	3.0	IEQ-1,6,8,9, 10	3.0	3.0	3.0	3.0	IEQ-11,17, 18	3.0	3.0	3.0	3.0	IEQ-11,17, 18
Average		**3.0**	**3.2**	**3.3**	**3.3**		**3.3**	**3.3**	**3.1**	**3.2**		**3.3**	**3.2**	**3.4**	**3.2**	

NOTES:
1) 1: Very bad; 3: Average; 5: Very good
2) TC: Thermal Comfort, IAQ: Indoor Air Quality, L: Lighting, A: Acoustics

accessible public domain benchmark for the occupant IEQ satisfaction survey(Issue IEQ-5). Some reliability issues were also found with the current version of the ASHRAE PMP, including: different results yielded by different benchmarks (Issue IEQ-2); different results between subjective versus instrumented measurements (Issue IEQ-3); no advice about how to resolve the issue of sampling during different seasons (Issue IEQ-6); no advice about how to reproduce dissatisfaction (Issue IEQ-8); and a lack of a step-by-step measurement protocol for IEQ spot measurements (Issue IEQ-9).

The costs required to perform the measurement were slightly different for the different performance areas due to the different costs of instruments required for the spot measurements. Generally, it was seen as average since it required both the occupant IEQ satisfaction survey and spot measurements of several IEQ parameters, which needed a higher level of data collection, compared to the Basic Level energy and water protocols. In terms of an ease-of-measurement, several issues were identified, including: no guidelines about how to display and interpret the results (Issue IEQ-1); no advice about how to resolve the issue with sampling during different seasons (Issue IEQ-6); no advice about how to reproduce dissatisfaction (Issue IEQ-8); a lack of a step-by-step measurement protocol for IEQ spot measurements (Issue IEQ-9); and a lack of a combined set of questions related to the basic building and system characteristics (Issue IEQ-10).

b) Level II: Intermediate Level

The average assigned score of the Intermediate Level IEQ protocol was 3.3 for thermal comfort, 3.3 for IAQ, 3.1 for lighting, and 3.2 for acoustics. The required metrics (i.e., the results of the occupant 'Right-now' thermal comfort survey and diagnostic lighting satisfaction survey in addition to the instrumented measurements of several IEQ parameters) were regarded as valid indicators that provided an enhanced level of evaluation of a building's IEQ performance against reliable benchmarks. However, several areas for improvement were also identified, including: the need for a method to evaluate room air circulation (Issue IEQ-15); a need for reliable benchmarks for acceptable low humidity limit (Issue IEQ-13); a need for reliable benchmarks for acceptable high illuminance limit (Issue IEQ-14); and a need to improve the existing ASHRAE RP-884 database (Issue IEQ-22). Some reliability issues were also found with the current version of the ASHRAE PMP, including: version issues of benchmarking standards (Issue IEQ-12); different results between subjective versus instrumented measurements (Issue IEQ-16); limitation of spot measurements for lighting and acoustics protocols (i.e., no advice on time-of day variations in measured variables) (Issue IEQ-17); no advice about how to consider the asymmetric nature of field measurements for thermal comfort, IAQ, and acoustics protocols (Issue IEQ-18); no guidelines about how to display and analysis continuous measurements (Issue IEQ-20); and no guidelines about how to display and interpret the results of 'right-now' survey (Issue IEQ-21).

The costs required to perform the field measurements were slightly different for the different performance areas due to the different costs of the instruments. Generally, it was seen as average or worse than average since accurate measurements required high-cost instruments as well as a higher level of data collection efforts. In terms of an ease-of- measurement, several issues were identified, including: a high reliance on multiple external standards and protocols (Issue IEQ-11); limitations of spot measurements for lighting and acoustics protocols (Issue IEQ-17); and no advice about how to consider the asymmetric nature of field measurements for thermal comfort, IAQ, and acoustics protocols (Issue IEQ-18).

c) Level III: Advanced Level

The average assigned score of the Advanced Level IEQ protocol was 3.3 for thermal comfort, 3.2 for IAQ, 3.4 for lighting, and 3.2 for acoustics. Since this study performed one field test that covered both the Intermediate and Advanced Level IEQ protocols[173], the assigned scores and related issues found at the Advanced Level were almost same as those at the Intermediate Level, with the exception of cost. The costs required to perform the Advanced Level measurement were slightly different from the cost required at the Intermediate Level due to the different costs of instruments between the two levels. For example, the Advanced Level IAQ protocol required a continuous measurement of $PM_{2.5}$ and TVOCs that required a much higher cost than the CO_2 continuous measurements at the Intermediate Level. Meanwhile, the Advanced Level lighting protocol required a high dynamic range (HDR) photography, which could be performed with a suitably equipped camera on a tripod[174]. Thus a lower cost was expected compared to the full grid illuminance and luminance measurements required at the Intermediate Level, which also suggested that an application of HDR for the Intermediate Level lighting evaluations would be desirable.

[173] One field test that covered both levels was developed and applied to the case-study building since both levels require similar data collection efforts of several IEQ parameters.
[174] The HDR image can be created by combining eight to ten high resolution photos using the freeware, Photosphere software (Anyhere 2010).

6.2. New or Modified Approaches to Improve the ASHRAE PMP

6.2.1. *Energy Use*

Of the thirteen issues noted from the field test, two modified approaches and three new approaches are proposed in this study for the following five issues:

- **Issue E-3:** The energy performance metrics required at the ASHRAE PMP Basic Level are indices at the whole-building level, although the data were previously collected separately for each energy source.
- **Issue E-7**: An issue was found that the instructions for calculating a monthly regression model in the current version of the ASHRAE PMP are not enough about the building that has a different operating mode for holidays.
- **Issue E-8**: The ASHRAE PMP does not describe how to deal with outliers for the IMT models when they are present in the dataset.
- **Issue E-10**: The energy performance metrics required at the Advanced Level used daily or hourly energy use for the whole building and major end-uses. However, the ASHRAE PMP does not provide detailed techniques or data analysis procedures that show how to interpret and analyze data at the daily or hourly level.
- **Issue E-12**: The ASHRAE PMP does not provide discussions about how to use chiller operation data to investigate a building's energy performance as well as how to evaluate the chiller performance data against external benchmarks.

Two of the three new approaches were addressed during the field test. Thus details on these two new approaches are presented in Section 5.1.2.2 for the Issue E-8 and Section 5.1.3.1 for Issue E-10.

6.2.1.1. Modified Approaches to Issue E-3: Separate Indices for Each Energy Source

In addition to the annual whole-building EUI and ECI that are required at the ASHRAE PMP Basic Level, the energy use and cost metrics were calculated separately for each energy source in this modified approach. The advantages of using these separate indices were then examined compared to the indices at the whole-building level. Figures 115 and 116 show the annual moving average whole-building total energy, electricity, and natural gas EUI (kBtu/ft^2·yr) and ECI (\$/ft^2·yr) of the case-study building calculated using the two procedures suggested in the ASHRAE PMP: ASHRAE Standard 105-2007 (ASHRAE 2007a) and the ENERGY STAR Portfolio Manager (EPA 2010b) from 2007 to 2012. In addition to these procedures, EUIs and

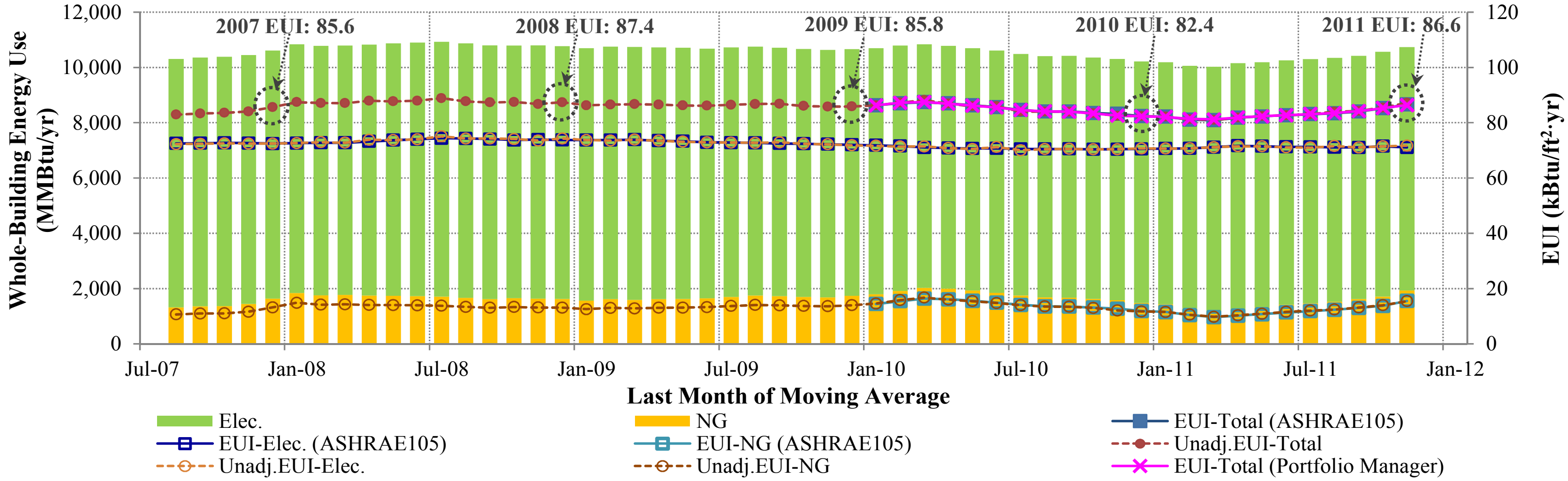


Figure 115: Annual Moving Average Whole-Building Electricity and Natural Gas Energy Use (Left Axis) and EUIs (Right Axis)

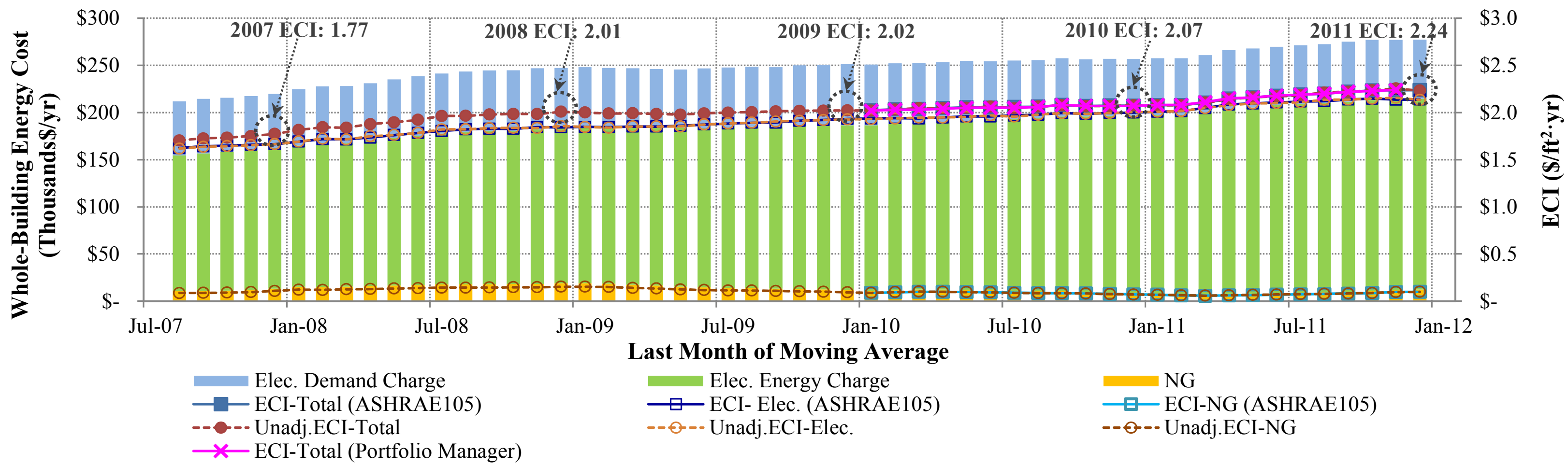


Figure 116: Annual Moving Average Whole-Building Electricity and Natural Gas Energy Cost (Left Axis) and ECIs (Right Axis)

ECIs were calculated without any adjustments and plotted in the figures as shown. The line graphs (right axis) show the EUIs (Figure 115) and ECIs (Figure 116) of the total and different fuel types calculated using different adjustment methods. The stacked bar charts (left axis) show the annual moving average whole-building electricity and natural gas use (MMBtu/yr) and cost (thousands$/yr) before applying normalization by the gross floor area of the building. The total height of the stacked bar represents the annual, moving average whole-building total energy use and cost.

Compared to the indices at the whole-building level (Figures 34 and 35), the proposed approach revealed that the metrics calculated separately for electricity and natural gas could give additional information that was helpful in understanding why energy performance of a building increased or decreased. First, using this new modified approach, the analysis could identify the areas where performance has improved or deteriorated. In the calculated, annual whole-building EUI of the case-study building over the entire analysis period, a variation was observed: between 80.9 and 88.9 kBtu/ft^2·yr. This variation was mainly caused by fluctuations in natural gas energy use performance, which varied between 9.7 and 16.4 kBtu/ft^2·yr. The electricity energy use performance of a building was relatively constant, varying between 70.4 and 74.4 kBtu/ft^2·yr.

The modified approach also gave information about how the different energy source contributed to the overall energy use of a building, which may provide the ASHRAE PMP users with a priority for the next level assessment. In the analysis of the case-study building, it was found that the case-study building's energy use was dominated by electricity use, which accounted for more than 80% of total site energy use in a building. Thus to improve the overall energy efficiency of the building, an assessment of electricity use should take priority over assessing natural gas consumption for the next level analysis since it represents such a large portion of the energy use and cost.

When comparing the cost indices calculated at the whole-building level against the indices calculated separately for electricity and natural gas, not surprisingly, the modified approach could identify additional information related to the demand charge in regards to the overall energy cost of a building. In this analysis, it was found that about 23% to 27% of the total energy cost of the case-study building was demand-related, about 66% to 74% was related to electricity use, and only 3% to 8% was related to natural gas use over the analysis period. Therefore, a higher priority would need to be given to an assessment of electricity use, which could include recommendations about reducing electric demands.

When applying the same evaluation criteria (i.e., validity, reliability, and practicality) that were used to evaluate the existing ASHRAE PMP procedures[175] to the proposed approach, the modified approach is expected to improve the validity of the ASHRAE PMP Basic Level energy protocol with additional characterization of the building's energy performance listed above. The scores for other criteria, reliability and practicality, remain the same since no additional data collection were necessary to perform this modified approach.

6.2.1.2. Modified Approaches to Issue E-7: 3-P Multi-Variable Regression Model for Energy Use

In this modified approach, a combination 3-P, multi-variable regression (3-P MVR) cooling model was developed using outdoor temperature and the number of holidays as an independent variable. The advantages of using the 3-P MVR model were then examined compared to the monthly 3-P cooling model.

a) Previous Studies on the Energy Use Model Including Occupancy

The energy use of commercial building is an internal-load dominated building that is sensitive to occupancy as well as weather conditions. Therefore, extra caution should be taken in the use of inverse models for weather normalization when the base load varies with ambient temperature, as pointed out by Rabl et al. (1986). There have been studies that examined a method about how to account for occupancy variable in regression models with daily or hourly data. Haberl and Vajda (1988b) showed how to adjust a daily variable-base degree day model using day-of-the week to account for occupancy variable. Abushakra and Claridge (2001) defined a dummy variable as a proxy for occupancy to estimate hourly energy consumption. Kim et al. (2011) modeled the daily data separately for weekdays and weekends.

However, few studies have examined the inclusion of an occupancy variable in a regression model to predict weather-normalized monthly energy consumption of a building using monthly data. Rabl and Rialhe (1992) tested the use of occupancy as an additional variable for a variable-base degree day model. Their dummy variable was defined to estimate occupancy, which was a fraction of occupied days to the total number of days for the period. They found the

[175] The applicability of the three levels of measurement approaches in the ASHRAE PMP was examined in terms of validity, reliability and practicality of each level of the protocols based on a scale from 1 (very bad) to 5 (very good). Evaluation criteria were developed in three domains: validity, reliability and practicality, which were built upon the framework originally suggested by the Malmqvist and Glaumann (2006). Details are presented in Section 6.1.2.1.

addition of occupancy significantly improved the model for ten of the thirty buildings[176] partly due to ambiguity in the assignment of days to the occupied versus unoccupied, for example, partially-conditioned Saturdays.

Sonderegger (1998) also examined the impact of adding an occupancy variable for a variable-base degree day monthly model. He found that for school buildings, the inclusion of occupancy (i.e., number of attendance days or number of occupancy hours) would improve the model fit.

To consider occupancy fluctuations in school buildings, Landman (1998) compared all monthly data models against the two separate models for summer months and school year months using multi-year monthly data. Not surprisingly, he showed that the two separate models for summer months and school year months for school buildings improved the results significantly.

However, all three previous studies did not differentiate holidays from weekends[177]. In addition, the building type examined in the two of them (Sonderegger 1998; Landman 1998) was a school building, which typically has completely different occupancy characteristics from an office building. Although the study by Rabl and Rialhe (1992) examined general commercial buildings, they used a variable-base degree day model for weather normalization, while the method proposed in this study uses a temperature dependent regression model that has been widely used to determine weather-normalized savings in commercial buildings (Kissock et al. 1998).

b) Proposed 3-P MVR Monthly WBE Use Model Including Occupancy

In this case study, a combination 3-P MVR cooling model was developed using outdoor temperature and a variable for the number of holidays (Thanksgiving and Christmas) as independent variables. The proposed method is intended to be used when the building has a different operating mode for holidays[178]. Once the models are calculated with the proposed method using the data collected from the case-study building, the changes in energy performance

[176] In this paper, it was considered significant if the regression model was improved when the standard error was reduced by more than 10%.
[177] In these three studies, both weekends and holidays were classified as "unoccupied periods." If a building has a completely different operating mode for holidays versus the weekends, an improvement from using the approaches in these three studies would not be significant.
[178] It was found that the monthly 3-P cooling model under-predicted the base-load consumption due to low energy use during the holidays in December and January since the building has a significantly different operating mode for holidays. From the hourly WBE and OBE usage profiles in Figures 58 and 59, it was confirmed that the fans were shut down for the Thanksgiving and Christmas holidays.

of the building (i.e., savings[179]) were calculated against the baseline year 2009. The calculated savings were then compared against the savings estimated with the monthly 3-P cooling model as well as the daily 3-P cooling models for weekdays, weekends, and holidays.

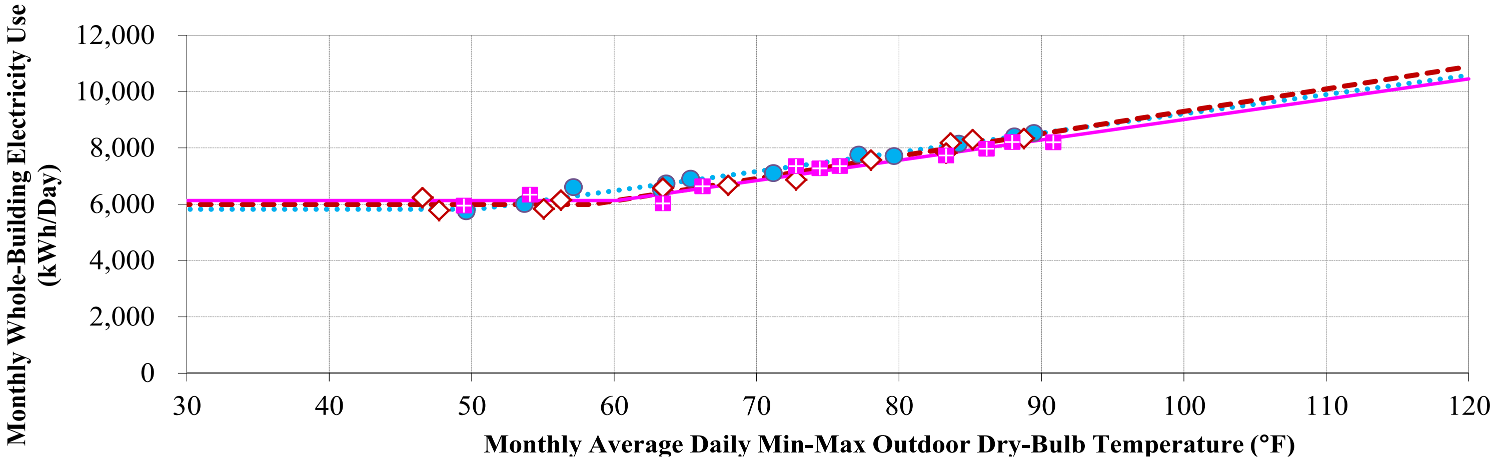
Figure 117 shows monthly whole-building electricity use normalized on a daily average basis against the monthly average of daily minimum and maximum temperatures (T_{minmax}) with (a) the 3-P cooling change-point model and (b) the 3-P MVR model represented with two lines. The proposed 3-P MVR model is: $E = Ycp + CS \times (T_{minmax} - Tcp)^{+} + X2 \times$ (Number of holidays), in which: E = monthly whole-building electricity use (kWh/day); Ycp = base load (kWh/day); CS = cooling slope (kWh/day/F); T_{minmax} = monthly average of daily minimum and maximum temperatures (F); Tcp = chance point temperature (F); and X2 = coefficient for occupancy (kWh/day-no. of holidays). In the figure, the upper and lower lines represent the models with a number of holidays =0 and 10, respectively. To eliminate net bias error due to billing period variation, each of the eleven or twelve data points was weighted by the number of days in the corresponding billing period, which is one of the compliance requirements of the ASHRAE Guideline 14-2002[180]. The model coefficients and statistical indicators are presented in Table 37.

The results showed that an addition of an occupancy variable (i.e., the number of holidays, Thanksgiving and Christmas holiday period) improved the model fit with a higher R^2 (i.e., from 0.98 to 0.99 in 2009, from 0.97 to 0.98 in 2010, and from 0.95 to 0.99 in 2011) as well as reduced CV-RMSE (i.e., from 1.8% to 1.3% in 2009, from 2.4% to 1.9% in 2010, and from 2.5% to 1.4% in 2011) for all years which means the proposed 3-P MVR models are an improved representation of the data set. The net determination biases of the two baseline 2009 models were also calculated and compared[181]. The calculated net determination bias in this study was: −0.025% for the 3-P model and −0.0001% for the 3-P MVR model. Therefore, the use of the proposed 3-P MVR model with a holiday variable significantly reduced the net determination bias to an acceptable level required in the ASHRAE Guideline 14-2002, which is 0.005% or

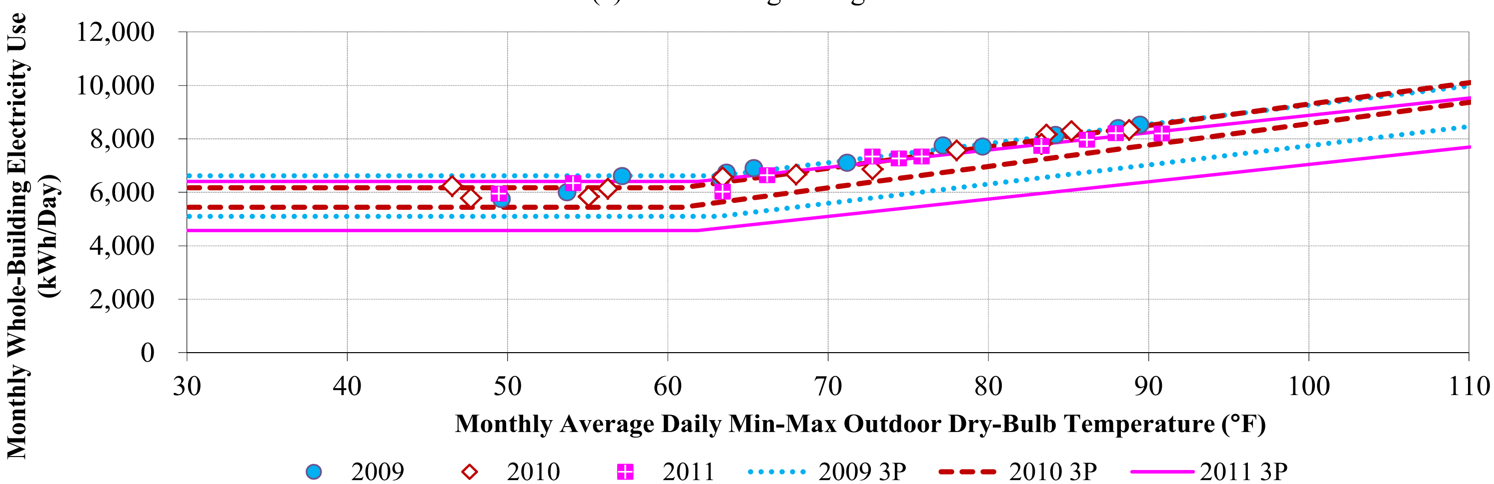
[179] In this dissertation, the word “savings” is used to denote the changes in energy or water use performance against the baseline year. Negative savings means increased energy or water use against the baseline year.

[180] Section 6.1.3.3 of the ASHRAE Guideline 14-2002 says “By using the average daily consumption (monthly consumption divided by reading period days), the regression procedure must use a weighted regression technique.”

[181] The net determination bias is used to test the algorithm (i.e., baseline model) for savings determination by comparing the energy use determined by the baseline model against the actual baseline energy usage. The ASHRAE Guideline 14-2002 (ASHRAE 2002) requires a net determination bias to be less than 0.005% per Section 5.2.10.



(a) 3-P Cooling Change-Point Model



(b) 3-P Multi-Variable Regression Model Represented with Two Lines (The Upper and Lower Lines Represent the Months with a Number of Holidays =0 and 10, Respectively.)

Figure 117: Monthly WBE Use versus Monthly Outdoor Temperature, Including (a) 3-P Cooling Change-Point Models and (b) 3-P Multi-Variable Regression Models for the Years from 2009 to 2011

Table 37: Model Coefficients and Statistical Indicators for Monthly WBE Use Models for (a) 3-P Cooling Change-Point Models and (b) 3-P Multi-Variable Regression Models for the Years from 2009 to 2011

(a) 3-P Cooling Change-Point Model

Coefficient	Description	2009 (N=12)	2010 (N=12)	2011 (N=11)[1]
Ycp	Base load (kWh/day)	5,814	5,983	6,131
CS	Cooling slope (kWh/day/ΔF)	68.4	79.5	72.1
Tcp	Change point temperature (F)	50.4	58.4	60.2
R^2	Squared correlation coefficients	0.98	0.97	0.95
CV-RMSE	Coefficient of variation of the root mean square error (%)	1.8%	2.4%	2.5%

(b) 3-P Multi-Variable Regression Model

Coefficient	Description	2009 (N=12)	2010 (N=12)	2011 (N=11)[1]
Ycp	Base load (kWh/day)	6,621	6,176	6,409
CS	Cooling slope (kWh/day/ΔF)	71.8	79.9	64.9
Tcp	Change point temperature (F)	63.2	60.9	61.9
X2	Coefficient for occupancy (kWh/day/no. of holidays)	-151.9	-73.6	-184.5
t-statistic	t-statistic of coefficient for occupancy	51.7	17.8	27.7
R^2	Squared correlation coefficients	0.99	0.98	0.99
CV-RMSE	Coefficient of variation of the root mean square error (%)	1.3%	1.9%	1.4%

NOTES:
1) December data was eliminated due to a change of occupancy in a case-study building in December 2011.

below.

The coefficients for occupancy variable (i.e., number of Thanksgiving and Christmas holidays) varied between −73.6 and −184.5 kWh/day-no. of holidays by year. The t-statistics (i.e., the value of the coefficient divided by its standard error) of the coefficients for occupancy variable were calculated between 18 and 52, which were higher than the criteria value for t-statistic (which is 2 or higher) provided in the Annex D of the ASHRAE Guideline 14-2002. Thus, the inclusion of occupancy variable would be statistically significant independent variable to predict the WBE use consumption.

c) Comparison of the Computed Savings in WBE Use

The savings[182] were calculated for 2010 and 2011 against the baseline year 2009 by subtracting the billed, actual consumption from the predicted consumption using the calculated models (i.e., both monthly 3-P cooling model and the proposed 3-P MVR model) for 2009. The calculated savings were then compared against the savings estimated with the daily 3-P cooling models for weekdays, weekends, and holidays, as shown in Figure 118 and Table 38. Figure 119 shows the three baselines models (i.e., 2009) used to calculate the savings, including the monthly 3-P model, the monthly 3-P MVR model represented with two lines (i.e., the upper and lower lines representing the models with a number of holidays =0 and 10, respectively), and the daily 3-P models with three lines for weekdays, weekends, and holidays.

The uncertainties associated with the calculated savings were also determined at the two levels of confidence: 68% and 95%, and the uncertainties with a 95% level of confidence are listed in the table[183]. The uncertainties at a 68% level of confidence were calculated to determine whether they met the requirements specified in the Whole-Building Performance Path of the ASHRAE Guideline 14-2002 (ASHRAE 2002). It was found that the calculated uncertainties at the 68% level of confidence to be lower than the maximum level of uncertainty required in this guideline, which is 50% of annual reported savings at 68% confidence.

Clearly, the use of the proposed 3P-MVR model fixed the issue that the monthly 3-P cooling model under-predicted the monthly base-load consumption of the case-study building due to Thanksgiving and Christmas holidays in December and January in addition to the issue of

[182] In this dissertation, the word "savings" is used to denote the changes in energy or water use performance against the baseline year. Negative savings means increased energy or water use against the baseline year.
[183] The uncertainties in savings were calculated based on the revised ASHRAE Guideline 14-2012 working draft, Measurement of Energy and Demand Savings (ASHRAE 2012).

the high net determination bias of the baseline models. At the annual-level savings calculation, it was found that the monthly 3-P cooling model underestimated the savings compared to the daily model by 25% for 2010 and 24% for 2011. Using the proposed 3-P MVR model, a difference against the daily model was reduced to 20% for 2010 and 11% for 2011. The uncertainties associated with the computed savings were also reduced with the 3-P MVR model. At the 95% confidence level, the calculated uncertainties were: 42 to 43 MWh/yr with the 3-P model; and 35 to 36 MWh/yr with the 3-P MVR model. Thus, the 3-P MVR model appeared to fix the under-predicted savings by using the 3-P cooling model, which occurred at temperatures below the change-point, with lower uncertainties in the computed savings.

d) Comparison of the Proposed Approach Against the Existing Approach

When applying the same evaluation criteria (i.e., validity, reliability, and practicality) that were used to evaluate the existing ASHRAE PMP procedures[184] to the proposed approach, the modified approach is expected to improve the reliability of the ASHRAE PMP Intermediate Level energy protocol with a lower level of uncertainty in the estimated savings against the baseline year. The scores for other criteria, validity and practicality, remain the same since no additional data collection were necessary to perform this modified approach.

[184] The applicability of the three levels of measurement approaches in the ASHRAE PMP was examined in terms of validity, reliability and practicality of each level of the protocols based on a scale from 1 (very bad) to 5 (very good). Evaluation criteria were developed in three domains: validity, reliability and practicality, which were built upon the framework originally suggested by the Malmqvist and Glaumann (2006). Details are presented in Section 6.1.2.1.

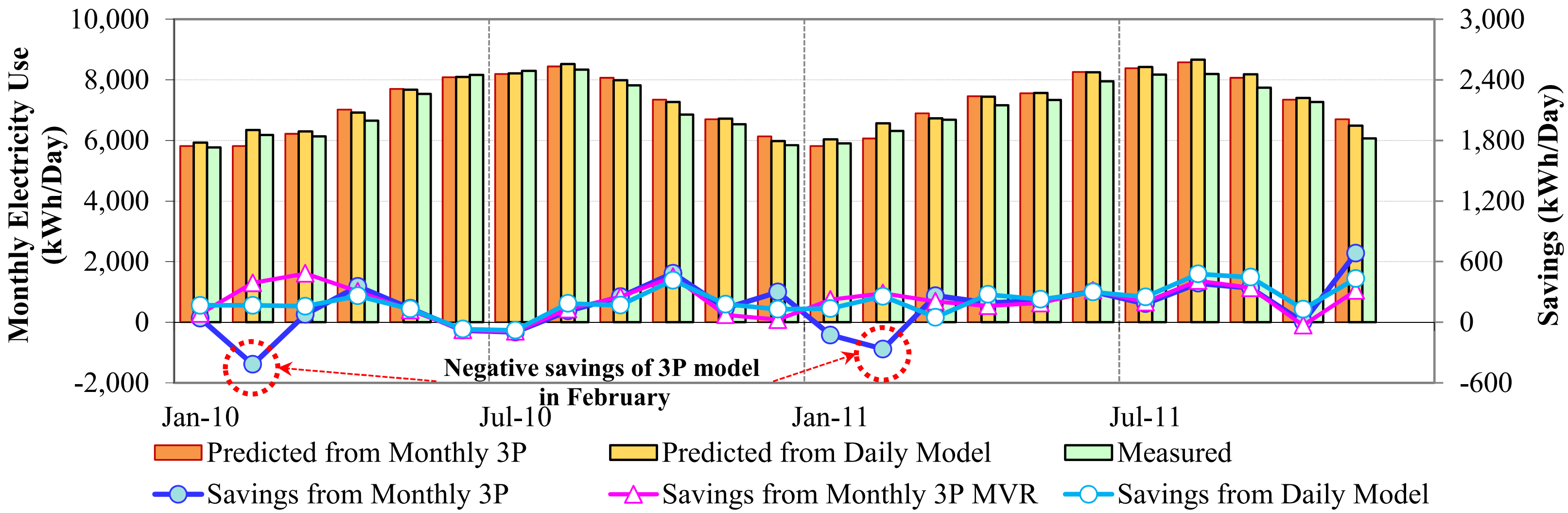


Figure 118: Monthly WBE Savings Against the Baseline Year 2009 Using the Monthly 3-P and 3-P MVR Models as well as the Daily Model for the Years from 2010 to 2011

Table 38: Annual Summary of WBE Savings Against the Baseline Year 2009 Using the Monthly 3-P and 3-P MVR Models as well as the Daily Model

	Monthly 3P Model			Monthly 3P-MVR Model			Daily Model		
	Total Predicted (MWh/period)	Savings[1] (MWh/period)	Savings[1] (%)	Total Predicted (MWh/period)	Savings[1] (MWh/period)	Savings[1] (%)	Total Predicted (MWh/period)	Savings[1] (MWh/period)	Savings[1] (%)
2010 (Jan. to Dec.)	2,608	41 ± 43	1.6 ± 1.6%	2,632	65 ± 36	2.5 ± 1.4%	2,619	54 ± 11	2.1 ± 0.4%
2011 (Jan. to Nov.)	2,470	69 ± 42	2.8 ± 1.7%	2,481	81 ± 35	3.2 ± 1.4%	2,488	91 ± 12	3.7 ± 0.5%

NOTES:
1) The uncertainties associated with the calculated savings were determined at the 95% level of confidence .

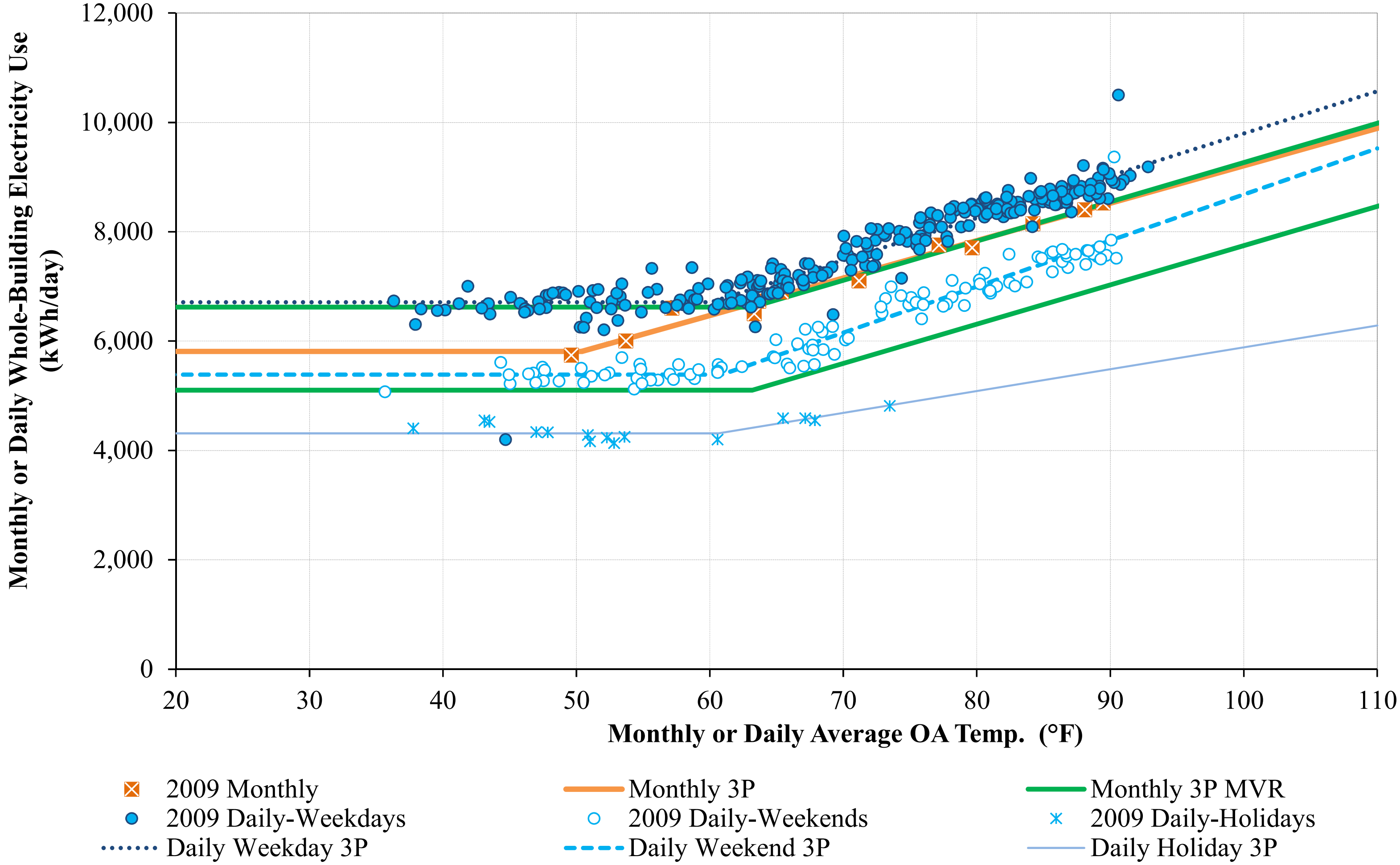


Figure 119: Monthly or Daily WBE Use versus Outdoor Temperature, Including the Monthly 3-P and 3-P MVR Models as well as the Daily 3-P Models for Weekdays, Weekends, and Holidays for the Baseline Year 2009

6.2.1.3. New Approaches to Issue E-12: Benchmarking of Measured Chiller Performance

The chillers are one of the largest energy consumers in the building. Sub-metering of chiller electricity use along with its thermal energy performance requires a high level of data collection, but not surprisingly, can provide additional insights that are helpful in understanding the energy performance of a building. For example, in this study, the sub-hourly chiller electricity use data was helpful in diagnosing the causes of the observed abnormally high peak demand. The use of the sub-hourly end-use data showed that the chillers' abnormal energy use behavior was responsible for high peak demand of the entire building. An inspection of additional chiller operation data (i.e., supply and return temperature and water flow) along with the 15 minute chiller electricity use data revealed that several abnormally high peaks occurred during a period when both chillers in operation for one hour after a short-term shutdown. Details are presented in Section 5.1.3.1.

a) Comparison Against the Manufacturer's Chiller Performance Data

Another advantage of sub-metering chiller power and thermal energy performance can be achieved by comparing the measured chiller performance data against external benchmarks, including the manufacturer's chiller performance curves data. This approach is a classic method used for chiller diagnosis that can detect the chiller's degraded performance over time. Figure 120 shows the rated chiller efficiency (kW/ton) as a function of the chiller loads (tons) for various entering (return) condenser water temperatures between 65 F and 86 F for new chillers. The chiller performance data was obtained via personal communications with a senior staff engineer at York/Johnson Controls Inc. (R.C. Wayne, personal communication, July 20, 2012). In this figure, the AHRI ECWT represents the part load performance at AHRI entering condenser water temperatures (ECWT) which varied between 65 F and 86 F (i.e., the numbers shown near each data points). Other lines represent the part load performance at a constant ECWT: 65 F, 70 F, 75 F, 80 F, 85 F, and 86 F.

The thermal plant of the case-study building is equipped with two 280-ton (3.36 MMBtu/h) York centrifugal chillers (model number: YT E1 E3 C1 - CK F S) with the rated full load efficiency of 0.693 kW/ton[185] and the rated non-standard part load value (NPLV) of 0.607 kW/ton. The chillers were installed in 1991 and designed to use R-11 to cool 560 gpm of 54 F water to 42 F using 840 gpm of 86 F water from a cooling tower. The cooling loads of the case-

[185] This rating was obtained with an entering (return) condenser water temperature of 86 F and a leaving (supply) evaporator water temperature of 42 F.

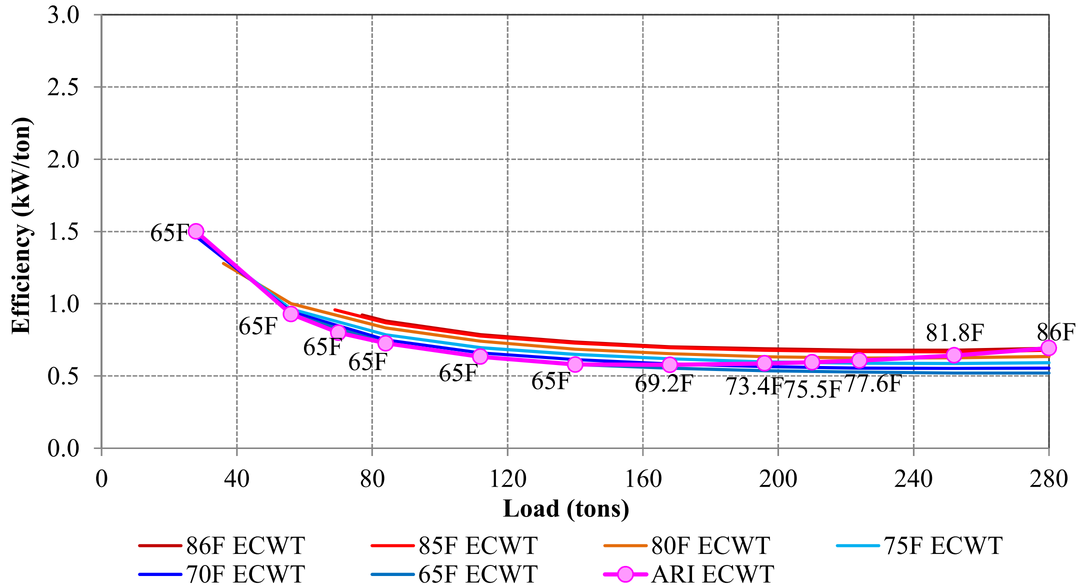


Figure 120: Manufacturer's Rated Chiller Performance Curves for Various Entering Condenser Water Temperatures (ECWT) for New Chillers (R.C. Wayne, personal communication, July 20, 2012)

study building are normally met by running one chiller. Chillers are sequenced to run equal amounts of time each year.

In Figure 121, for comparison, the manufacturer's performance data is overlaid with the measured performance data of chiller efficiency (kW/ton) versus the measured thermal loads (tons) of the chiller No.2[186] for the period 2009 through 2011. In the figure, the outlying points caused by transients were removed. In addition, since the manufacturer's data is valid only for a limited range of ECWT, the data sets with ECWT higher than 75 F were plotted, including: 1,918 hourly data points for 2009; 953 hourly data points for 2010; and 1,621 hourly data points for 2011.

The chiller No.2 appears to be performing as predicted at higher part load conditions over 160 tons. However, at lower part load conditions, the measured performance had a higher kW/ton than the predictions based on the manufacturer's data, which is not an unexpected degradation for this 21 years old chiller. At very low part load conditions below 70 tons (i.e., 25% of full load), most of data points represent nighttime operations when the AHU systems are

[186] Because of the failed chilled water supply temperature sensor for the chiller No.1, the analysis could not be performed for the chiller No.1 over the entire analysis period. However, a simple comparison of the two chillers' performance was made for a certain time period before sensor failure in Figure 124.

in unoccupied mode. Between years, no noticeable differences were observed in the measured performance of the chiller No.2 at the first glance. However, since the data points significantly overlap each other, it was difficult to confirm no changes in the measured chiller performance over the years from this plot. Thus, for additional characterization of the measured chiller performance, thermodynamic chiller models were calculated using the simple chiller model developed under the ASHRAE Research Project RP-827 (Brandemuehl et al. 1996).

The RP-827 simple chiller model used in this analysis is based on a linear relationship of the chiller efficiency (1/ Coefficient of Performance (COP)) with the thermal loads ($kBtu^{-1}$). Figure 122 presents the measured chiller efficiency expressed as 1/COP against the measured loads ($kBtu^{-1}$) along with all three models calculated for 2009, 2010, and 2011. The models calculated for 2009 and 2010 were found to have almost identical linear regression lines, while the 2011 model has slightly higher efficiency than the 2009 and 2010 models at low part load conditions below 0.001 $kBtu^{-1}$ (i.e., 83 tons). Figure 123 shows the same models using more conventional units of efficiency (kw/ton) and load (tons) along with the manufacturer's data.

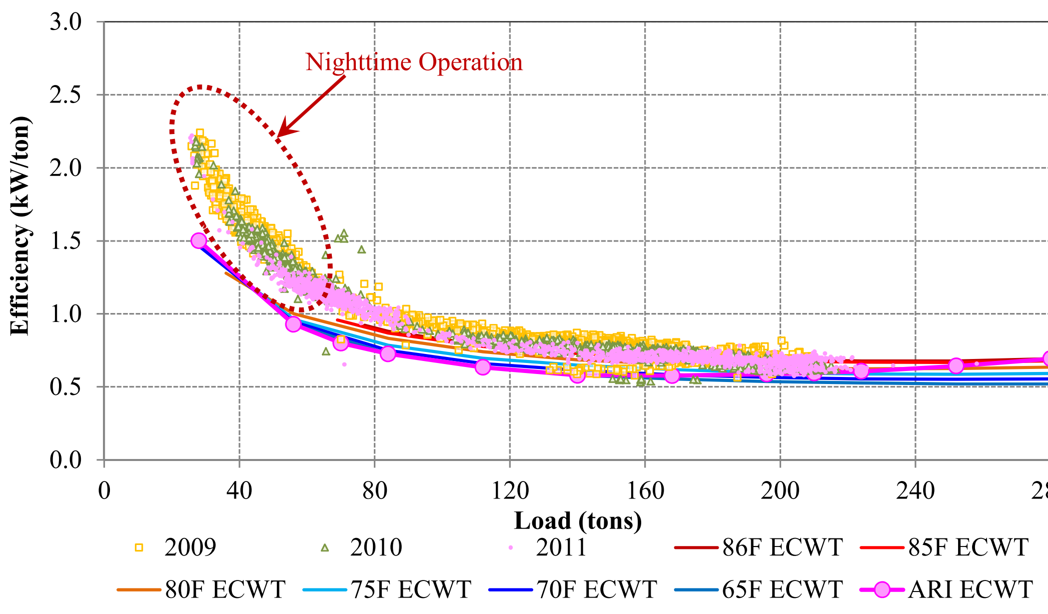


Figure 121: Measured Chiller Efficiency (kW/ton) versus Load (tons) of the Chiller No.2 for the Years from 2009 to 2011, including the Manufacturer's Rated Chiller Performance Curves

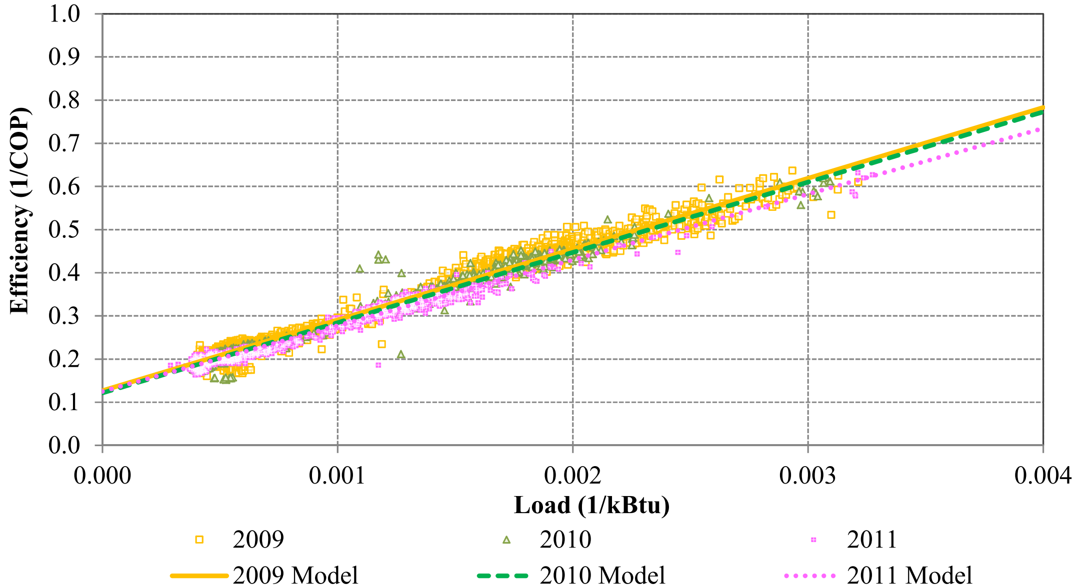


Figure 122: ASHRAE RP-827 Chiller Performance Simple Models for the Chiller No.2 (i.e., Chiller Efficiency (1/COP) versus Load ($kBtu^{-1}$)) Calculated Using the Measured Chiller Performance Data for the Years from 2009 to 2011

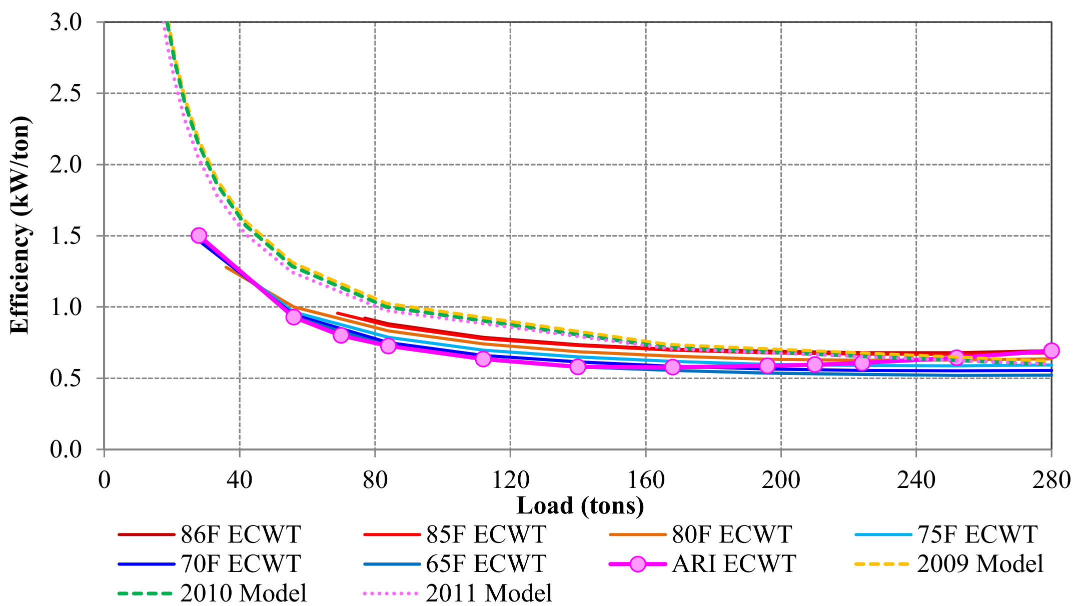


Figure 123: ASHRAE RP-827 Chiller Performance Simple Models for the Chiller No.2 in Conventional Units (i.e., Chiller Efficiency (kW/ton) versus Load (tons)), including the Manufacturer's Rated Chiller Performance Curves

b) Efficiency Comparison of Two Individual Chillers

Unfortunately, the same analysis could not be performed for the chiller No.1 because of the failed chilled water supply temperature sensor for the chiller No.1. However, a simple comparison of the two chillers' performance was made for a limited time period in 2010 (i.e., before sensor failure). Figure 124 presents the measured chiller efficiency expressed as 1/COP against the measured loads ($kBtu^{-1}$) along with two ASHRAE RP-827 simple chiller models calculated for both chiller No.1 and No.2. Figure 125 shows the same models using more conventional units of efficiency (kW/ton) and load (tons) along with the manufacturer's data. Since the manufacturer's data is valid only for a limited range of ECWT, the data sets with ECWT higher than 75 F were plotted in the figures, including: 403 hourly data points for the chiller No.1; and 953 hourly data points for the chiller No.2. As a result, the two chillers appear to have similar efficiency although the chiller 1 was predicted to have a slightly better performance at low part load conditions below 0.002 $kBtu^{-1}$ (i.e., 42 tons) when extrapolating the model.

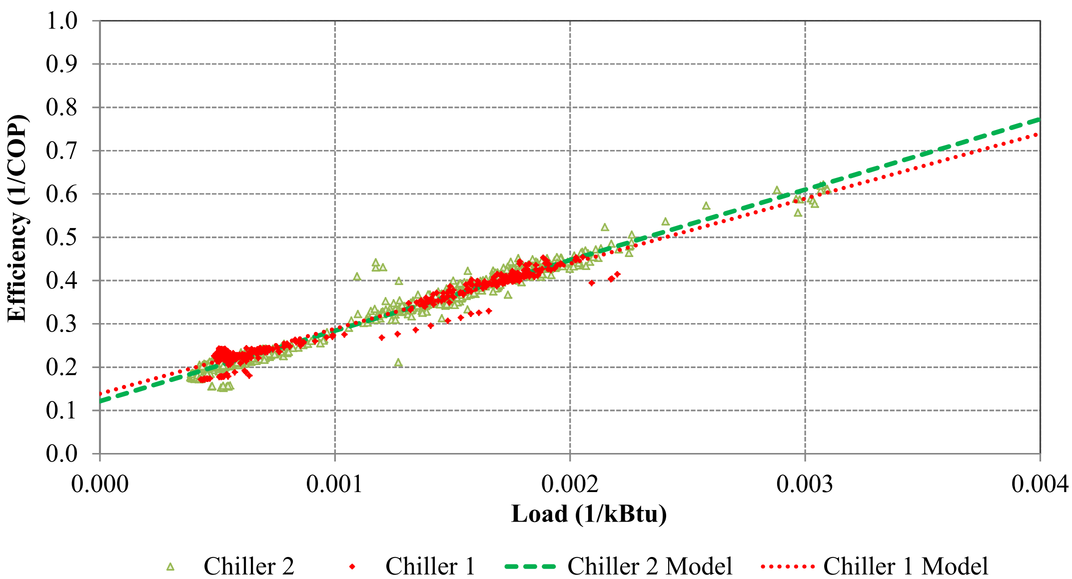


Figure 124: Comparison of the ASHRAE RP-827 Chiller Performance Simple Models of the Chiller No.1 versus the Chiller No.2 (i.e., Chiller Efficiency (1/COP) versus Load ($kBtu^{-1}$))

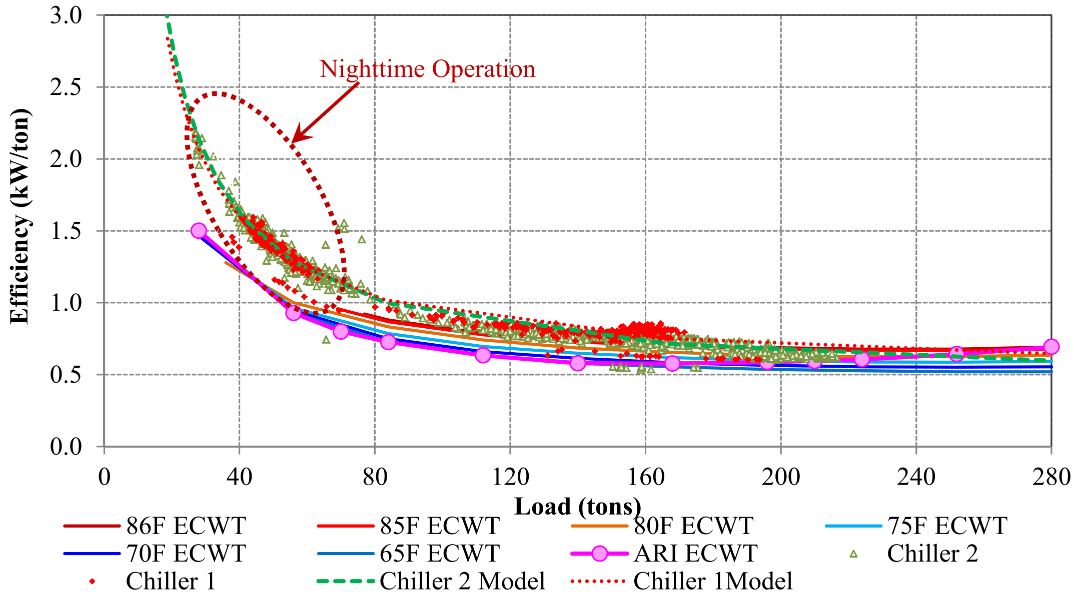


Figure 125: Comparison of the Measured Chiller Performance (i.e., Chiller Efficiency (kW/ton) versus Load (tons)) of the Chiller No.1 versus the Chiller No.2, including the Manufacturer's Rated Chiller Performance Curves

c) Comparison Against the Minimum Efficiency Requirements in the ASHRAE Standard 90.1-2007 and Standard 90.1-2010

The ASHRAE Standard 90.1-2007 (ASHRAE 2007g) and Standard 90.1-2010 (ASHRAE 2010e) specifies the minimum efficiency requirements based on full load efficiency (kW/ton) as well as integrated part load value (IPLV, kW/ton) by the type and size of chillers. The IPLV (or NPLV) does not accurately represent the actual on-site performance of the chiller as acknowledged by Geister andThompson (2009), since these ratings are determined at the operating conditions specified by the AHRI Standard 550/590-2011 (AHRI 2011), including four part load conditions (i.e., 25%, 50%, 75%, and 100% load) with a pre-determined weighting factors for each part load conditions as well as entering (return) condenser water temperature. Although, for an economic decision making, it is desirable to perform a comprehensive analysis based on the measured on-site data with actual operational hours and building loads, a comparison of the part load performance ratings (i.e., IPLV or NPLV) calculated using the measured data against the current minimum efficiency requirements can be used as a simple indicator to estimate the need for improvement of the chiller performance.

Table 39: Summary of the Manufacturer's and Measured Chiller Efficiency Ratings with the Minimum Efficiency in the ASHRAE Standard 90.1-2007 and Standard 90.1-2010

	Full Load Efficiency (kW/ton)[1]	NPLV (kW/ton)[2]
Manufacturer's Data	0.693	0.607
Measured 2009	-	0.757
Measured 2010	-	0.738
Measured 2011	-	0.727
ASHRAE Standard 90.1-2007 and 2010	0.634	0.596

NOTES:
1) Since the chiller No.2 at the case-study building has never experienced full load conditions over the analysis period, the measrued full load efficiency is not listed in the table.
2) The measrued NPLV was calculated using the weighting factors at each of the four part load operating conditions specified in the AHRI Standard 550/590-2011 (AHRI 2011): 0.01 at 100% load; 0.42 at 75% load; 0.45 at 50% load; and 0.12 at 25% load.

Table 39 lists the chiller efficiency ratings calculated using the measured data of the chiller No.2 and the ratings from the manufacturer as well as the minimum efficiency required to comply with the ASHRAE Standard 90.1-2007 and Standard 90.1-2010. To calculate the measured NPLV, the part load energy efficiencies (kW/ton) at four operating conditions (i.e., 25%, 50%, 75%, and 100% load) were calculated using the ASHRAE RP-827 simple chiller models presented in Figure 123. As a result, it was found that the measured NPLV is higher than the minimum efficiency requirements in the ASHRAE Standard 90.1-2007 and Standard 90.1-2010 as well as the rating from the manufacturer. Thus, there is an opportunity to improve the energy performance of the building by optimizing the operation of this "21 year old chiller."

d) Comparison of the Proposed Approach Against the Existing Approach

When applying the same evaluation criteria (i.e., validity, reliability, and practicality) that were used to evaluate the existing ASHRAE PMP procedures[187] to the proposed approach, this new approach is expected to improve the validity of the ASHRAE PMP Advanced Level energy protocol with additional characterization of the building's energy performance listed above. The scores for other criteria, reliability and practicality, remain the same since no additional data collection were necessary to perform this new approach if the user selects system

[187] The applicability of the three levels of measurement approaches in the ASHRAE PMP was examined in terms of validity, reliability and practicality of each level of the protocols based on a scale from 1 (very bad) to 5 (very good). Evaluation criteria were developed in three domains: validity, reliability and practicality, which were built upon the framework originally suggested by the Malmqvist and Glaumann (2006). Details are presented in Section 6.1.2.1.

and component evaluation (retrofit isolation) approach in the ASHRAE PMP Advanced Level energy protocol.

6.2.2. *Water Use*[188]

Of the five issues noted from the field test, one new approach is proposed in this study for the following one issue:

- **<u>Issue W-5:</u>** There are few detailed analysis techniques or modeling methods to analyze and evaluate a building's water performance beyond a log of the calculated WUIs.

6.2.2.1. *<u>New Approach to Issue W-5: 3-P Multi-Variable Regression Model for Water Use</u>*

This new approach developed a combination 3-P multi-variable regression (3-P MVR) cooling model using outdoor temperature and precipitation amount/occurrence as independent variables. The advantages of using the proposed 3-P MVR model to analyze and evaluate a building's water performance were then examined compared to a log of the calculated WUIs, which are the required metrics at the Intermediate Level in the current version of the ASHRAE PMP.

At the whole-building level, there are few discussions in the ASHRAE publications about modeling techniques or data analysis procedures about how to analyze water use data. Recently, as the need for water conservation has increased, the revised ASHRAE Guideline 14-2012 working draft, Measurement of Energy and Demand Savings, developed a section that discusses methods of calculating water savings from water conservation measures (ASHRAE 2012). However, unfortunately, it does not provide any advice on suitable independent variables to be used for a baseline model of the whole-building water use.

a) Previous Studies on the Water Use Model at the Municipal Level

At the municipal or community (i.e., residential) level, numerous studies have been conducted to develop reliable water use models either to forecast demand for supply-side water management purpose or to examine community-wide water savings achieved from water conservation programs. The water use models that were proposed typically consist of base and seasonal water use parameters, including: various demographic (i.e., population), economic (i.e., water price, income, or house value), and policy (water conservation or restriction) variables as

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[188] There are no modified approaches proposed for the ASHRAE PMP water use protocols.

well as weather variables (i.e., outdoor temperature, precipitation, or evapotranspiration). The statistical approaches adopted, included multiple regression or time-series analysis. The weather variables were typically regarded as the major factor influencing seasonal water use, while other factors contributed to the base level adjustment.

Weather variables such as outdoor air temperature as well as precipitation have been identified the influential variables that affect seasonal water use (Morgan and Smolen 1976; Hansen and Narayanan 1981; Maidment et al. 1985; Maidment and Miaou 1986; Miaou 1990; Billings and Agthe 1998; Griffin and Chang 1990; Schultz et al. 2000; Martinez-Espiñeira 2002; Gutzler and Nims 2005; Kenney et al. 2008). Some studies introduced an alternate indicator such as net evapotranspiration (i.e., potential evapotranspiration (ETp) minus actual precipitation, in inches/day), which can be indirectly estimated from outdoor air temperature, humidity, or solar radiation (Howe and Lineweaver 1967; Morgan and Smolen 1976; Anderson et al. 1980; Billing and Agthe 1980; Billings 1982). However, despite a vast amount of published work, only a few studies focused on the weather variables due to their relatively lower impact on the water use compared to the other socioeconomic variables. Thus, this study reviewed five selected studies in 1970s to 1980s that closely examined the relationship between seasonal water use and climatic variables (Morgan and Smolen 1976; Anderson et al. 1980; Hansen and Narayanan 1981; Maidment et al. 1985; and Maidment and Miaou 1986), which may be applicable to the building-level data consisting of 12 monthly observations with a fairly constant level of other socioeconomic variables.

Morgan and Smolen (1976) compared three different seasonal water use models based on different climatic variables, including outdoor temperature and total precipitation; net evapotranspiration (i.e., ETp – Precipitation) computed by the Thornthwaite method[189]; and monthly binary dummy variable. The comparison was made using data from twelve monthly municipal water deliveries for each of 33 cities in Southern California. They found that a seasonal water use model based on temperature and precipitation performed marginally better than the model using net evapotranspiration. Thus, they concluded that the use of temperature and precipitation appeared to be an appropriate method for calculating weather-normalized water

[189] The monthly potential evapotranspiration was computed using the Thornthwaite method which requires an input value for monthly mean temperature (Thornthwaite 1948). $e= 1.6\times(10\times t/I)^a$, in which: e = unadjusted potential evapotranspiration (cm/mo); t = monthly average temperature; I = annual heat index, which is the sum of the 12 monthly heat indices i where $i=(t/5)^{1.514}$; and $a=6.75\times10^{-7}\times I^3-7.71\times10^{-5}\times I^2+0.01792\times I+0.49239$.

demand.

To estimate weather-normalized savings from lawn watering restrictions in Fort Collins, CO, Anderson et al. (1980) used multiple regression models that predicted water use at the municipal level from net evapotranspiration (i.e., ETp – Precipitation) computed by the Jensen-Haise equation[190]. For precipitation, they set upper and lower thresholds between 0.1 and 0.6 inches, which were termed effective rainfall that would actually impact the water usage. In addition, they found the inclusion of a one-day lagged precipitation would improve the model. By comparing the predicted consumption against actual water use, they concluded that about one half of the total reduction in water use could be attributed to the imposed restrictions.

Hansen and Narayanan (1981) proposed a multivariate monthly municipal water demand model that calculated seasonal water use from four climatic indicators: monthly average temperature, total precipitation, percentage of daylight hours, and a non-growing season dummy variable. The model was determined empirically using a multi-year monthly data set (1961 to 1974) for Salt Lake City, UT, that yielded a high R^2 value. The calculated model was validated using the data from 1975 to 1977. The authors concluded that the proposed model adequately predicted seasonal water use. They also tested the inclusion of a one-month lagged monthly temperature and precipitation in the model. However, these two variables appeared to be statistically insignificant at the monthly level.

Maidment et al. (1985) and Maidment and Miaou (1986) developed a daily water use model that predicts seasonal water use from the outdoor air temperature as well as precipitation occurrence and amount. Using the multi-year daily data (1975 to 1981) for Austin, TX, Maidment et al. (1985) built a piecewise-linear function between seasonal water uses against the weekly average of daily minimum and maximum outdoor air temperatures. The proposed model was applied to nine cities in Florida, Pennsylvania, and Texas using the weekly average of daily maximum temperatures instead of daily minimum and maximum outdoor air temperatures. (Maidment and Miaou 1986). Both studies found that there was a threshold limit of outdoor air temperature (i.e., 56 F daily minimum and maximum outdoor temperature for Austin; and approximately 70 F daily maximum temperature for the other nine cities) below which the water use was not dependent on the temperature. Above this threshold, two different levels of linear

[190] The daily potential evapotranspiration was calculated using the Jensen-Haise equation which requires input values for daily mean temperature and daily solar radiation (Jensen and Haise 1963). $Etp=(0.014\times T - 0.37)\times Rs$, in which: Etp = potential evapotranspiration (inches/day); T = daily mean temperature (F); and Rs = solar radiation, in evaporation equivalent (inches/day).

relationship were observed between water uses and temperature. For example, about three to five times higher temperature-dependent water use (i.e., gal/day/F) was observed when the daily maximum temperature exceeded 88 to 93 F in Texas cities and 82 to 88 F in Florida compared to that below that level.

In addition, according to the authors, rainfall appeared to yield immediate drops in the usage for a number of subsequent days. A different level of impact was expected to occur by a threshold level of 0.05 inches. For example, in the analysis of the nine cities, an immediate drop of about 30% of the previous day's seasonal water use was expected if the rainfall exceeded 0.05 inches for Austin, TX, while approximately 23% usage drops were expected if the rainfall was less than or equal to 0.05 inches. The study also confirmed the one-day lag effect of rainfall, which decreased seasonal water use by 38% in Texas cities; 42% in Florida cities; and 7% in Pennsylvania cities, on average.

In summary, the models with evapotranspiration appeared in early published studies. In recent studies, temperature and precipitation are more typically considered as climatic variables. However, disagreement appeared between the studies in the selected outdoor temperature index (i.e., monthly average of daily temperatures[191] versus monthly average of daily maximum temperatures[192]) as well as a selected precipitation index (i.e., total amount[193] versus occurrence[194]). In addition, some studies considered a time lag effect of precipitation, while some did not. The discrepancy in the previous models are partly because that the impact of selected climatic variables on the water use is situation-dependent, including: 1) how much of the water use of interest involves outdoor water use activities (i.e., the consumption which are sensitive to weather); and 2) climate of a location (i.e., dry versus humid climate).

b) Calculation of Weather Variables for the Proposed Water Use Models

Therefore, in this case study, a combination 3-P MVR cooling model was developed using outdoor temperature and precipitation during the growing season as independent variables. Two outdoor temperature indices were considered, including: (a) the monthly average of daily

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[191] Examples include the studies by Hansen and Narayanan (1981), Maidment et al. (1985), Griffin and Chang (1990), Billings and Agthe (1998), and Martinez-Espiñeira (2002).

[192] Examples include the studies by Maidment and Miaou (1986), Miaou (1990), Schultz et al. (2000), Gutzler and Nims (2005), and Kenney et al. (2008).

[193] Examples include the studies by Hansen and Narayanan (1981), Billings and Agthe (1998), Schultz et al. (2000), Gutzler and Nims (2005), and Kenney et al. (2008).

[194] Examples include the studies by Maidment et al. (1985), Maidment and Miaou (1986), Griffin and Chang (1990), and Martinez-Espiñeira (2002).

minimum and maximum outdoor temperatures (T_{minmax}) [195] and (b) the monthly average of daily maximum outdoor temperatures (T_{max}) [196] in a billing period. The precipitation variable during the growing season was computed in three ways: (a) total precipitation (P in inches) in a billing period[197]; (b) number of rainy days with greater than or equal to 0.3 inches in a billing period; and (c) number of rainy days with greater than or equal to 0.1 inches in a billing period. In addition to a threshold limit of 0.1 inches that was typically used in the literature, this study determined to test 0.3 inches, which is the threshold limit used for the case-study building's landscape irrigation.

The proposed water use model is based on twelve monthly, building-level water use data, which should be available for most buildings that are supplied water from a municipal provider. This model will allow a year-to-year, weather-normalized comparison for self-referencing.

Figure 126 presents the distribution of the monthly average temperatures calculated using the two methods (i.e., T_{minmax} and T_{max}) with residuals as well as the total precipitation in a billing period from 2008 to 2011. On average, the monthly average of daily maximum temperatures, T_{max}, was 11.1 F higher than the monthly average of daily minimum and maximum temperatures, T_{minmax}. The residuals (i.e., $T_{max} – T_{minmax}$) varied between 7.9 F and 14.3 F. The high residuals occurred during time when the temperature differences between night and day were relatively large, while the residuals were lower than average occurred in the reverse situation. Thus, the residuals tend to increase in winter months, however, there was no obvious pattern observed in residuals.

When comparing year-to-year variations, the annual peak temperatures of both T_{minmax} and T_{max} continuously increased from 2008 (i.e., 85.5 F for T_{minmax} and 97.3 F for T_{max}) to 2011 (i.e., 90.8 F for T_{minmax} and 103.5 F for T_{max}). The precipitation also showed some variations between years. The highest annual average monthly total precipitation was 3.2 inches per month in 2009, while the lowest was found in 2011 with 1.5 inches per month. Apparently, such year-

[195] T_{minmax} is the average monthly value calculated using the daily minimum and maximum outdoor dry-bulb temperatures measured by the National Oceanic and Atmospheric Administration (NOAA) National Weather Service (NWS) using the Automated Surface Observation Station (ASOS) at the College Station Easterwood Airport. These data were obtained through the NOAA National Climatic Data Center (NCDC) weather database (NCDC 2012).
[196] T_{max} is the average monthly value calculated using the daily maximum outdoor dry- bulb temperatures measured by the NOAA NWS using the ASOS at the College Station Easterwood Airport. These data were also obtained through the NOAA NCDC weather database (NCDC 2012).
[197] P is the sum of daily total precipitation in a billing period that was measured by the NOAA NWS using the ASOS Heated Tipping Bucket (HTB) precipitation gauge at the College Station Easterwood Airport. These data were also obtained through the NOAA NCDC weather database (NCDC 2012).

to-year variations observed in temperature and precipitation variables are expected to affect landscape water use.

Figure 127 presents the distribution of the number of rainy days with greater than or equal to 0.1 and 0.3 inches in a billing period as well as the total precipitation. The grey shaded areas in the figure represent the data during the winter months from December to February (i.e., non-growing season), which were handled by assigning zero in the model calculations. Generally, the three precipitation variables exhibited similar trends over the analysis period. However, some deviations were observed during certain periods[198]. Apparently, the deviations observed in the three precipitation variables are expected to have a different impact on landscape water use models.

c) Proposed Water Use Models for Building (Indoor) Water Use

Figure 128 shows monthly building (i.e., indoor) water use normalized on a daily average basis against the two selected monthly outdoor temperature indices, including the monthly average of daily minimum and maximum temperatures (T_{minmax}) and the monthly average of daily maximum temperatures (T_{max}) in a billing period with the 3-P cooling change-point models from 2008 to 2011. To eliminate net bias error due to billing period variation, each of the eleven or twelve data points was weighted by the number of days in the corresponding billing period, which is one of the compliance requirements of the ASHRAE Guideline 14-2002. The model coefficients and statistical indicators are presented in Table 40.

Except in 2009, the models with both T_{minmax} and T_{max} were well determined with R^2 between 0.87 and 0.97 as well as an acceptable CV-RMSE between 5.9% and 15.4%. The 2009 model has a somewhat worse fit with a R^2 between 0.71 and 0.72 and a CV-RMSE of 20%. A R^2 of 0.71 is lower than the threshold value of 0.8 specified in the ASHRAE PMP, which can be deemed a good fit. The main reason for a worse fit in the 2009 model is due to a considerably low building water use in September 2009 (2.8 kgal/day) compared to August (5.4 kgal/day) or October (5.3 kgal/day). The reason for this is unknown.

In the year-to-year comparison of the calculated model coefficients, similar results were obtained overall using the two different monthly outdoor temperature indices (i.e., T_{minmax} and

[198] For example, there was one day when the one-day precipitation total was 4.3 inches, which occupied about 59% of the total precipitation of June 2010. Thus, despite the high monthly total precipitation (i.e., 7.3 inches), the calculated number of rainy days over 0.1 and 0.3 inches are 5 and 4 days, respectively, which are relatively low compared to the months that have similar amounts of total precipitation (i.e., August 2008 and September 2009).

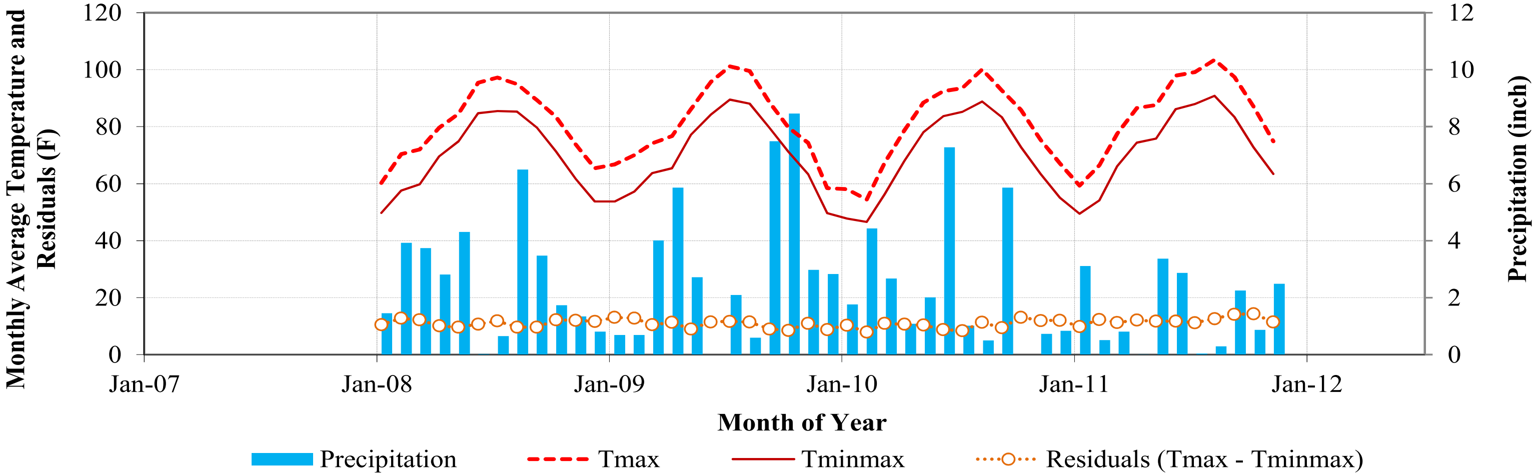


Figure 126: Distribution of the Monthly Average Temperatures Calculated Using the Two Methods (i.e., T_{minmax} and T_{max}) with Residuals (Left Axis) and the Total Precipitation (Right Axis) in a Billing Period from 2008 to 2011

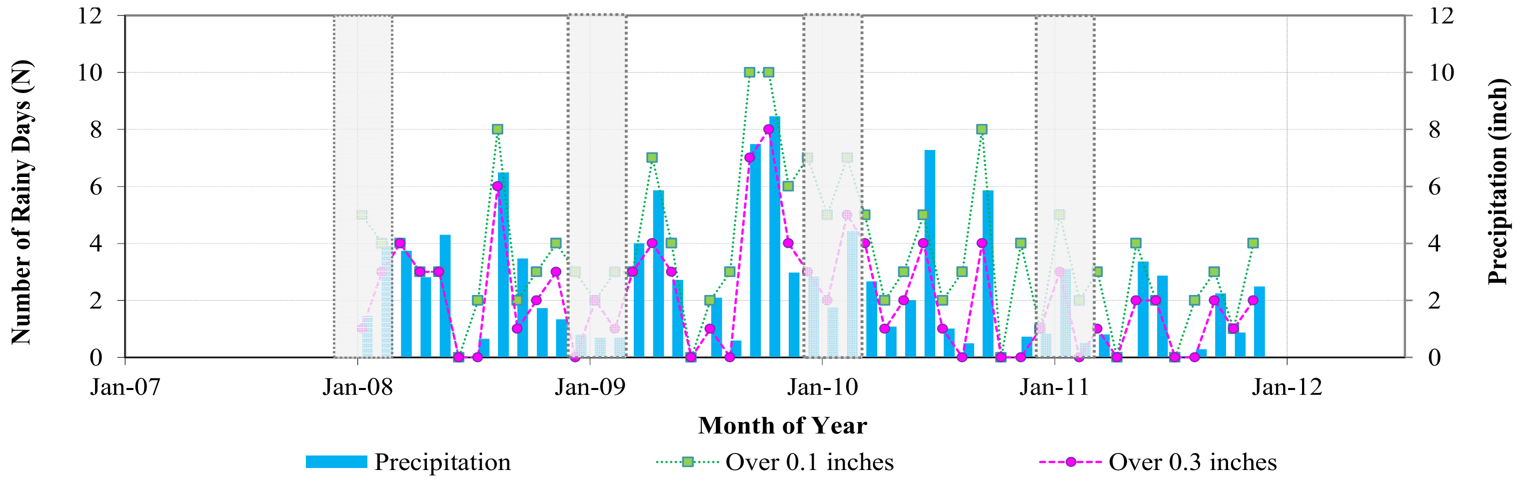
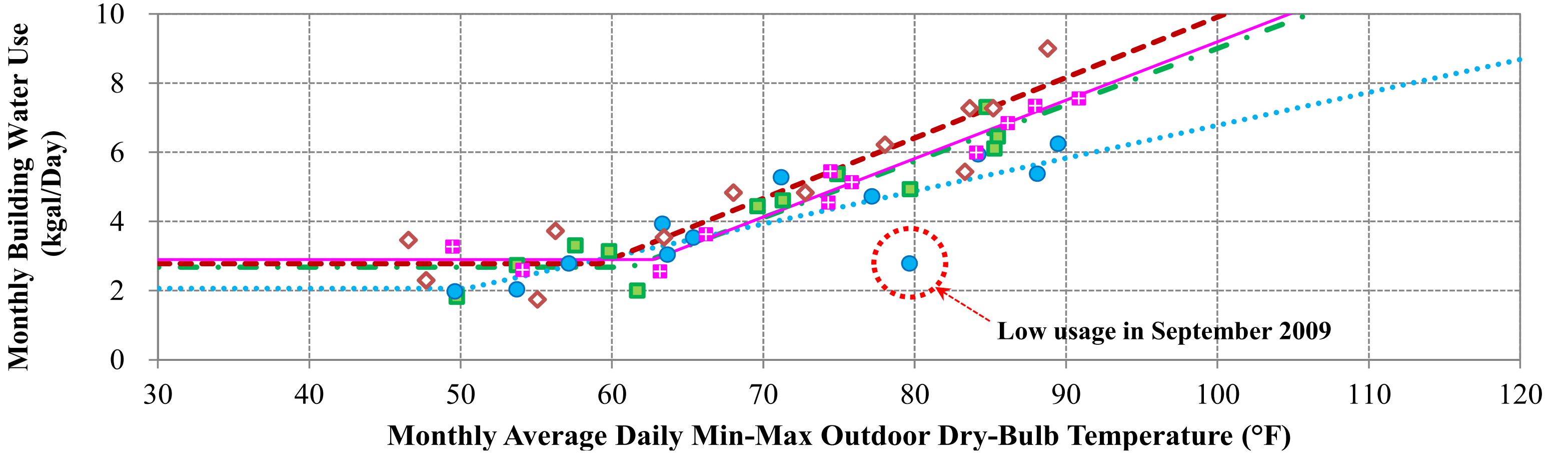


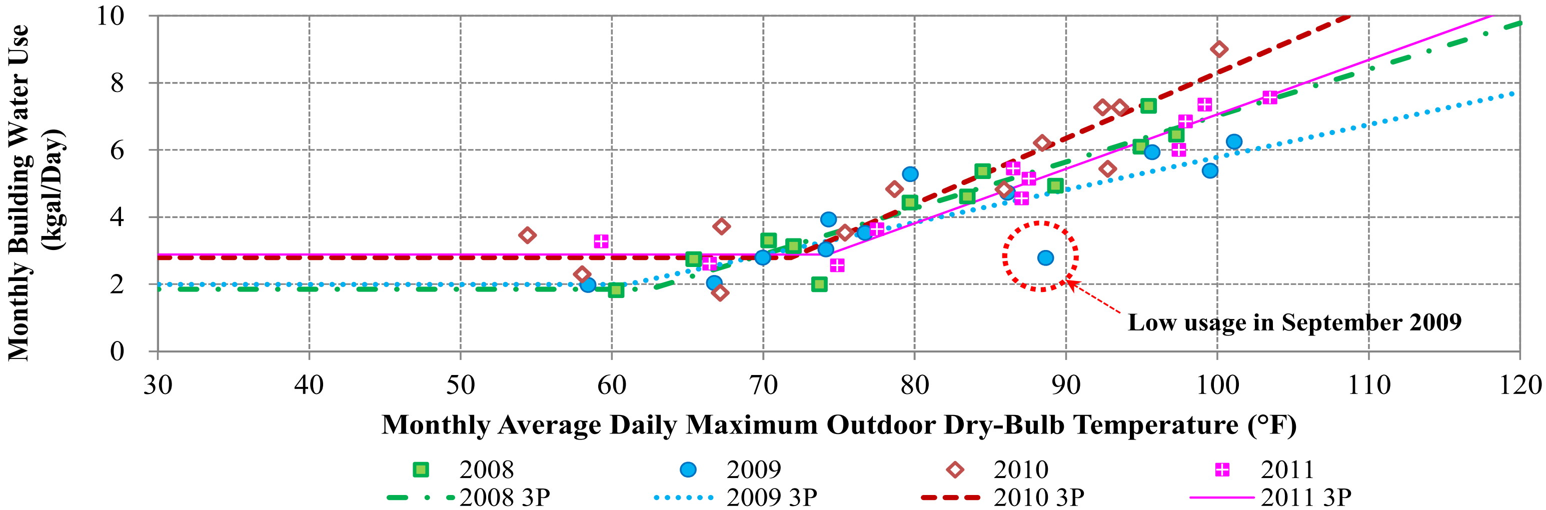
Figure 127: Distribution of the Number of Rainy Days Over 0.1 and 0.3 Inches (Left Axis) and the Total Precipitation (Right Axis)

T_{max}) except in 2008. In 2008, the T_{minmax} model determined its base loads from the four months of data, while the base loads of the T_{max} model was calculated using one month of data, which resulted in a higher base-load building water use (Ycp) and change-point temperature (i.e., the temperature above which weather-dependent water use begins, Tcp) of the T_{minmax} model compared to the T_{max} model. The weather-independent, base-load building water use (Ycp) varied between 2.1 and 2.9 kgal/day (T_{minmax} models) and between 2.0 and 2.9 kgal/day (T_{max} models) per year, with the highest consumption in 2011. The temperature-dependent building water consumption (i.e., right slope, RS (kgal/day/F)) varied between 0.10 and 0.18 kgal/day/F (T_{minmax} models) and between 0.10 and 0.20 kgal/day/F (T_{max} models), and the change-point temperature was calculated to be between 50.4 and 62.7 F (T_{minmax} models) and between 61.0 and 74.3 F (T_{max} models) per year.

In addition to the 3-P cooling change-point models with outdoor temperature variables, the 3-P MVR building water use models were calculated to examine the impact of adding a precipitation variable during the growing season (i.e., total precipitation, number of rainy days over 0.3 inches, or number of rainy days over 0.1 inches) on the model fit. Table 41 presents the model coefficients and statistical indicators. Not surprisingly, it was found that the 3-P MVR building water use models with outdoor temperature as well as one of the precipitation variables did not improve the model fit, which was deemed reasonable for indoor water use models. The results show that there were no meaningful differences in the calculated R^2 and CV-RMSE between the 3-P MVR and the 3-P cooling change-point models, although slightly lower CV-RMSE was calculated for the 3-P MVR models.



(a) Monthly Average of Daily Minimum and Maximum Outdoor Temperatures (T_{minmax}) for the Billing Period



(b) Monthly Average of Daily Maximum Outdoor Temperatures (T_{max}) for the Billing Period

Figure 128: Monthly Building Water Use versus Monthly Outdoor Temperatures, Including 3-P Cooling Change-Point Models for the Years from 2008 to 2011

Table 40: Model Coefficients and Statistical Indicators for Monthly Building Water Use 3-P Models

(a) Monthly Average of Daily Minimum and Maximum Outdoor Temperatures (T_{minmax}) for the Billing Period

Coefficient	Description	2008 (N=12)	2009 (N=12)	2010 (N=12)	2011 (N=11)[1]
Ycp	Base load (kgal/day)	2.67	2.06	2.78	2.89
RS	Right slope (kgal/day/F)	0.16	0.10	0.18	0.17
Tcp	Change point temperature (F)	61.2	50.4	59.2	62.7
R^2	Squared correlation coefficients	0.89	0.71	0.87	0.97
CV-RMSE	Coefficient of variation of the root mean square error (%)	13.0%	19.8%	15.4%	5.9%

(b) Monthly Average of Daily Maximum Outdoor Temperatures (T_{max}) for the Billing Period

Coefficient	Description	2008 (N=12)	2009 (N=12)	2010 (N=12)	2011 (N=11)[1]
Ycp	Base load (kgal/day)	1.85	1.99	2.79	2.89
RS	Right slope (kgal/day/F)	0.14	0.10	0.20	0.16
Tcp	Change point temperature (F)	62.5	61.0	71.8	74.3
R^2	Squared correlation coefficients	0.89	0.72	0.87	0.95
CV-RMSE	Coefficient of variation of the root mean square error (%)	12.9%	19.7%	15.2%	7.5%

NOTES:
1) December data was eliminated due to a change of occupancy in a case-study building in December 2011.

Table 41: Model Coefficients and Statistical Indicators for Monthly Building Water Use 3-P MVR Models
(a) Monthly Average of Daily Minimum and Maximum Outdoor Temperatures (T_{minmax}) for the Billing Period

Coefficient	Description	2008 (N=12)	2009 (N=12)	2010 (N=12)	2011 (N=11)[1]
(a-1) Total Percipitation					
Ycp	Base load (kgal/day)	1.95	2.15	2.82	2.95
RS	Right slope (kgal/day/F)	0.14	0.10	0.18	0.17
Tcp	Change point temperature (F)	50.5	50.4	59.2	61.9
X2	Coefficient for total precipitation (kgal/day/precipitation in inches)	-0.11	-0.04	-0.07	-0.13
R^2	Squared correlation coefficients	0.91	0.72	0.88	0.98
CV-RMSE	Coefficient of variation of the root mean square error (%)	12.0%	19.6%	15.1%	5.1%
(a-2) Number of Rainy Days Over 0.3 inches					
Ycp	Base load (kgal/day)	2.01	2.14	2.80	2.94
RS	Right slope (kgal/day/F)	0.13	0.10	0.18	0.16
Tcp	Change point temperature (F)	50.5	50.4	59.2	61.1
X2	Coefficient for no. of rainy days ≥ 0.3 in. (kgal/day/no. of days)	-0.12	-0.04	-0.02	-0.23
R^2	Squared correlation coefficients	0.91	0.72	0.87	0.98
CV-RMSE	Coefficient of variation of the root mean square error (%)	11.8%	19.6%	15.4%	4.8%
(a-3) Number of Rainy Days Over 0.1 inches					
Ycp	Base load (kgal/day)	2.02	2.17	2.66	2.94
RS	Right slope (kgal/day/F)	0.14	0.10	0.16	0.16
Tcp	Change point temperature (F)	50.5	50.4	55.0	60.2
X2	Coefficient for no. of rainy days ≥ 0.1 in. (kgal/day/no. of days)	-0.15	-0.04	-0.06	-0.16
R^2	Squared correlation coefficients	0.93	0.73	0.87	0.98
CV-RMSE	Coefficient of variation of the root mean square error (%)	10.8%	19.4%	15.3%	4.6%

NOTES:
1) December data was eliminated due to a change of occupancy in a case-study building in December 2011.

Table 41: Continued

(b) Monthly Average of Daily Maximum Outdoor Temperatures (T_{max}) for the Billing Period

Coefficient	Description	2008 (N=12)	2009 (N=12)	2010 (N=12)	2011 (N=11)[1]
(b-1) Total Precipitation					
Ycp	Base load (kgal/day)	1.83	1.97	2.81	2.95
RS	Right slope (kgal/day/F)	0.14	0.10	0.20	0.16
Tcp	Change point temperature (F)	61.8	60.1	71.8	73.4
X2	Coefficient for total precipitation (kgal/day/precipitation in inches)	-0.07	-0.01	-0.02	-0.14
R^2	Squared correlation coefficients	0.90	0.72	0.87	0.96
CV-RMSE	Coefficient of variation of the root mean square error (%)	12.5%	19.7%	15.2%	6.9%
(b-2) Number of Rainy Days Over 0.3 inches					
Ycp	Base load (kgal/day)	1.83	1.99	2.76	2.96
RS	Right slope (kgal/day/F)	0.14	0.10	0.19	0.16
Tcp	Change point temperature (F)	61.0	61.0	71.8	72.6
X2	Coefficient for no. of rainy days ≥ 0.3 in. (kgal/day/no. of days)	-0.10	0.00	0.04	-0.26
R^2	Squared correlation coefficients	0.90	0.72	0.87	0.97
CV-RMSE	Coefficient of variation of the root mean square error (%)	12.2%	19.7%	15.2%	6.3%
(b-3) Number of Rainy Days Over 0.1 inches					
Ycp	Base load (kgal/day)	1.84	1.99	2.80	2.95
RS	Right slope (kgal/day/F)	0.15	0.10	0.20	0.15
Tcp	Change point temperature (F)	61.0	60.1	71.8	71.7
X2	Coefficient for no. of rainy days ≥ 0.1 in. (kgal/day/no. of days)	-0.14	-0.02	0.00	-0.16
R^2	Squared correlation coefficients	0.92	0.72	0.87	0.97
CV-RMSE	Coefficient of variation of the root mean square error (%)	11.1%	19.6%	15.3%	6.4%

NOTES:

1) December data was eliminated due to a change of occupancy in a case-study building in December 2011.

d) Proposed Water Use Models for Landscape Water Use

Figure 129 shows monthly landscape (i.e., outdoor) water use normalized on a daily average basis against the two selected monthly outdoor temperature indices (i.e., T_{minmax} and T_{max}) in a billing period with the 3-P cooling change-point models from 2008 to 2011. To eliminate net bias error due to billing period variation, each of the eleven or twelve data points was weighted by the number of days in the corresponding billing period, which is one of the compliance requirements of the ASHRAE Guideline 14-2002. The model coefficients and statistical indicators are presented in Table 42.

It was found that the models with T_{max} had similar or slightly better goodness-of-fit indicators compared to the models with T_{minmax}. The R^2 of the models were between 0.80 and 0.96 (T_{minmax} models) and between 0.85 and 0.97 (T_{max} models), and the CV-RMSE varied between 18.6% and 35.8% (T_{minmax} models) and between 19.5% and 31.6% (T_{max} model). The R^2 of all models were higher than the threshold value of 0.8 specified in the ASHRAE PMP, which can be deemed a good fit. However, the 2008 and 2010 models had a high CV-RMSE over 30%.

In the year-to-year comparison of the calculated model coefficients, similar results were obtained using two different monthly outdoor temperature indices (i.e., T_{minmax} and T_{max}). The weather-independent, base-load landscape water use (Ycp) varied between 0.00 and 0.25 kgal/acre-day per year for both models. The temperature-dependent landscape water consumption (i.e., right slope, RS (kgal/acre-day/F)) varied between 0.13 and 0.37 kgal/acre-day/F (T_{minmax} models) and between 0.15 and 0.30 kgal/acre-day/F (T_{max} models), and the change-point temperature (i.e., the temperature above which weather-dependent landscape water use begins, Tcp) was calculated to be between 49.9 and 71.9 F (T_{minmax} models) and between 63.6 and 79.8 F (T_{max} models) per year.

In addition to the 3-P cooling change-point models with outdoor temperature variables, the 3-P MVR landscape water use models were calculated to examine the impact of adding a precipitation variable during the growing season (i.e., total precipitation, number of rainy days over 0.3 inches, or number of rainy days over 0.1 inches) on the model fit. Table 43 presents the model coefficients and statistical indicators. Clearly, the 3-P MVR landscape water use model with outdoor temperature as well as one of the precipitation variables significantly improved the model fit with a higher R^2 as well as a lower CV-RMSE, although the impact was slightly different according to which precipitation variable was used in the model and which year it was applied[199]. For example, the use of number of rainy days over 0.1 inches and T_{max} generated the best fit in 2008, but in 2009, the use of number of rainy days over 0.3 inches with T_{max} generated the best fit. In 2010, the T_{max} model with total precipitation had the best fit. Finally, in 2011, the T_{minmax} model with the number of rainy days over 0.3 inches resulted in the best goodness-of-fit indicators.

Due to the different results in goodness-of-fit indicators by year, the functional forms of the calculated 3-P MVR models were examined to select the most appropriate model. Overall, the use of number of rainy days over 0.3 inches, which was the actual threshold limit used for the case-study building's landscape irrigation, was found to generate a functional form that better described the relationship between water use and a precipitation variable with relative lower CV-RMSE across the four years (between 14.7% and 23.2% CV-RMSE with T_{max} model). For example, the 2009 T_{minmax} models with either total precipitation or number of rainy days over 0.1 inches had a nearly flat coefficient for the corresponding precipitation variables with high change point temperatures, which means the effect of precipitation on landscape water use was not adequately accounted in the model.

Figure 130 shows monthly landscape water use normalized on a daily average basis against the T_{minmax} and T_{max} in a billing period with the best-fit 3-P MVR models (i.e., models with number of rainy days over 0.3 inches) from 2008 to 2011, which are represented with two lines. The proposed 3-P MVR model is: $W_{land} = Ycp + RS \times (T - Tcp)^{+} + X2 \times$ Number of rainy days over 0.3 inches, in which: W_{land} = monthly landscape water use (kgal/acre-day); Ycp = base load (kgal/acre-day); RS = right slope (kgal/acre-day/F); T = monthly outdoor temperature (T_{minmax} or T_{max}); Tcp = chance point temperature (F); and X2 = coefficient for no. of rainy days

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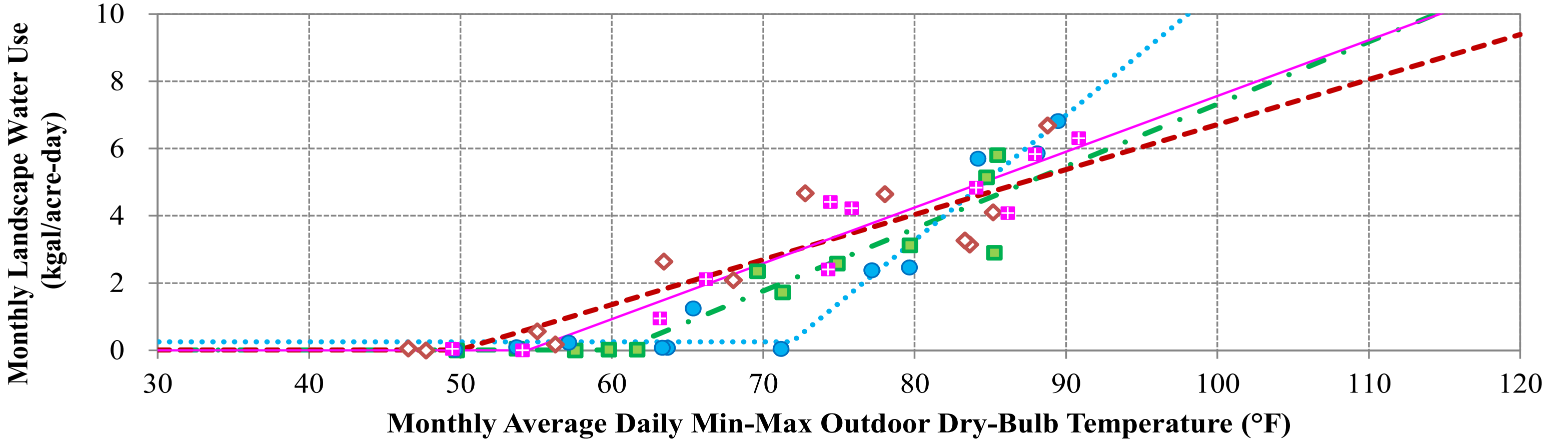
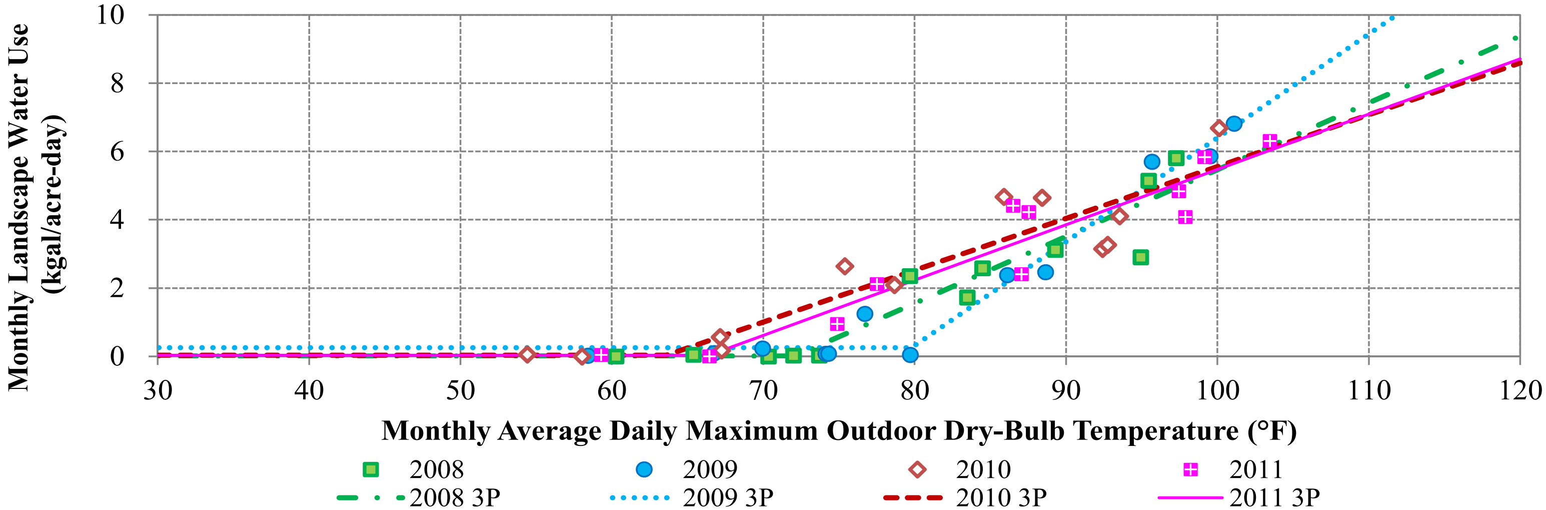
[199] The calculated R^2 of the 3-P MVR models based on T_{minmax} variable are between 0.92 and 0.97 ((a-1) total precipitation models), between 0.91 and 0.97 ((a-2) models with number of rainy days over 0.3 inches), and between 0.86 and 0.97 ((a-3) models with number of rainy days over 0.1 inches), which are higher than the R^2 of the 3-P models based on T_{minmax} only (i.e., between 0.80 and 0.96). The R^2 of the 3-P MVR models based on T_{max} variable are between 0.92 and 0.97 ((b-1) total precipitation models), between 0.93 and 0.99 ((b-2) models with number of rainy days over 0.3 inches), and between 0.91 and 0.98 ((b-3) models with number of rainy days over 0.1 inches), which are higher than the R^2 of the 3-P models based on T_{max} only (i.e., between 0.85 and 0.97). The CV-RMSE of the 3-P MVR models based on T_{minmax} variable are between 17.0% and 22.2% ((a-1) total precipitation models), between 16.1% and 23.3% ((a-2) models with number of rainy days over 0.3 inches), and between 18.3% and 29.4% (a-3) models with number of rainy days over 0.1 inches), which are lower than the CV-RMSE of the 3-P models based on T_{minmax} only (i.e., between 18.6% and 35.8%). The CV-RMSE of the 3-P MVR models based on T_{max} variable are between 17.4% and 24.3% ((b-1) total precipitation models), between 14.7% and 23.2% ((b-2) models with number of rainy days over 0.3 inches), and between 17.4% and 24.4% ((b-3) models with number of rainy days over 0.1 inches), which are lower than the CV-RMSE of the 3-P models based on T_{max} only (i.e., between 19.5% and 31.6%).



(a) Monthly Average of Daily Minimum and Maximum Outdoor Temperatures (T_{minmax}) for the Billing Period



(b) Monthly Average of Daily Maximum Outdoor Temperatures (T_{max}) for the Billing Period

Figure 129: Monthly Landscape Water Use versus Monthly Outdoor Temperatures, Including 3-P Cooling Change-Point Models for the Years from 2008 to 2011

Table 42: Model Coefficients and Statistical Indicators for Monthly Landscape Water Use 3-P Models

(a) Monthly Average of Daily Minimum and Maximum Outdoor Temperatures (T_{minmax}) for the Billing Period

Coefficient	Description	2008 (N=12)	2009 (N=12)	2010 (N=12)	2011 (N=11)[1]
Ycp	Base load (kgal/acre-day)	0.00	0.25	0.01	0.00
RS	Right slope (kgal/acre-day/F)	0.19	0.37	0.13	0.17
Tcp	Change point temperature (F)	60.5	71.9	49.9	54.4
R^2	Squared correlation coefficients	0.89	0.96	0.80	0.92
CV-RMSE	Coefficient of variation of the root mean square error (%)	33.9%	22.3%	35.8%	18.6%

(b) Monthly Average of Daily Maximum Outdoor Temperatures (T_{max}) for the Billing Period

Coefficient	Description	2008 (N=12)	2009 (N=12)	2010 (N=12)	2011 (N=11)[1]
Ycp	Base load (kgal/acre-day)	0.01	0.25	0.04	0.04
RS	Right slope (kgal/acre-day/F)	0.20	0.30	0.15	0.16
Tcp	Change point temperature (F)	72.1	79.8	63.6	66.4
R^2	Squared correlation coefficients	0.90	0.97	0.85	0.91
CV-RMSE	Coefficient of variation of the root mean square error (%)	31.6%	19.5%	30.4%	19.9%

NOTES:

1) December data was eliminated due to a change of occupancy in a case-study building in December 2011.

Table 43: Model Coefficients and Statistical Indicators for Monthly Landscape Water Use 3-P MVR Models
(a) Monthly Average of Daily Minimum and Maximum Outdoor Temperatures (T_{minmax}) for the Billing Period

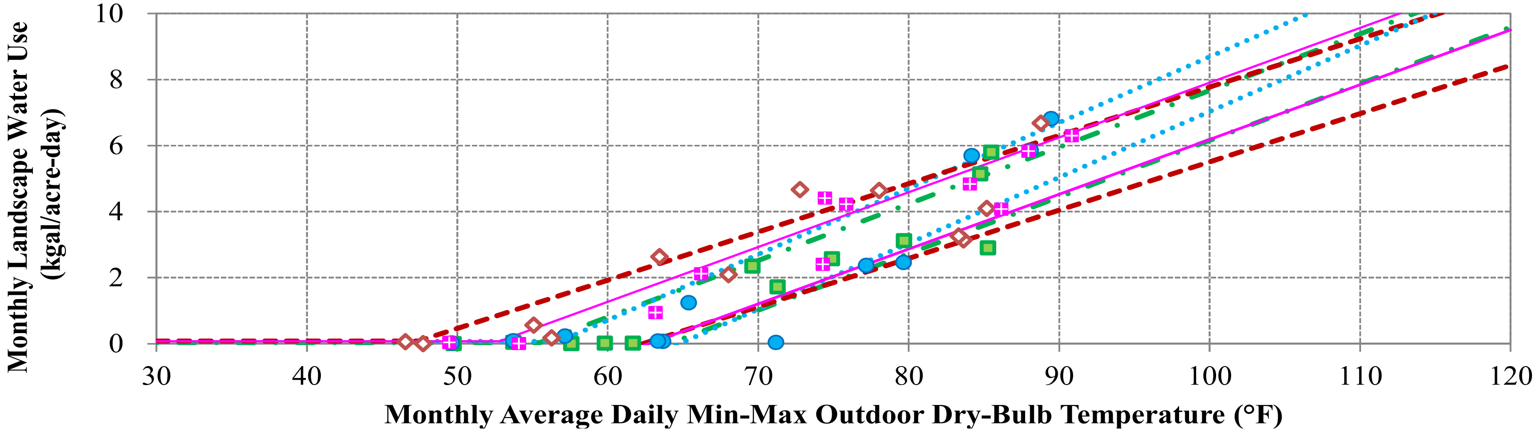
Coefficient	Description	2008 (N=12)	2009 (N=12)	2010 (N=12)	2011 (N=11)[1]
(a-1) Total Percipitation					
Ycp	Base load (kgal/acre-day)	0.00	0.31	0.01	0.08
RS	Right slope (kgal/acre-day/F)	0.19	0.37	0.16	0.17
Tcp	Change point temperature (F)	56.2	71.9	49.1	53.6
X2	Coefficient for total precipitation (kgal/acre-day/precipitation in inches)	-0.30	-0.02	-0.36	-0.20
R^2	Squared correlation coefficients	0.95	0.97	0.92	0.93
CV-RMSE	Coefficient of variation of the root mean square error (%)	22.1%	22.2%	22.0%	17.0%
(a-2) Number of Rainy Days Over 0.3 inches					
Ycp	Base load (kgal/acre-day)	0.03	0.08	0.08	0.08
RS	Right slope (kgal/acre-day/F)	0.17	0.20	0.15	0.17
Tcp	Change point temperature (F)	55.5	56.8	47.4	52.8
X2	Coefficient for no. of rainy days ≥ 0.3 in. (kgal/acre-day/no. of days)	-0.30	-0.33	-0.45	-0.34
R^2	Squared correlation coefficients	0.95	0.97	0.91	0.94
CV-RMSE	Coefficient of variation of the root mean square error (%)	22.7%	19.5%	23.3%	16.1%
(a-3) Number of Rainy Days Over 0.1 inches					
Ycp	Base load (kgal/acre-day)	-0.01	0.35	0.04	0.04
RS	Right slope (kgal/acre-day/F)	0.18	0.37	0.15	0.17
Tcp	Change point temperature (F)	55.5	71.9	47.4	53.6
X2	Coefficient for no. of rainy days ≥ 0.1 in. (kgal/acre-day/no.of days)	-0.28	-0.02	-0.26	-0.08
R^2	Squared correlation coefficients	0.95	0.97	0.86	0.92
CV-RMSE	Coefficient of variation of the root mean square error (%)	22.1%	22.0%	29.4%	18.3%

NOTES:
1) December data was eliminated due to a change of occupancy in a case-study building in December 2011.

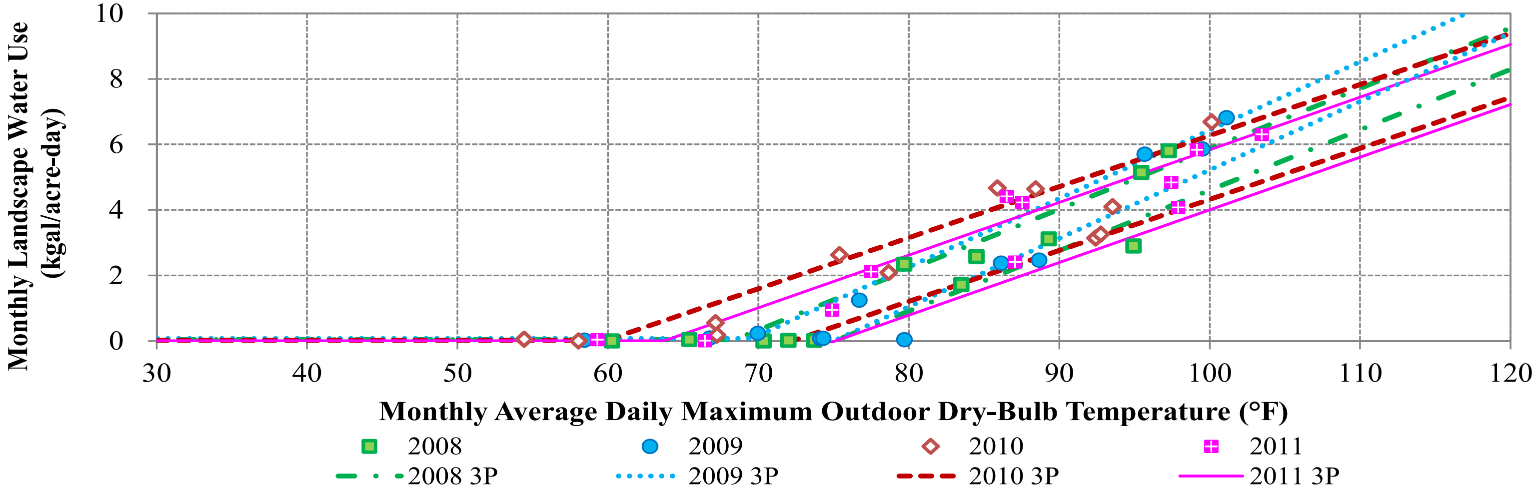
Table 43: Continued
(b) Monthly Average of Daily Maximum Outdoor Temperatures (T_{max}) for the Billing Period

Coefficient	Description	2008 (N=12)	2009 (N=12)	2010 (N=12)	2011 (N=11)[1]
(b-1) Total Precipitation					
Ycp	Base load (kgal/acre-day)	0.02	0.12	-0.01	0.00
RS	Right slope (kgal/acre-day/F)	0.20	0.22	0.17	0.16
Tcp	Change point temperature (F)	69.2	71.2	61.7	64.6
X2	Coefficient for total precipitation (kgal/acre-day/precipitation in inches)	-0.23	-0.18	-0.31	-0.20
R^2	Squared correlation coefficients	0.94	0.97	0.95	0.92
CV-RMSE	Coefficient of variation of the root mean square error (%)	24.3%	19.2%	17.4%	18.6%
(b-2) Number of Rainy Days Over 0.3 inches					
Ycp	Base load (kgal/acre-day)	0.04	0.07	0.03	0.01
RS	Right slope (kgal/acre-day/F)	0.18	0.21	0.16	0.16
Tcp	Change point temperature (F)	68.4	69.5	59.9	63.7
X2	Coefficient for no. of rainy days ≥ 0.3 in. (kgal/acre-day/no. of days)	-0.25	-0.24	-0.39	-0.37
R^2	Squared correlation coefficients	0.95	0.99	0.94	0.93
CV-RMSE	Coefficient of variation of the root mean square error (%)	23.2%	14.7%	19.6%	17.5%
(b-3) Number of Rainy Days Over 0.1 inches					
Ycp	Base load (kgal/acre-day)	0.02	0.10	0.05	0.04
RS	Right slope (kgal/acre-day/F)	0.20	0.22	0.16	0.16
Tcp	Change point temperature (F)	68.4	70.4	60.8	65.5
X2	Coefficient for no. of rainy days ≥ 0.1 in. (kgal/acre-day/no. of days)	-0.25	-0.16	-0.23	-0.07
R^2	Squared correlation coefficients	0.96	0.98	0.91	0.91
CV-RMSE	Coefficient of variation of the root mean square error (%)	21.1%	17.4%	24.4%	19.7%

NOTES:
1) December data was eliminated due to a change of occupancy in a case-study building in December 2011.



(a) Monthly Average of Daily Minimum and Maximum Outdoor Temperatures (T_{minmax}) for the Billing Period



(b) Monthly Average of Daily Maximum Outdoor Temperatures (T_{max}) for the Billing Period

Figure 130: Monthly Landscape Water Use versus Monthly Outdoor Temperatures, Including 3-P Multi-Variable Regression Models Represented with Two Lines (The Upper and Lower Lines Represent the Months with a Number of Rainy Days Over 0.3 inches =0 and 5, Respectively.) for the Years from 2008 to 2011

over 0.3 inches during the growing season (kWh/acre-day/no. of days). In the figure, the upper and lower lines represent the models with a number of rainy days =0 and 5, respectively.

e) Proposed Water Use Models for Total Site Water Use

In the previous sections, the monthly building and landscape water use of the case-study building were separately modeled using outdoor temperature and precipitation amount/occurrence as independent variables. It was found that both the monthly building and landscape water use were dependent on outdoor temperature[200], and that the addition of one of the precipitation variables improved the model fit for the landscape water use[201]. Thus, based on these findings from the previous sections, it seems reasonable to propose the monthly total site water use models (i.e., indoor and outdoor combined water use) using outdoor temperature and precipitation as independent variables, which are discussed in this section.

Figure 131 shows monthly total site water use normalized on a daily average basis against the two selected monthly outdoor temperature indices (i.e., T_{minmax} and T_{max}) in a billing period with the 3-P cooling change-point models from 2008 to 2011. To eliminate net bias error due to billing period variation, each of the eleven or twelve data points was weighted by the number of days in the corresponding billing period, which is one of the compliance requirements of the ASHRAE Guideline 14-2002. The model coefficients and statistical indicators are presented in Table 44.

It was found that the total site water use models with T_{max} had similar or slightly better goodness-of-fit indicators compared to the models with T_{minmax}, which agrees with the results for landscape water use. The R^2 of the models were between 0.87 and 0.95 (T_{minmax} models) and between 0.91 and 0.95 (T_{max} models), and the CV-RMSE varied between 11.9% and 21.2% (T_{minmax} models) and between 13.4% and 18.4% (T_{max} model). The R^2 of all models were higher than the threshold value of 0.8 specified in the ASHRAE PMP, which can be deemed a good fit.

In the year-to-year comparison of the calculated model coefficients, similar results were obtained using two different monthly outdoor temperature indices (i.e., T_{minmax} and T_{max}) except in 2009. In 2009, the T_{minmax} model determined its base loads from the seven months of data,

[200] For the building (i.e., indoor) water use models, it was found that there were no noticeable differences in the models obtained using the two different monthly outdoor temperature indices (T_{minmax} versus T_{max}). On the other hand, for the landscape (i.e., outdoor) water use models, it was found that the models with T_{max} had slightly better goodness-of-fit indicators compared to the models with T_{minmax}.

[201] The addition of one of the precipitation variables did not improve the model fit for the building water use, which was deemed reasonable for indoor water use models. On the other hand, for the landscape water use models, the use of number of rainy days over 0.3 inches resulted in the best fit compared to the use of either total precipitation or number of rainy days over 0.1 inches.

while the base loads of the T_{max} model was calculated using three months of data, which caused the T_{minmax} model to have a higher base-load total site water use (Ycp) and change-point temperature (i.e., the temperature above which weather-dependent total site water use begins, Tcp) with high right slope (i.e., the temperature-dependent total site water consumption, RS (kgal/day/F)) compared to the T_{max} model. The weather-independent, base-load total site water use (Ycp) varied between 2.76 and 3.70 kgal/day (T_{minmax} models) and between 2.42 and 2.98 kgal/day (T_{max} models) per year. The right slope varied between 0.43 and 0.91 kgal/day/F (T_{minmax} models) and between 0.47 and 0.55 kgal/day/F (T_{max} models), and the change-point temperature was calculated to be between 53.3 and 72.7 F (T_{minmax} models) and between 65.4 and 73.0 F (T_{max} models) per year.

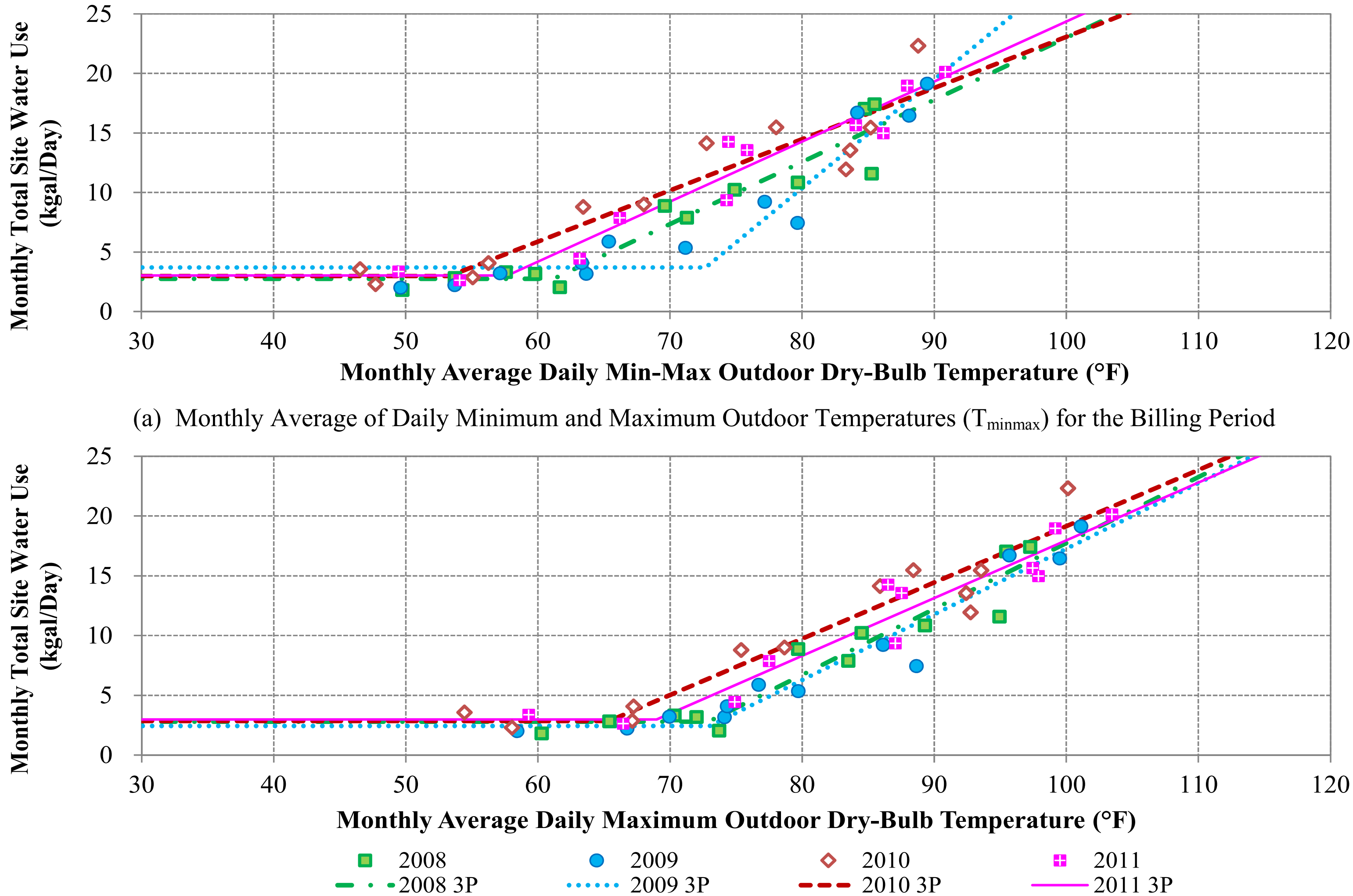
In addition to the 3-P cooling change-point models with outdoor temperature variables, the 3-P MVR total site water use models were calculated to examine the impact of adding a precipitation variable during the growing season (i.e., total precipitation, number of rainy days over 0.3 inches, or number of rainy days over 0.1 inches) on the model fit. Table 45 presents the model coefficients and statistical indicators. Clearly, the 3-P MVR total site water use model with outdoor temperature as well as one of the precipitation variables significantly improved the model fit with a higher R^2 as well as a lower CV-RMSE, although the impact was slightly different by the precipitation variable used in the model and by the year[202]. For example, the use

[202] The calculated R^2 of the 3-P MVR models based on T_{minmax} variable are between 0.94 and 0.96 ((a-1) total precipitation models), between 0.93 and 0.97 ((a-2) models with number of rainy days over 0.3 inches), and between 0.91 and 0.96 ((a-3) models with number of rainy days over 0.1 inches), which are higher than the R^2 of the 3-P models based on T_{minmax} only (i.e., between 0.87 and 0.95). The R^2 of the 3-P MVR models based on T_{max} variable are between 0.95 and 0.97 ((b-1) total precipitation models), between 0.95 and 0.98 ((b-2) models with number of rainy days over 0.3 inches), and between 0.94 and 0.98 ((b-3) models with number of rainy days over 0.1 inches), which are higher than the R^2 of the 3-P models based on T_{max} only (i.e., between 0.91 and 0.95). The CV-RMSE of the 3-P MVR models based on T_{minmax} variable are between 10.5% and 15.9% ((a-1) total precipitation models), between 9.5% and 15.9% ((a-2) models with number of rainy days over 0.3 inches), and between 11.3% and 17.9% (a-3) models with number of rainy days over 0.1 inches), which are lower than the CV-RMSE of the 3-P models based on T_{minmax} only (i.e., between 11.9% and 21.2%). The CV-RMSE of the 3-P MVR models based on T_{max} variable are between 11.8% and 15.4% ((b-1) total precipitation models), between 10.9% and 14.6% ((b-2) models with number of rainy days over 0.3 inches), and between 11.7% and 14.9% ((b-3) models with number of rainy days over 0.1 inches), which are lower than the CV-RMSE of the 3-P models based on T_{max} only (i.e., between 13.4% and 18.4%).

of number of rainy days over 0.1 inches and T_{max} generated the best fit in 2008, but in 2009, the use of number of rainy days over 0.3 inches with T_{max} generated the best fit. In 2010, the T_{max} model with total precipitation had the best fit. Lastly, in 2011, the T_{minmax} model with the number of rainy days over 0.3 inches resulted in the best goodness-of-fit indicators.

In addition to a comparison of goodness-of-fit indicators, the functional forms of the calculated 3-P MVR total site water use models were also examined to select the most appropriate model, and all six models were found to have similar functional forms. Therefore, there was no one model that better described the relationship between total site water use and one precipitation variable with low CV-RMSE across the four years.

As an example, Figure 132 shows monthly total site water use normalized on a daily average basis against the T_{minmax} and T_{max} in a billing period with the 3-P MVR models with number of rainy days over 0.3 inches from 2008 to 2011, which are represented with two lines. The proposed 3-P MVR model is: $W_{total\ site} = Ycp + RS \times (T - Tcp)^{+} + X2 \times$ Number of rainy days over 0.3 inches, in which: $W_{total\ site}$ = monthly total stie water use (kgal/day); Ycp = base load (kgal/day); RS = right slope (kgal/day/F); T = monthly outdoor temperature (T_{minmax} or T_{max}); Tcp = chance point temperature (F); and X2 = coefficient for no. of rainy days over 0.3 inches during the growing season (kWh/day/no. of days). In the figure, the upper and lower lines represent the models with a number of rainy days =0 and 5, respectively.



(a) Monthly Average of Daily Minimum and Maximum Outdoor Temperatures (T_{minmax}) for the Billing Period

(b) Monthly Average of Daily Maximum Outdoor Temperatures (T_{max}) for the Billing Period

Figure 131: Monthly Total Site Water Use versus Monthly Outdoor Temperatures, Including 3-P Cooling Change-Point Models for the Years from 2008 to 2011

Table 44: Model Coefficients and Statistical Indicators for Monthly Total Site Water Use 3-P Models

(a) Monthly Average of Daily Minimum and Maximum Outdoor Temperatures (T_{minmax}) for the Billing Period

Coefficient	Description	2008 (N=12)	2009 (N=12)	2010 (N=12)	2011 (N=11)[1]
Ycp	Base load (kgal/day)	2.76	3.70	2.99	3.02
RS	Right slope (kgal/day/F)	0.52	0.91	0.43	0.51
Tcp	Change point temperature (F)	61.2	72.7	53.3	57.7
R^2	Squared correlation coefficients	0.92	0.93	0.87	0.95
CV-RMSE	Coefficient of variation of the root mean square error (%)	19.4%	20.2%	21.2%	11.9%

(b) Monthly Average of Daily Maximum Outdoor Temperatures (T_{max}) for the Billing Period

Coefficient	Description	2008 (N=12)	2009 (N=12)	2010 (N=12)	2011 (N=11)[1]
Ycp	Base load (kgal/day)	2.80	2.42	2.86	2.98
RS	Right slope (kgal/day/F)	0.55	0.55	0.47	0.48
Tcp	Change point temperature (F)	72.9	73.0	65.4	69.0
R^2	Squared correlation coefficients	0.92	0.95	0.91	0.93
CV-RMSE	Coefficient of variation of the root mean square error (%)	18.4%	17.6%	17.6%	13.4%

NOTES:

1) December data was eliminated due to a change of occupancy in a case-study building in December 2011.

Table 45: Model Coefficients and Statistical Indicators for Monthly Total Site Water Use 3-P MVR Models
(a) Monthly Average of Daily Minimum and Maximum Outdoor Temperatures (T_{minmax}) for the Billing Period

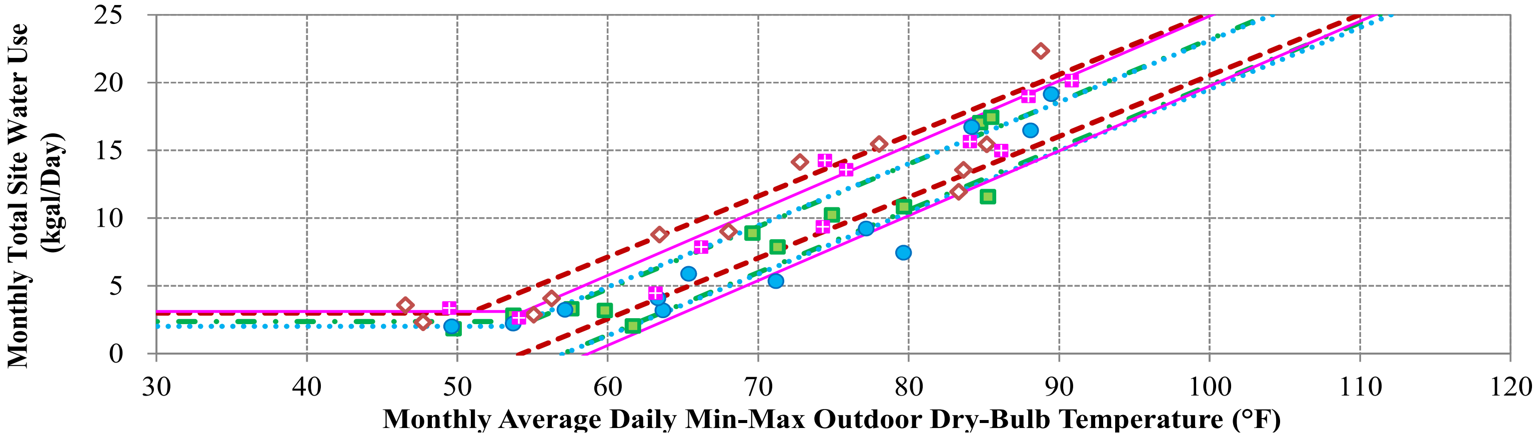
Coefficient	Description	2008 (N=12)	2009 (N=12)	2010 (N=12)	2011 (N=11)[1]
(a-1) Total Percipitation					
Ycp	Base load (kgal/day)	2.27	2.08	3.02	2.98
RS	Right slope (kgal/day/F)	0.49	0.47	0.49	0.49
Tcp	Change point temperature (F)	55.5	54.4	52.5	55.3
X2	Coefficient for total precipitation (kgal/day/precipitation in inches)	-0.67	-0.62	-0.78	-0.60
R^2	Squared correlation coefficients	0.96	0.96	0.94	0.96
CV-RMSE	Coefficient of variation of the root mean square error (%)	14.0%	15.9%	14.1%	10.5%
(a-2) Number of Rainy Days Over 0.3 inches					
Ycp	Base load (kgal/day)	2.35	2.01	2.98	3.10
RS	Right slope (kgal/day/F)	0.46	0.45	0.45	0.48
Tcp	Change point temperature (F)	54.8	53.6	50.8	54.4
X2	Coefficient for no. of rainy days ≥ 0.3 in. (kgal/day/no. of days)	-0.68	-0.72	-0.91	-1.03
R^2	Squared correlation coefficients	0.96	0.97	0.93	0.97
CV-RMSE	Coefficient of variation of the root mean square error (%)	14.1%	13.4%	15.9%	9.5%
(a-3) Number of Rainy Days Over 0.1 inches					
Ycp	Base load (kgal/day)	2.30	2.09	2.95	3.01
RS	Right slope (kgal/day/F)	0.49	0.48	0.46	0.48
Tcp	Change point temperature (F)	54.8	54.4	50.8	55.3
X2	Coefficient for no. of rainy days ≥ 0.1 in. (kgal/day/no. of days)	-0.66	-0.52	-0.56	-0.35
R^2	Squared correlation coefficients	0.96	0.96	0.91	0.95
CV-RMSE	Coefficient of variation of the root mean square error (%)	12.6%	14.7%	17.9%	11.3%

NOTES:
1) December data was eliminated due to a change of occupancy in a case-study building in December 2011.

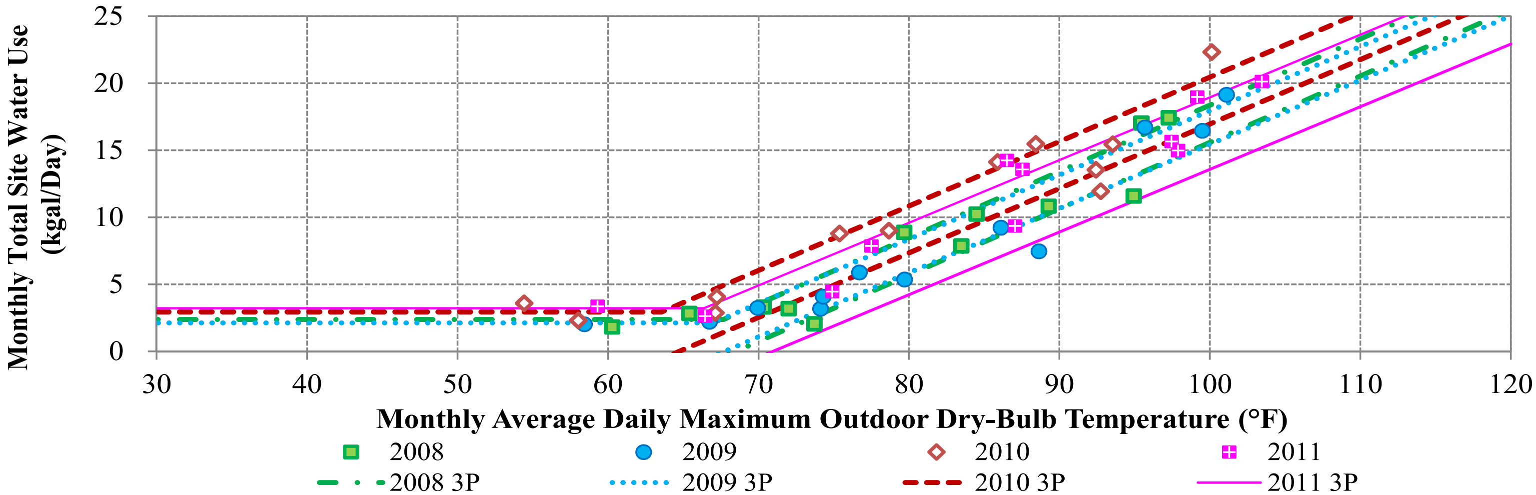
Table 45: Continued
(b) Monthly Average of Daily Maximum Outdoor Temperatures (T_{max}) for the Billing Period

Coefficient	Description	2008 (N=12)	2009 (N=12)	2010 (N=12)	2011 (N=11)[1]
(b-1) Total Precipitation					
Ycp	Base load (kgal/day)	2.32	2.04	2.90	2.94
RS	Right slope (kgal/day/F)	0.52	0.49	0.52	0.47
Tcp	Change point temperature (F)	68.4	67.0	64.5	66.4
X2	Coefficient for total precipitation (kgal/day/precipitation in inches)	-0.49	-0.44	-0.63	-0.61
R^2	Squared correlation coefficients	0.95	0.97	0.96	0.95
CV-RMSE	Coefficient of variation of the root mean square error (%)	15.4%	12.9%	11.8%	12.1%
(b-2) Number of Rainy Days Over 0.3 inches					
Ycp	Base load (kgal/day)	2.37	2.12	2.93	3.22
RS	Right slope (kgal/day/F)	0.49	0.48	0.48	0.47
Tcp	Change point temperature (F)	67.7	67.0	63.6	66.4
X2	Coefficient for no. of rainy days ≥ 0.3 in. (kgal/day/no. of days)	-0.56	-0.50	-0.70	-1.07
R^2	Squared correlation coefficients	0.95	0.98	0.95	0.96
CV-RMSE	Coefficient of variation of the root mean square error (%)	14.6%	11.6%	13.8%	10.9%
(b-3) Number of Rainy Days Over 0.1 inches					
Ycp	Base load (kgal/day)	2.37	2.07	2.91	2.99
RS	Right slope (kgal/day/F)	0.52	0.49	0.50	0.46
Tcp	Change point temperature (F)	67.7	67.0	63.6	66.4
X2	Coefficient for no. of rainy days ≥ 0.1 in. (kgal/day/no. of days)	-0.58	-0.38	-0.45	-0.37
R^2	Squared correlation coefficients	0.97	0.98	0.94	0.94
CV-RMSE	Coefficient of variation of the root mean square error (%)	12.4%	11.7%	14.9%	12.8%

NOTES:
1) December data was eliminated due to a change of occupancy in a case-study building in December 2011.



(a) Monthly Average of Daily Minimum and Maximum Outdoor Temperatures (T_{minmax}) for the Billing Period



(b) Monthly Average of Daily Maximum Outdoor Temperatures (T_{max}) for the Billing Period

Figure 132: Monthly Total Site Water Use versus Monthly Outdoor Temperatures, Including 3-P Multi-Variable Regression Models Represented with Two Lines (The Upper and Lower Lines Represent the Months with a Number of Rainy Days Over 0.3 inches =0 and 5, Respectively.) for the Years from 2008 to 2011

f) Calculation of Performance Changes in Total Site Water Use

To track the changes in total site water performance over several years, the savings[203] were calculated for 2009 to 2011 against the baseline year 2008 by subtracting the billed, actual consumption from the predicted consumption using the selected 2008 3-P MVR total site water use model. To select the most appropriate baseline model for savings calculation, the six 3-P MVR baseline models were compared.

Of the six models, three met the requirements for net determination biases in the ASHRAE Guideline 14-2002 (i.e., 0.005%), including: 0.002% with the T_{minmax} model with the number of rainy days over 0.1 inches; 0.003% with the T_{max} model with the number of rainy days over 0.3 inches; and 0.004% with the T_{minmax} model with the number of rainy days over 0.3 inches. However, the two T_{minmax} models with the number of rainy days either over 0.1 inches or over 0.3 inches were found to significantly under-predict water use for March in 2010 (i.e., lower than the base load) due to high amounts of rainfall in this month, which did not appropriately describe the relationship between water use and two independent variables (i.e., temperature and precipitation variables). On the other hand, the T_{max} baseline model with the number of rainy days over 0.3 inches did not under-predict the water use with a change-point temperature higher than the T_{max} of March, 2010. Therefore, the T_{max} baseline model with the number of rainy days over 0.3 inches was selected as the baseline model for savings calculation.

Figure 133 and Table 46 show the savings calculation results using the selected 3-P MVR model using T_{max} and the number of rainy days over 0.3 inches as independent variables. The uncertainties associated with the calculated savings were also determined at the two levels of confidence: 68% and 90% as listed in the table. The calculated uncertainties at the 68% level of confidence were higher than the maximum level of uncertainty required in the ASHRAE Guideline 14-2002 (i.e., 50% of annual reported savings at 68% confidence) except for the savings computed for 2010[204]. The uncertainties for 2010 with T_{min} model met the requirements with 36% of the reported savings. The high uncertainties in the computed total site water use savings are mainly due to a small amount of reported savings in 2009 and 2011.

Compared to 2008, the building's total site water use was estimated to decrease in 2009

[203] In this dissertation, the word "savings" is used to denote the changes in energy or water use performance against the baseline year. Negative savings means increased energy or water use against the baseline year.

[204] The calculated uncertainties were 961% of the reported savings (i.e., 9.61× 20 kgal/yr = 192 kgal/yr) for 2009; 36% of the reported savings for 2010; and 200% of the reported savings for 2011.

by 0.7% with a savings of 20 kgal/yr with very high uncertainties that were several times greater than the computed savings. In 2010 and 2011, the total site water use of the building increased by: 18.6% in 2010 with uncertainties of 6.6% (68% level of confidence) and 12.1% (90% level of confidence); and 3.4% in 2011 with high uncertainties of 6.8% (68% level of confidence) and 12.5% (90% level of confidence). Therefore, at the 90% confidence level, it would be difficult to justify a decrease or an increase of the total site water use for 2009 and 2011. For 2010, at the 90% confidence level, an increase in the total site water use was observed, which was mainly attributed to an increased landscape water use.

g) Comparison of the Proposed Approach Against the Existing Approach

The generalized building water use model developed in this study is a 3-P cooling change-point model based on a single outdoor temperature variable for indoor building water use; and a 3-P MVR model based on an outdoor temperature in a change-point model and a precipitation variable as an additional independent variable if the water use of interest includes outdoor landscape water use. When applying the same evaluation criteria (i.e., validity, reliability, and practicality) that were used to evaluate the existing ASHRAE PMP procedures[205] to the proposed approach, this new approach is expected to improve the validity of the ASHRAE PMP Intermediate Level water protocol with improved characterization of the building's water performance listed above (i.e., weather-normalized performance changes). The scores for other criteria, reliability and practicality, remain the same since no extra data collection efforts are necessary to perform this new approach.

[205] The applicability of the three levels of measurement approaches in the ASHRAE PMP was examined in terms of validity, reliability and practicality of each level of the protocols based on a scale from 1 (very bad) to 5 (very good). Evaluation criteria were developed in three domains: validity, reliability and practicality, which were built upon the framework originally suggested by the Malmqvist and Glaumann (2006). Details are presented in Section 6.1.2.2.

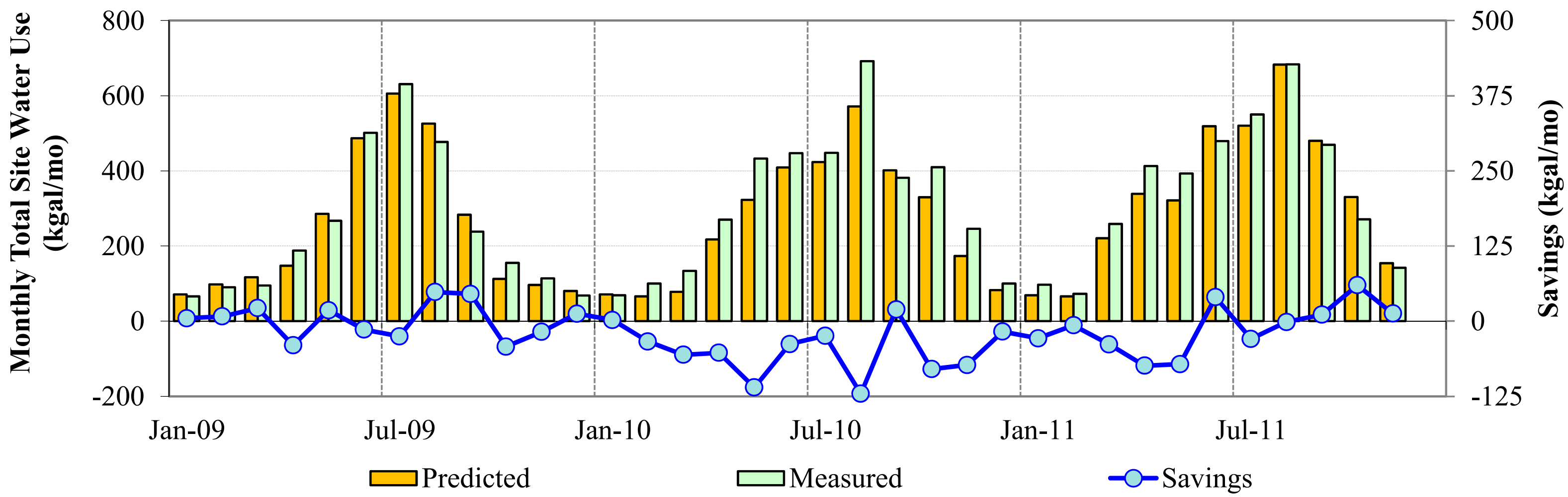


Figure 133: Monthly Total Site Water Savings Against the Baseline Year 2008 Using the Selected Monthly 3-P MVR Model (T_{max} Model with the Number of Rainy Days Over 0.3 Inches) for the Years from 2009 to 2011

Table 46: Annual Summary of Total Site Water Savings Against the Baseline Year 2008 Using the Selected Monthly 3-P MVR Model

	Total Billed (kgal/lperiod)	Total Predicted (kgal/period)	Savings with 68% Confidence		Savings with 90% Confidence	
			(kgal/period)	(%)	(kgal/period)	(%)
2009 (Jan. to Dec.)	2,890	2,910	20 ± 192	0.7 ± 6.6%	20 ± 351	0.7 ± 12.1%
2010 (Jan. to Dec.)	3,731	3,147	-584± 207	-18.6 ± 6.6%	-584 ± 379	-18.6 ± 12.1%
2011 (Jan. to Nov.)	3,830	3,704	-126 ± 253	-3.4 ± 6.8%	-126 ± 462	-3.4 ± 12.5%

6.2.3. *IEQ (Thermal Comfort, IAQ, Lighting, and Acoustics)*[206]

Of the twenty-two issues noted from the field test, six new approaches are proposed in this study for the following six issues:

- **<u>Issue IEQ-1</u>**: The ASHRAE PMP Basic Level IEQ protocol does not provide clear guidelines how to display and interpret the results
- **<u>Issue IEQ-9</u>**: There is a lack of a specific step-by-step measurement protocol that can be used for IEQ spot measurements.
- **<u>Issue IEQ-15</u>**: The required IAQ measurements (i.e., continuous measurements of CO_2 and TVOCs) could not verify the occupants' complaints about stuffy and stale air due to poor air circulation within a room.
- **<u>Issue IEQ-17</u>**: The ASHRAE PMP Intermediate and Advanced Level lighting and acoustics protocols do not require a continuous measurement. However, in this study, time-of-day variations were observed in the measured lighting and acoustics performance metrics.
- **<u>Issue IEQ-19</u>**: The octave band measurements required at the Intermediate Level have low practical applicability (i.e., very few manufacturers who make the equipment and high equipment cost).
- **<u>Issue IEQ-20</u>**: The ASHRAE PMP Intermediate and Advanced Level IEQ protocols do not provide clear guidelines about how to analyze the results of continuous, time-series measurements for benchmarking, although continuous measurements are required for thermal comfort and IAQ protocols.

Three of the six new approaches were addressed during the field test. Thus details on these three new approaches are presented in Section 4.1.4.1 for the Issue IEQ-9; Section 5.3.2.2 for the Issue IEQ-19; and Section 5.3.2.2 for Issue IEQ-20.

6.2.3.1. <u>New Approach to Issue IEQ-1: Graphical Index for Displaying the Surveyed IEQ Satisfaction</u>

This proposed approach discusses a new graphical index for displaying the surveyed IEQ satisfaction votes. The occupant IEQ satisfaction survey results were visualized by mapping them on the floor plans of a building using color-coded satisfaction scale (i.e., very satisfied: green, neutral: yellow, dissatisfied: red). An example of the proposed approach is presented in Figure 134. This figure displays the two selected floor plans of the case-study building

[206] There are no modified approaches proposed for the ASHRAE PMP IEQ protocols.

superposed by color-coded thermal comfort satisfaction votes, which allows identifying the problematic locations of the building at a single glance and correlating them with the orientation, geometry, or type of workspace (i.e., private or open office). In this thesis, to assure the confidentiality of the surveyed data, only two floors were randomly displayed. However, a vertical stack of all floor plans would be more effective for the ASHRAE PMP users to make comparisons of the surveyed responses by locations across an entire building. The proposed graphic form is one of the ways of displaying the collected data efficiently to maximize the information contained in the data in addition to the statistical analysis of the results suggested in the current version of the ASHRAE PMP Basic Level IEQ protocol.

When applying the same evaluation criteria (i.e., validity, reliability, and practicality) that were used to evaluate the existing ASHRAE PMP procedures[207] to the proposed approach, this new approach is expected to improve the practicality of the ASHRAE PMP Basic Level IEQ protocols with a quick characterization of the measured occupants' IEQ satisfaction and self-reported productivity across an entire building. The scores for other criteria, validity and reliability, remain the same since no additional data collection efforts were necessary to perform this new approach.

[207] The applicability of the three levels of measurement approaches in the ASHRAE PMP was examined in terms of validity, reliability and practicality of each level of the protocols based on a scale from 1 (very bad) to 5 (very good). Evaluation criteria were developed in three domains: validity, reliability and practicality, which were built upon the framework originally suggested by the Malmqvist and Glaumann (2006). Details are presented in Section 6.1.2.3.

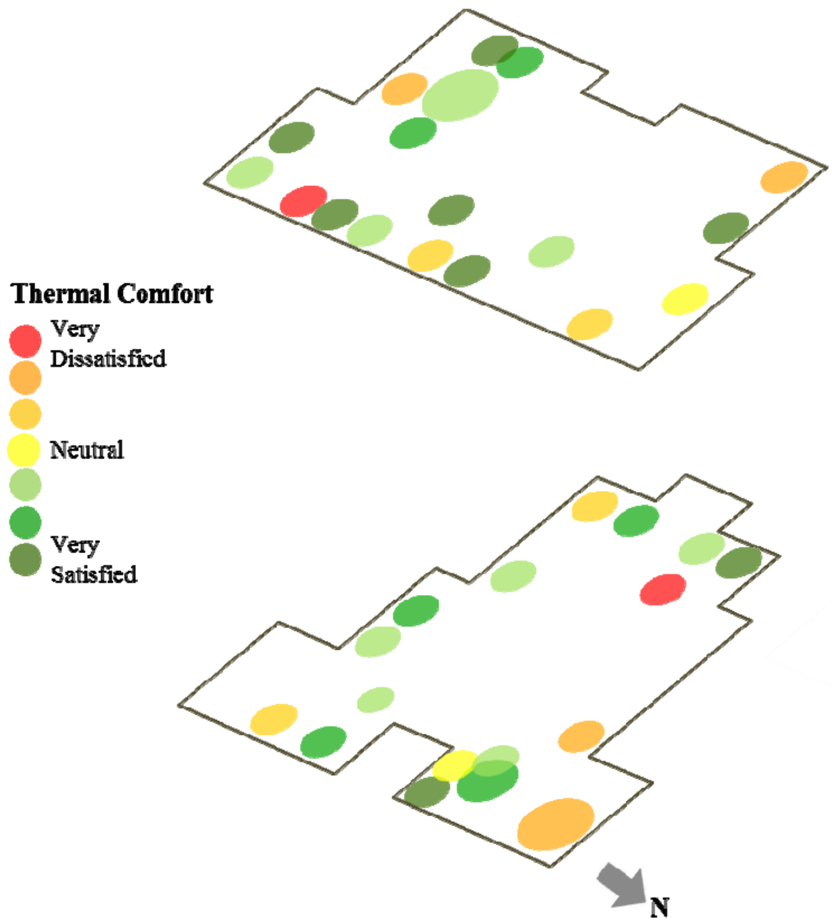


Figure 134: Floor Plans of the Case-Study Building Superposed by Surveyed Satisfaction for Thermal Comfort[208]

[208] In this figure, colored circles are used to protect the confidentiality of the surveyed data. It would be an improvement for the future version of the figure to color the corresponding entire room.

6.2.3.2. New Approach to Issue IEQ-15: Vertical Temperature Profile as a Simple Indicator to Evaluate Room Air Circulation

In this study, no differences were identified between the measurement results of CO_2 and TVOCs in offices where occupants expressed dissatisfaction (two offices) versus satisfaction (eight offices). The two dissatisfied offices were ventilated adequately based on the CO_2 measurement results. However, the occupants complained about stuffy and stale air due to poor circulation within a room, which could not be verified from the measurements of CO_2 and TVOCs. Thus, in this proposed approach, a simple method that can be used to diagnose air circulation problems within a room was discussed using a vertical temperature profile.

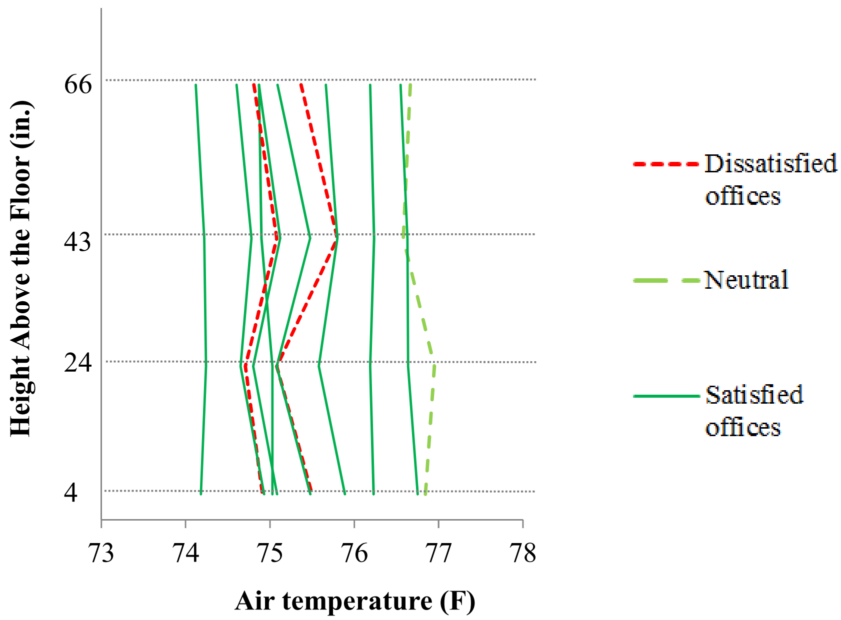
Figure 135 illustrates vertical temperature profiles of two dissatisfied (dotted lines), one neutral (dashed line), and eight satisfied offices (solid lines) during the occupied periods measured over one week based on (a) the median temperatures at four heights (i.e., 4 in., 24 in., 43 in., and 66 in.); and (b) the median temperature differentials at four heights relative to the 24 in. median temperature. In the figure, the median temperature at 24 in. was used to calculate vertical temperature differentials at other three levels (i.e., 4 in., 43 in., and 66 in.) as an effective way to present potential temperature stratification in the breathing zones.

For the two dissatisfied offices, hot air stratification was observed at 43 in. (1.1 m), possibly indicating poor air circulation in these two offices that might prevent the delivery of fresh air in the breathing zones. In addition, the measured air speeds at 43 in. in these two offices remained constant and was lower when compared to other offices (two north offices in a dissatisfied group in Figure 102 (d)), which also implies poor circulation. Thus, in these offices, the use of vertical temperature profile was found to be an effective method to evaluate room air circulation which is related to the stuffiness and staleness of the room air.

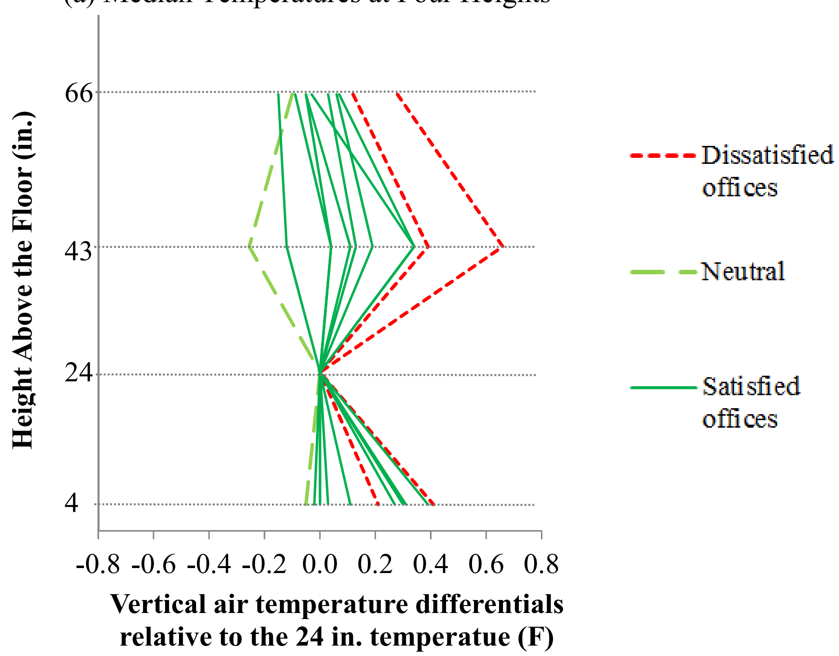
When applying the same evaluation criteria (i.e., validity, reliability, and practicality) that were used to evaluate the existing ASHRAE PMP procedures[209] to the proposed approach, this new approach is expected to improve the content validity of the ASHRAE PMP Intermediate and Advanced Level IAQ protocol with additional characterization of the building's IAQ performance listed above. The scores for other criteria, reliability and practicality, remain the

[209] The applicability of the three levels of measurement approaches in the ASHRAE PMP was examined in terms of validity, reliability and practicality of each level of the protocols based on a scale from 1 (very bad) to 5 (very good). Evaluation criteria were developed in three domains: validity, reliability and practicality, which were built upon the framework originally suggested by the Malmqvist and Glaumann (2006). Details are presented in Section 6.1.2.3.

same. No additional data collection efforts were necessary to perform this new approach since the temperature measurements at various levels are the metrics required at the thermal comfort protocols.



(a) Median Temperatures at Four Heights



(b) Median Temperature Differentials at Four Heights Relative to the 24 In. Temperature

Figure 135: Vertical Air Temperature Profiles of Eleven Offices during the Occupied Periods

6.2.3.3. New Approach to Issue IEQ-17: Development of Real-Time Wireless IEQ Monitoring System for the Continuous IEQ Measurements

The ASHRAE PMP Intermediate and Advanced Level lighting and acoustics protocols do not require any continuous measurement while it is required in thermal comfort and IAQ protocols. The IEQ spot measurements are helpful to discover possible causes of problems if the measurements are conducted at the same time when discomfort arises, which is not easy to accomplish. Meanwhile, the IEQ continuous measurements become a considerable option to evaluate a building's IEQ performance in light of rapidly evolving field instruments and data loggers. Although the thermal comfort and IAQ protocols require continuous measurements, the current version of the ASHRAE PMP does not provide any guidelines about how to continuously collect and record the data as well as how to process and interpret the recorded data. Thus, this proposed approach discusses a method to collect and analyze the continuously measured IEQ performance data using a comprehensive IEQ continuous monitoring cart developed in this study (Figure 27).

a) Development of IEQ Wireless Monitoring Cart

This study developed a comprehensive instrumentation cart to collect continuous, time-series data from selected IEQ-related parameters while recording the occupancy using an occupancy sensor, including: four vertical air temperatures, four vertical globe temperatures, humidity, air speed, CO_2, total volatile organic compounds (TVOCs), horizontal and vertical illuminance, as well as A-weighted and C-weighted sound pressure levels, as shown in Table 8 and Figures 27 through 33. The appropriate sensors were determined based on the survey of currently available equipment on the market, including: sensor type, accuracy, resolution, response time, and power consumption, along with cost information, as shown in the Appendix B. The selected sensors were then calibrated, as shown in the Appendix C.

Once the sensors were calibrated, they were connected to the data acquisition system (DAS) of the instrumentation cart. The DAS of the monitoring cart is comprised of a Campbell Scientific CR 1000 data logger, a Campbell Scientific AM16/32B multiplexer, and a Campbell Scientific PS100 rechargeable power supply for the data logger and peripherals, which are distributed in two enclosures mounted to the pole. To secure the wires that connect sensor and data logger, connectors with solder termination were used, as shown in Figure 136. Furthermore, to eliminate the clicking sound when the mechanical relays of the AM16/32B multiplexer were operating, the multiplexer in an enclosure was enclosed in appropriate soundproofing materials, as shown in Figure 137.

The proposed DAS system was used to collect and store 10 second scan interval data from 18 channels with three different data logging intervals (1 minute, 5 minute, and 15 minute). The system included a Campbell Scientific NL115 Ethernet interface and a router for real-time wireless communications in addition to a direct communication by connecting the logger to a computer port. Figure 138 shows a schematic diagram of the developed DAS system.

The instrumentation cart was designed to be as compact as possible to maximize its mobility and portability while minimizing disturbance to the occupants in a building. The sensors and DAS were mounted over a rolling stand with a pole adjustable to a height of 83 inches. Air temperature sensors were shielded from solar radiation, and both air and globe temperature sensors were located away from the heat plume from other equipment mounted on the stand such as the battery pack and 18 VAC transformers. To protect the air and globe temperature sensors (i.e., T-type thermocouples), protection steel rings were fabricated and mounted around the sensors at four different heights (4, 24, 43, 66 in.).

A real-time monitoring dashboard of IEQ performance data was assembled using the three Campbell Scientific software applications, including the LoggerNet datalogger support software packages; the RTMCPro (real-time monitoring and control software, professional); and the RTMC Web Server. Figures 139 to 145 are the example snapshots of the IEQ performance dashboard applications. First, Figure 139 shows example real-time IEQ performance data with concurrent outdoor weather conditions measured at the nearby Solar Test Bench (STB) (ESL 2012) on the roof of the Texas A&M Langford Architecture Center. Figure 140 shows example time-series IEQ performance data with 5 minute data interval continuously measured in the same office over a one week. Figure 141 shows example indoor climate conditions (5 minute interval data) that were continuously measured in the same office over a one week plotted onto the ASHRAE 55-2004 comfort zone[210] with concurrent outdoor weather conditions for the occupied versus unoccupied periods. Figures 142 to 145 present example time-series plots of 1 minute interval data that were continuously measured in the same office over one week for thermal comfort, IAQ, lighting, and acoustics, respectively, with the corresponding benchmarks as

[210] The ASHRAE Standard 55-2004 comfort zone consists of two zones. The left zone in red is for 1.0 clo of clothing insulation which is the insulation level of clothing typically worn in winter, while the right zone in blue is for 0.5 clo of insulation which is the insulation level of clothing typically worn in summer.

applicable. Discussions on these example time-series plots of IEQ dashboard (i.e., Figures 142 to 145) are presented in Appendix F.

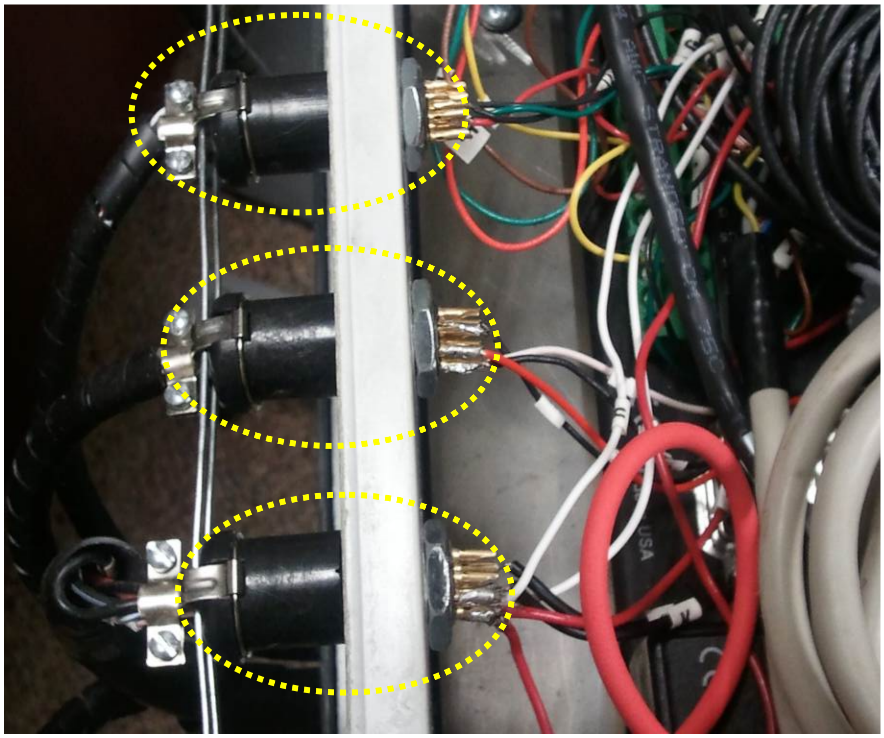


Figure 136: Connectors with Solder Termination for Securing the Wires

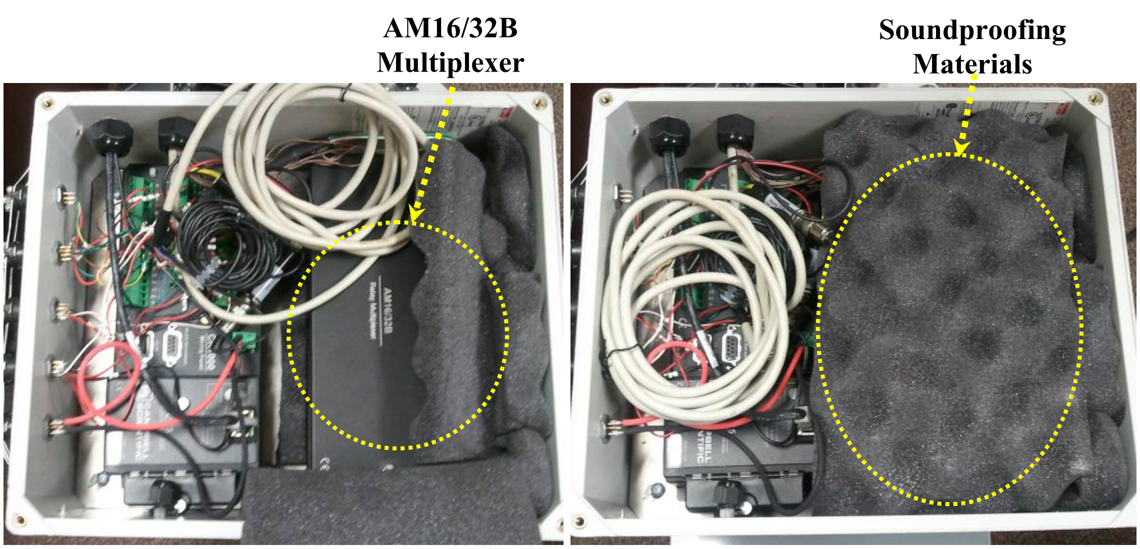


Figure 137: Soundproofing Materials Wrapping the AM16/32B Multiplexer

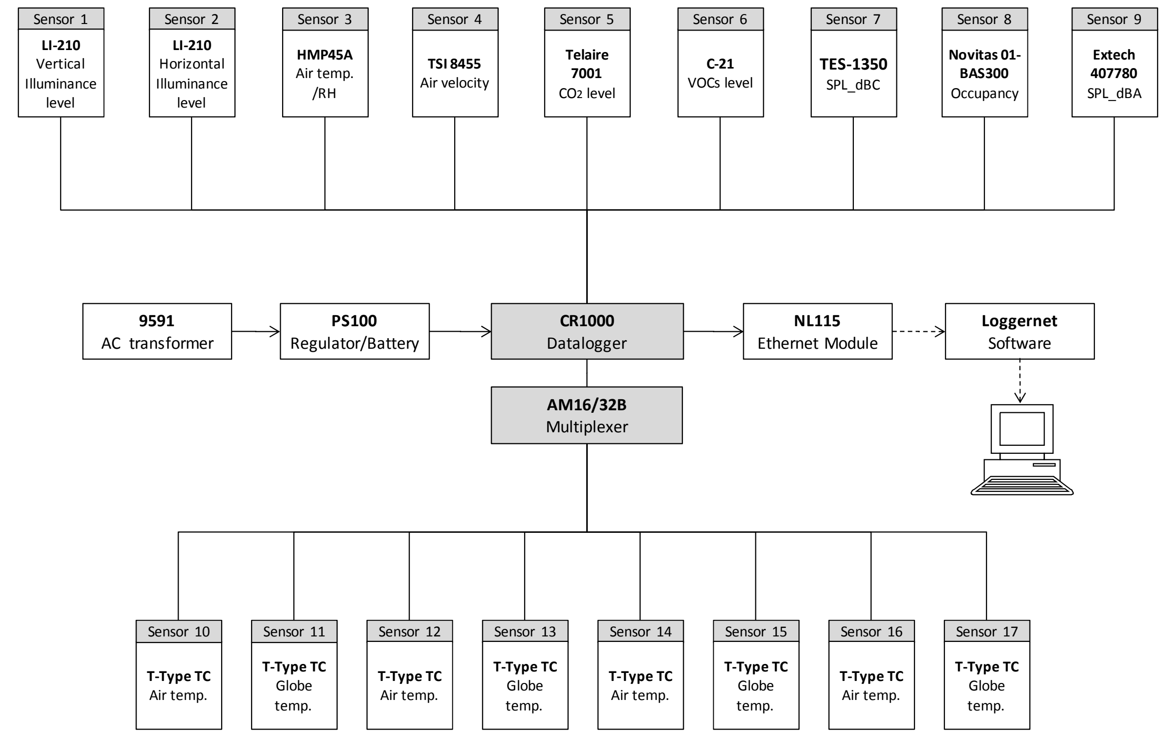


Figure 138: Schematic Diagram of the Developed IEQ Performance Data Acquisition System

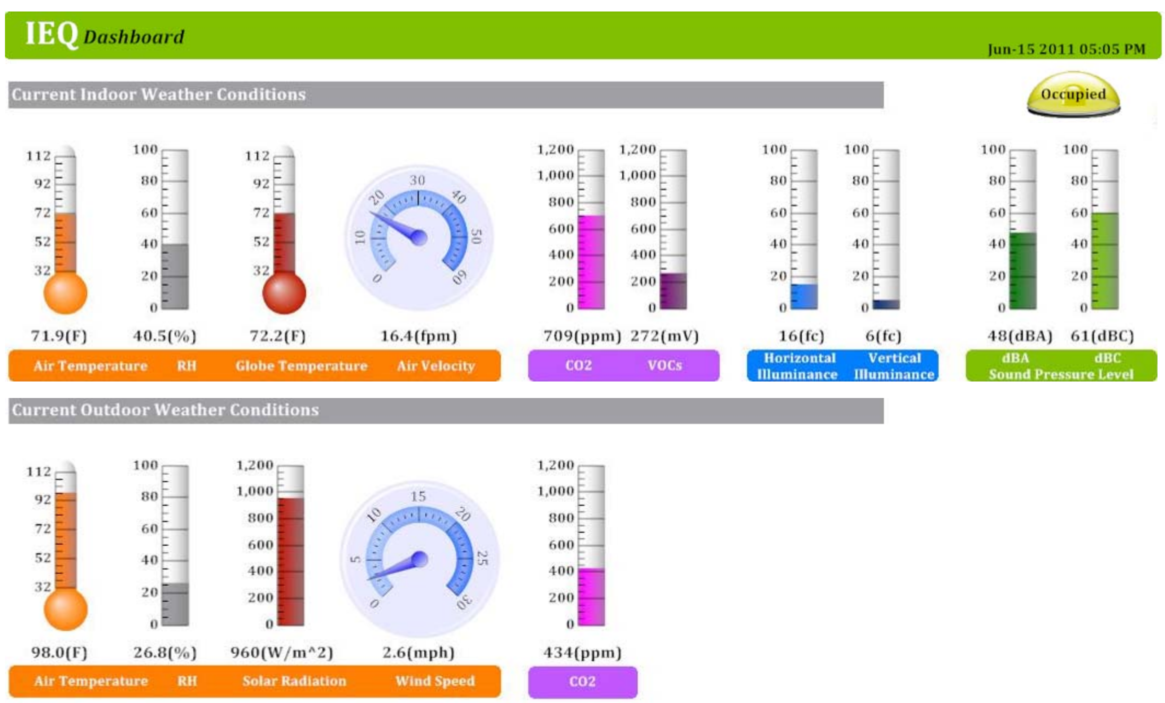


Figure 139: Example Dashboard Snapshot Showing Real-Time IEQ Performance with Concurrent Outdoor Weather Conditions

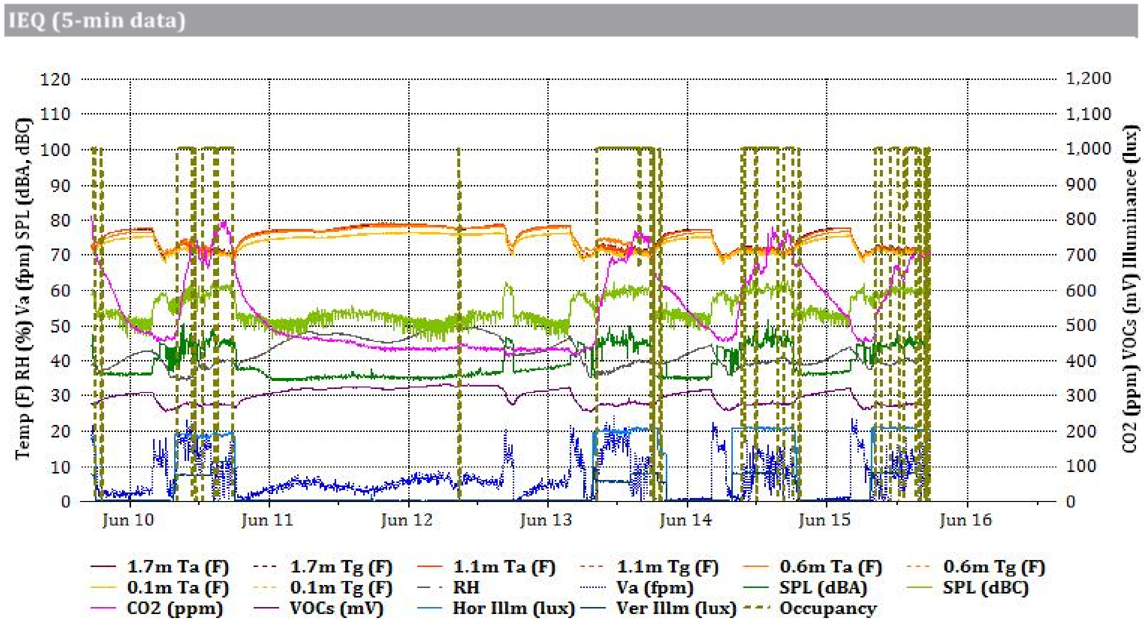


Figure 140: Example Dashboard Snapshot Showing Time-Series IEQ Performance Data with 5 Minute Data Interval Continuously Measured In the Same Office Over One Week

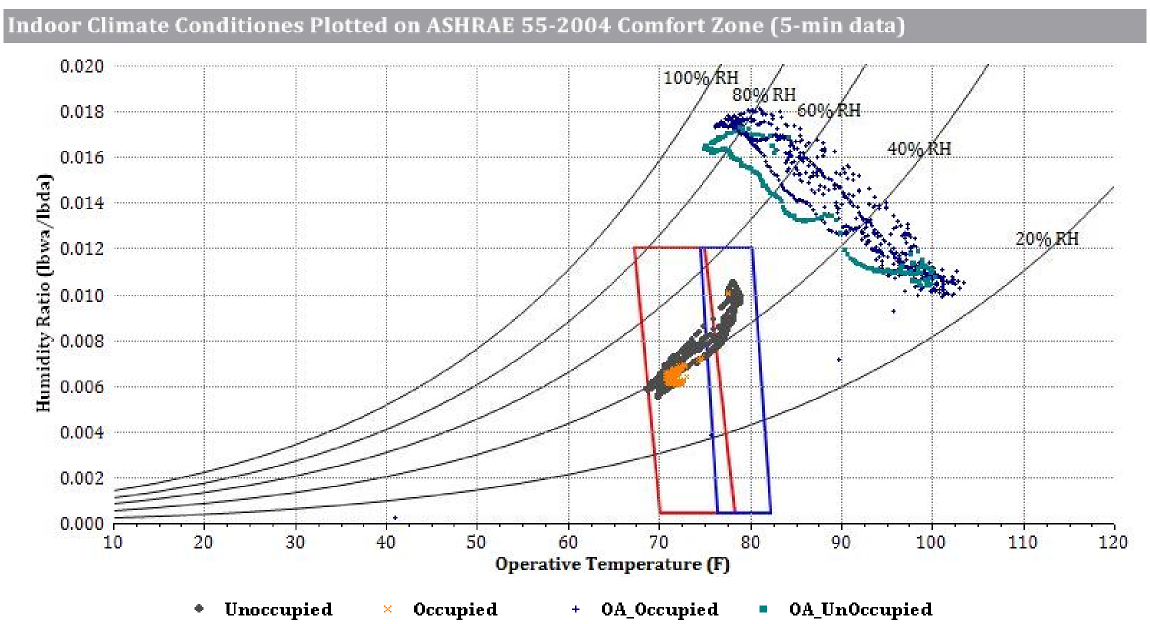


Figure 141: Example Dashboard Snapshot Showing Indoor Climate Conditions (5 Minute Interval Data) Continuously Measured In the Same Office Over One Week Plotted onto the ASHRAE 55-2004 Comfort Zone with Concurrent Outdoor Weather Conditions: Occupied versus Unoccupied Periods

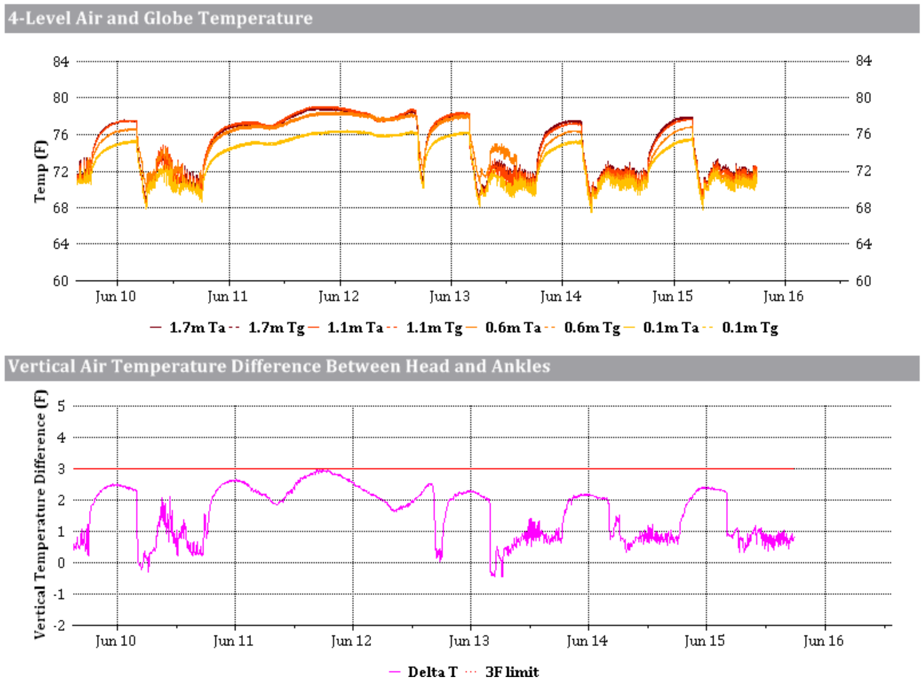


Figure 142: Example Dashboard Snapshot Showing Time-Series Thermal Comfort Performance Data with 1 Minute Data Interval Continuously Measured In the Same Office Over One Week

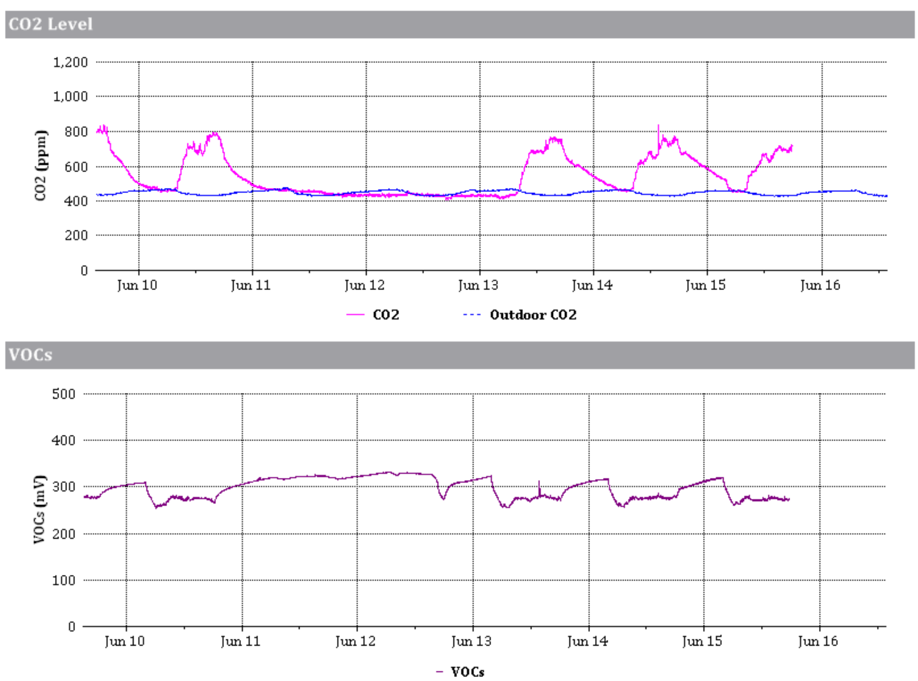


Figure 143: Example Dashboard Snapshot Showing Time-Series IAQ Performance Data with 1 Minute Data Interval Continuously Measured In the Same Office Over One Week

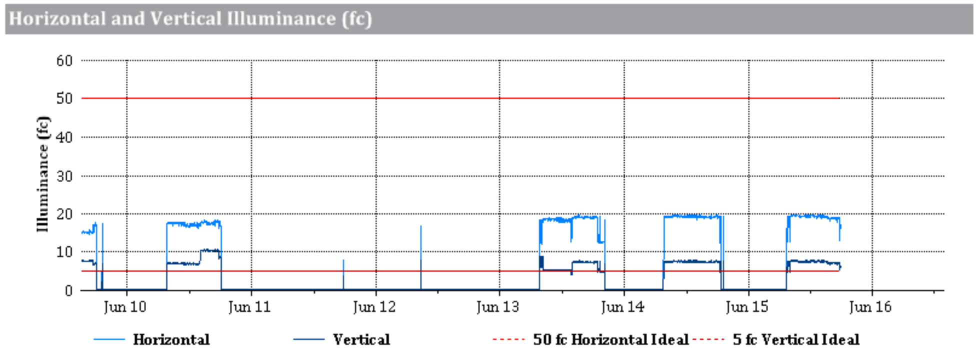


Figure 144: Example Dashboard Snapshot Showing Time-Series Lighting Performance Data with 1 Minute Data Interval Continuously Measured In the Same Office Over One Week

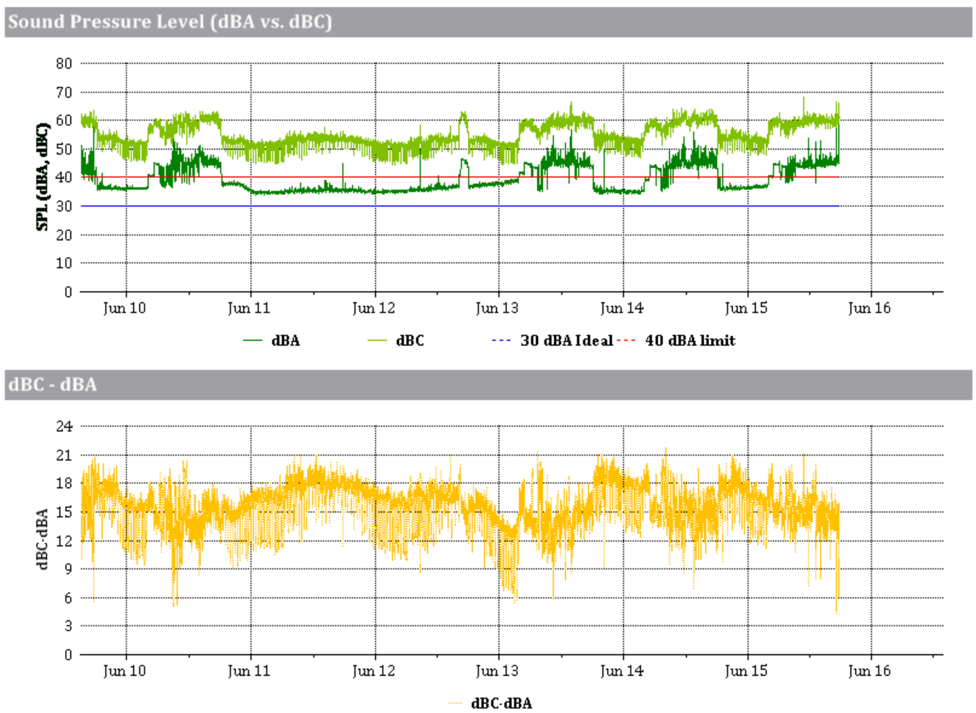


Figure 145: Example Dashboard Snapshot Showing Time-Series Acoustics Performance Data with 1 Minute Data Interval Continuously Measured In the Same Office Over One Week

b) Analysis of Continuously Monitored IEQ Performance Data

In Section 5.3.2.2, this study selected statistical analysis to describe the time-varying distribution of the continuously measured IEQ performance metrics during the occupied hours: maximum, 95th, median, 5th, minimum. The 95th and 5th percentiles were chosen to characterize extreme variations based on ±5% of deviation. The median was chosen as a convenient way to describe the average of skewed distributions by a single number for a comparison between locations, while also conveying information on that variation for a half the measurement period. The statistical approach taken in this study was found to be useful when compared the measurements against the benchmarks. This section discusses other ways of displaying and analyzing the collected data to maximize the information contained in the data.

- Thermal comfort analysis using the psychrometric chart and hourly profiles

In this proposed method, the continuously measured indoor climate conditions are analyzed using the psychrometric chart and hourly profiles. The use of the psychrometric chart provides a graphically rich description of the continuously measured sub-hourly thermal comfort performance data that integrates the four environmental variables (i.e., air temperature, humidity, mean radiant temperature, and air speed). The hourly profiles allow the viewer to determine when and how often the abnormal behaviors occur if they are present. Of the eleven offices of a case-study building where the measurements were made over a one week period in each office, two offices were selected as examples to discuss the proposed approach.

Figures 146 shows the indoor climate conditions collected in one west-facing office on the second floor of the case-study building over one week from August 16 to 23, 2011, which are plotted onto the ASHRAE Standard 55-2010 comfort zone[211]. In this figure, the data are presented separately for the occupied and unoccupied periods during weekday business hours (i.e., 8 a.m. to 5 p.m.) as well as unoccupied periods during non-business hours. Not surprisingly, the proposed method shows how the measurement space is conditioned for occupied versus unoccupied periods. In this example office, it was observed that its thermal environments were conditioned differently for occupied versus unoccupied periods, which was controlled by a setup schedule in the EMCS[212]. Once the building's regular thermostat set point for an occupied mode turned-on, which was about two hours before the building is occupied, the building's thermal

[211] The ASHRAE Standard 55-2010 comfort zone consists of two zones. The left zone in red is for 1.0 clo of clothing insulation which is the insulation level of clothing typically worn in winter, while the right zone in blue is for 0.5 clo of insulation which is the insulation level of clothing typically worn in summer.
[212] About 3F temperature difference was observed between occupied versus unoccupied periods.

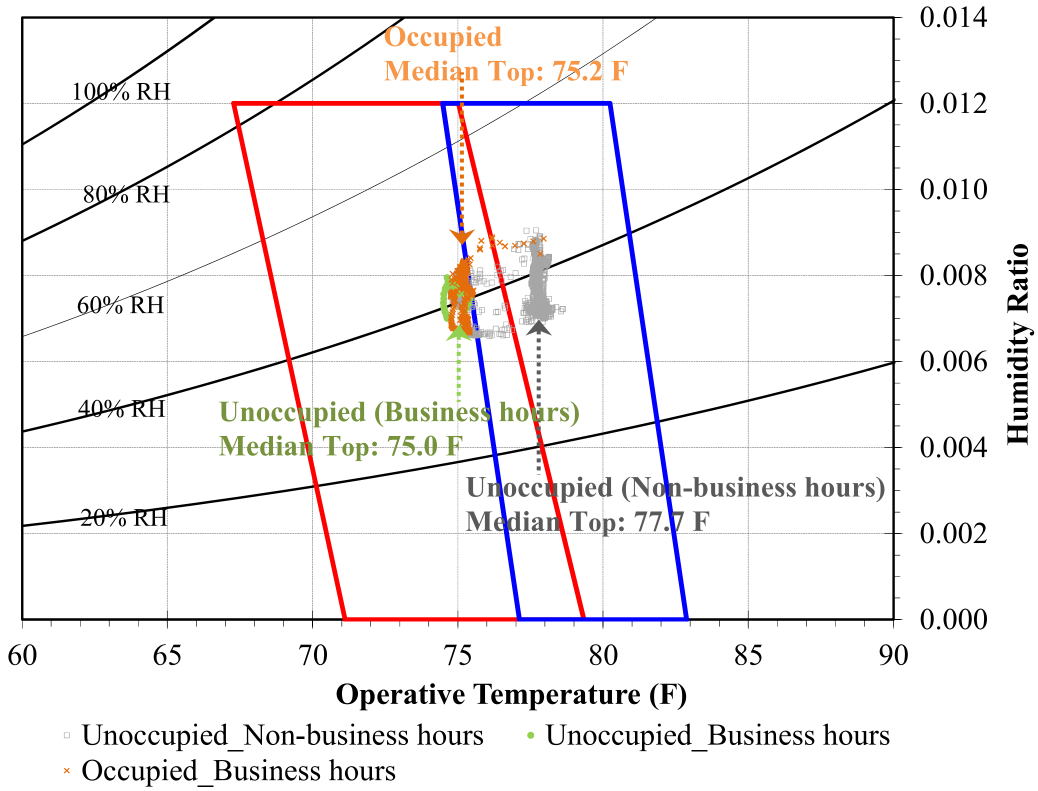


Figure 146: Measured Indoor Climate Conditions of One West-Facing Office on the Second Floor of the Case-Study Building on ASHRAE Standard 55-2010 Comfort Zones (August 16 to 23, 2011)

conditions started moving to the left toward the winter comfort zone or the cool side of summer comfort zone based on the ASHRAE Standard 55-2010.

The proposed graphical method also shows whether the systems respond to the thermostat quickly enough. The data points that connect an unoccupied group (i.e., gray dots) with an occupied group (i.e., orange dots) in the figure represent the transition periods before and after the system's unoccupied mode (i.e., set-up schedule) turned-on. In this example office, it was observed that the conditions were controlled in a designed way by providing pre-conditioned thermal environments before the room was occupied.

In addition, the proposed method is helpful in detecting selected operational issues if they are present. In this example, there was an event where the occupied conditions were approaching to the unoccupied conditions, which are represented orange dots connecting an occupied group (i.e., orange dots) with an unoccupied group (i.e., gray dots) in the figure. In a 5 minute interval time-series plot and a time-of-day graphical display of the measured time-series data using a color-coded data points by occupancy (i.e., Occupied during business hours: orange, Unoccupied during business hours: green, Unoccupied during non-business hours: gray) as shown in Figure 147 and Figure 148, respectively, unexpectedly increasing temperatures were observed around 11 a.m. in this west-facing office, which was a one-time event. In a subsequent inspection of the sub-hourly chiller electricity use data, it was confirmed that there was an operational problem of the chiller at this exact time, which caused a chiller failure for one hour on August 22, 2011 (Figure 149).

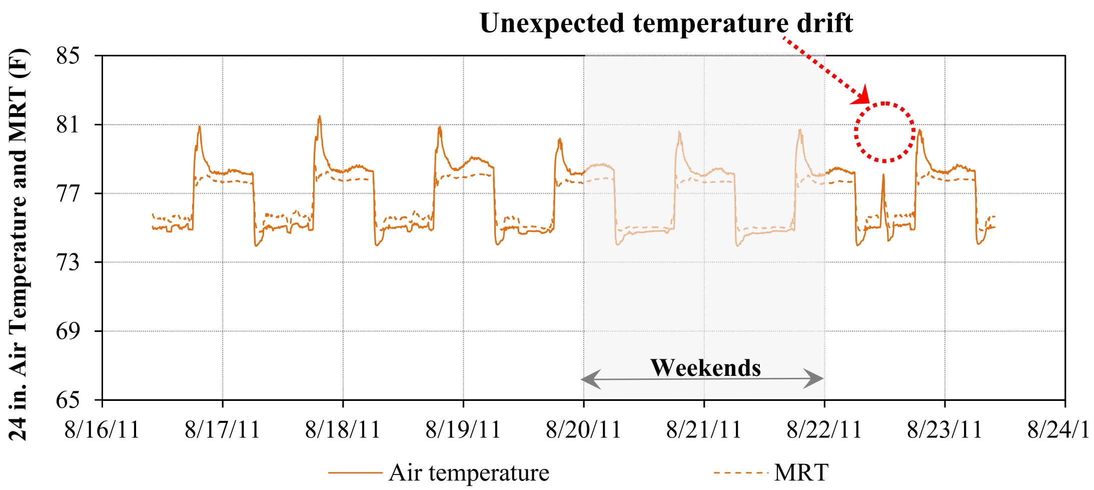


Figure 147: 5 Minute Air and Mean Radiant Temperature at 24 Inches of the West-Facing Office on the Second Floor of the Case-Study Building (August 16 to 23, 2011)

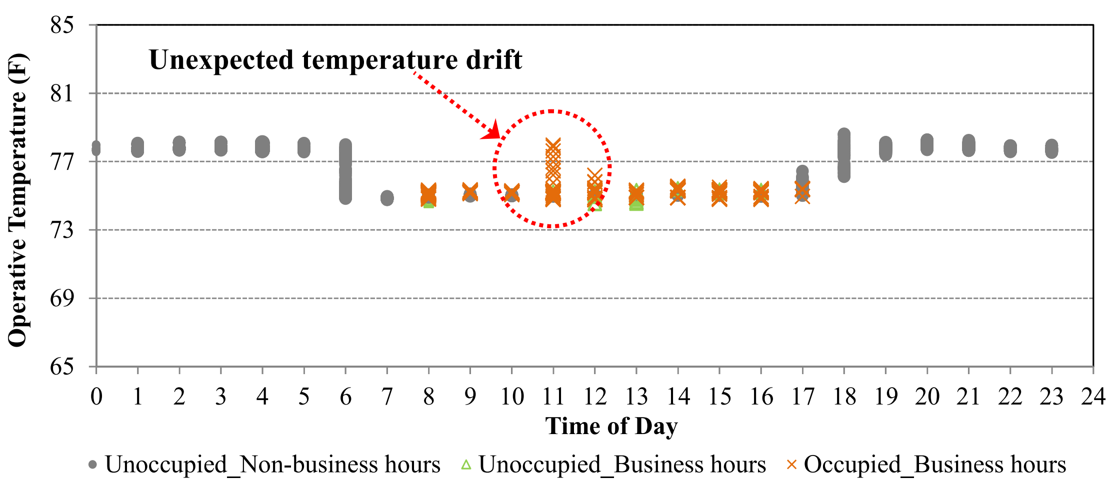


Figure 148: Hourly Profiles of Operative Temperatures of the West-Facing Office on the Second Floor of the Case-Study Building (August 16 to 23, 2011)

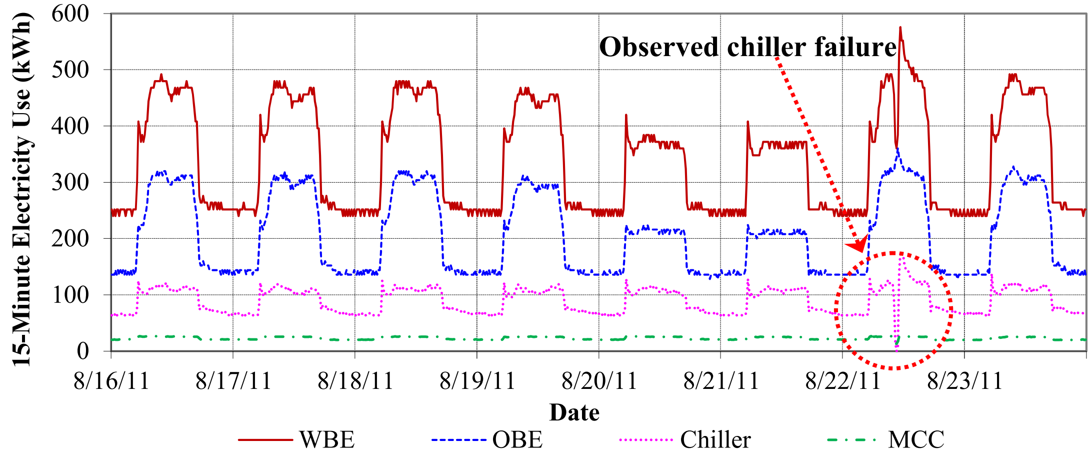


Figure 149: 15 Minute Electricity Use of the Case-Study Building for the Whole-Building and Major End-Uses (August 16 to 23, 2011)

Another example which shows the usefulness of the proposed method is presented in Figure 150. This figure shows the indoor climate conditions collected in one west-facing office on the sixth floor of the case-study building over one week from August 30 to September 6, 2011, which are plotted onto the ASHRAE Standard 55-2010 comfort zone, for the occupied and unoccupied periods during weekday business hours (i.e., 8 a.m. to 5 p.m.) as well as unoccupied periods during non-business hours.

In this example, no distinct differences were observed in the measured thermal environments between occupied versus unoccupied periods, which means the EMCS setup schedule was not observable in the measured data for this room. This may be because the location of the thermostat that controls this office's thermal environment is placed on the interior wall of the office next door[213]. During unoccupied periods, it was observed the data were spread over a wide range of temperature. In a 5 minute interval time-series plot and a time-of-day graphical display of the measured time-series data using a color-coded data points by occupancy (i.e., Occupied during business hours: orange, Unoccupied during business hours: green, Unoccupied during non-business hours: gray) as shown in Figure 151 and Figure 152, respectively, it was observed that the left side (i.e., lower temperature) of the unoccupied group in Figure 150 happened during the pre-conditioning periods, which was about two hours before

[213] To further confirm this condition, it would be necessary to take simultaneous measurements in the office and at the thermostat to observe the faulty control.

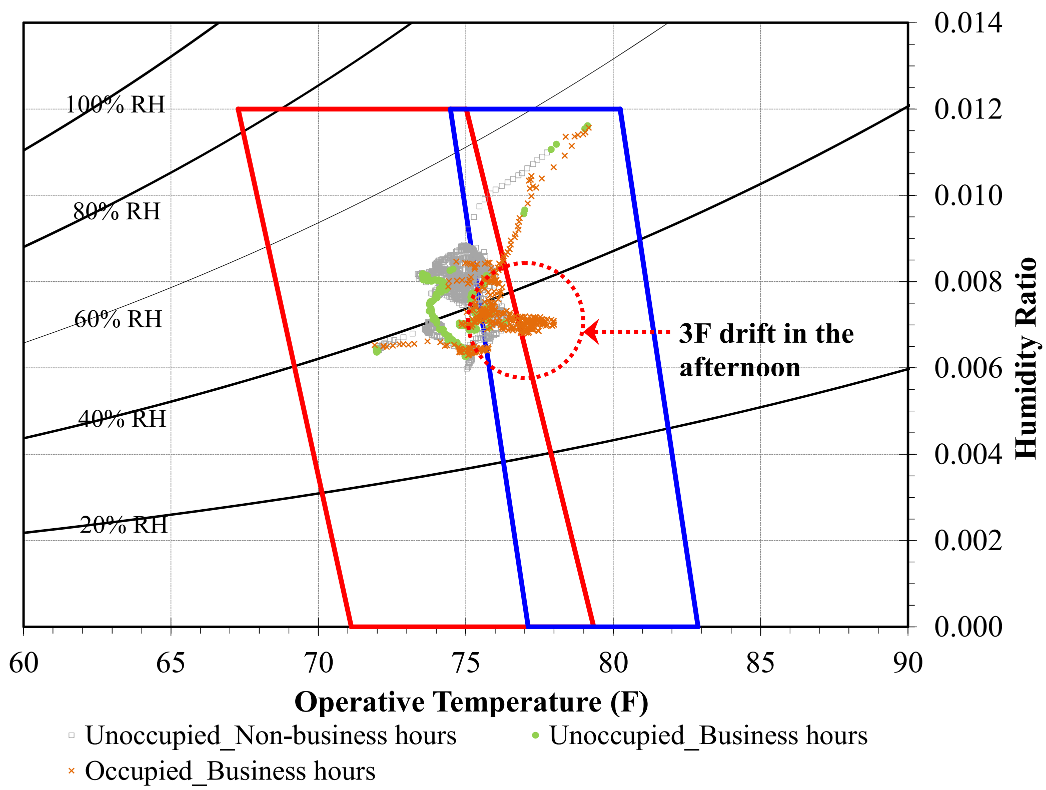


Figure 150: Measured Indoor Climate Conditions of One West-Facing Office on the Sixth Floor of the Case-Study Building on ASHRAE Standard 55-2010 Comfort Zones (August 30 to September 6, 2011)

the building is occupied, while the right side (i.e., higher temperature) of the unoccupied group in Figure 150 happened just after people left around 5 p.m.

During occupied periods, there were some periods when the room temperatures increased by approximately 3F. In a time-of-day graphical display, increasing temperatures due to solar radiation from the window were observed in the afternoon in this west-facing office, which caused the occupied group (i.e., orange dots) to extend to the right in Figure 150. Therefore, this office's thermal environment during the occupied periods were found not to be conditioned as scheduled, especially in the afternoon due to solar radiations from the window.

In this example, an unexpected temperature drift (i.e., higher temperature) was also observed, which is suspected of some operational problems with HVAC systems. The observed drift existed over both unoccupied and occupied periods, which means it happened just before the building is occupied. In a subsequent inspection of the sub-hourly chiller electricity use data,

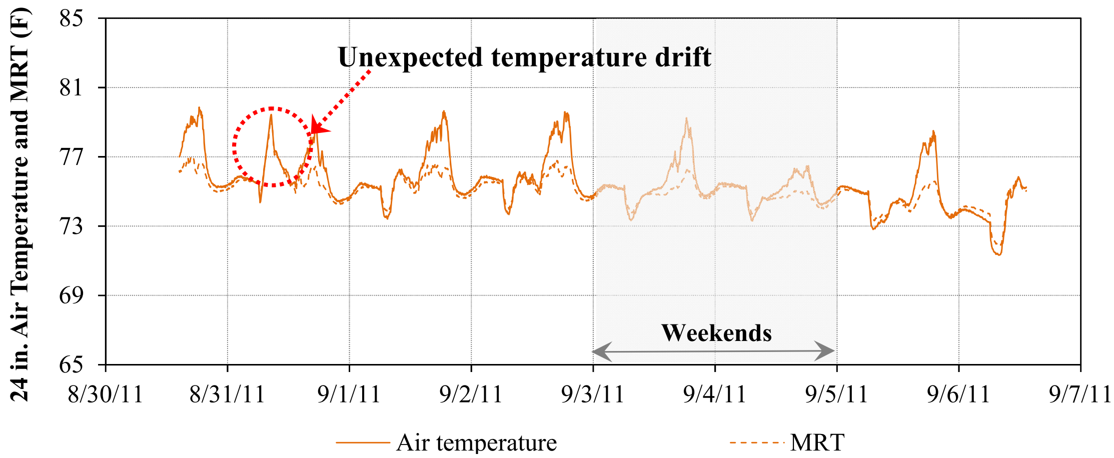


Figure 151: 5 Minute Air and Mean Radiant Temperature at 24 Inches of the West-Facing Office on the Sixth Floor of the Case-Study Building (August 30 to September 6, 2011)

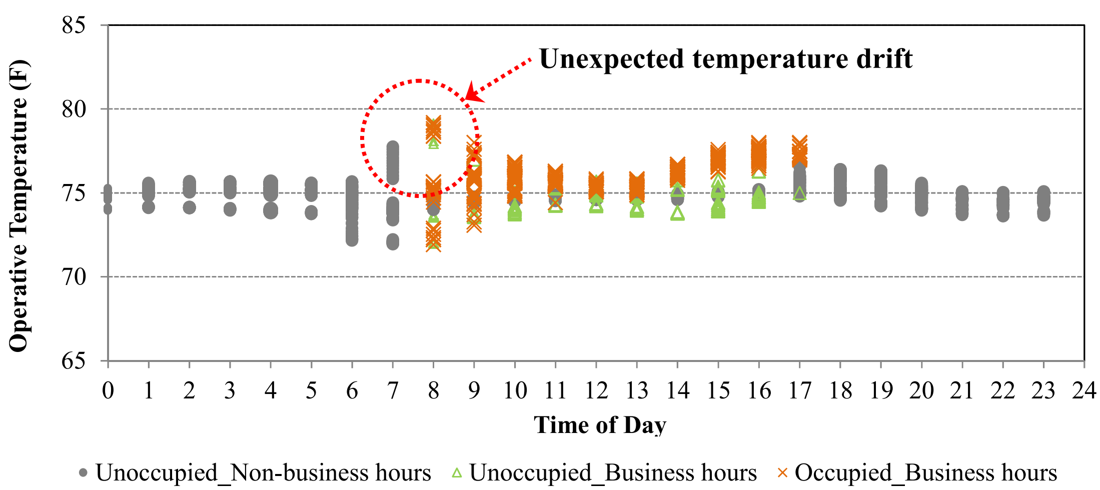


Figure 152: Hourly Profiles of Operative Temperatures of the West-Facing Office on the Sixth Floor of the Case-Study Building (August 30 to September 6, 2011)

it was confirmed that there was an operational problem of the chiller, which caused a chiller failure for two hours between 5:30 a.m. and 7:30 a.m. on August 31, 2011 (Figure 153).

In addition, there was a temperature drop near 72 F in Figure 150. This happened in the early morning on September 6, 2011, when the outdoor temperature significantly dropped to 65 F[214] (Figure 154). As mentioned above, since the thermostat is placed on the interior wall of the

[214] Figure 152 shows outdoor weather conditions measured at the Solar Test Bench (STB) (ESL 2012) on the roof of the Texas A&M Langford Architecture Center from August 30 to September 6, 2011.

next office, the systems were operating although the physical conditions of the measurement location were much lower than the set point. This observation also shows the importance of the concurrently measured outdoor climate conditions in interpreting IEQ performance data.

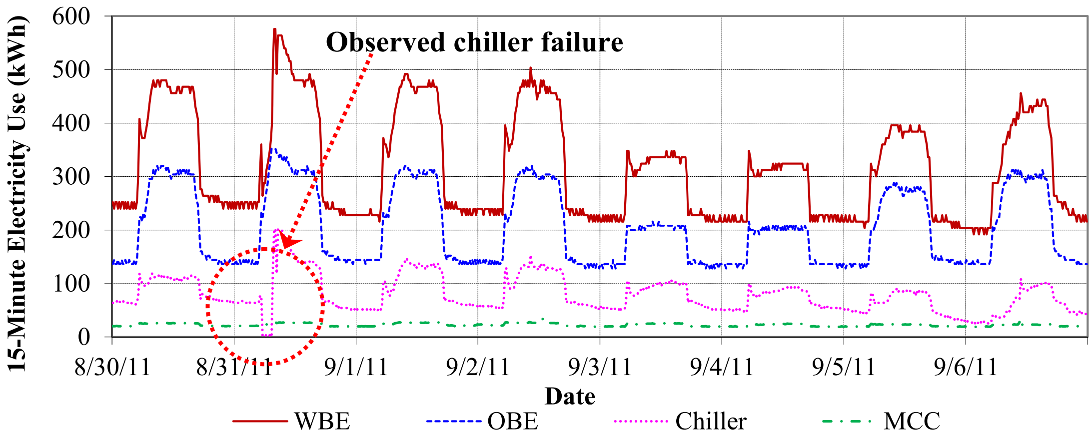


Figure 153: 15 Minute Electricity Use of the Case-Study Building for the Whole-Building and Major End-Uses (August 30 to September 6, 2011)

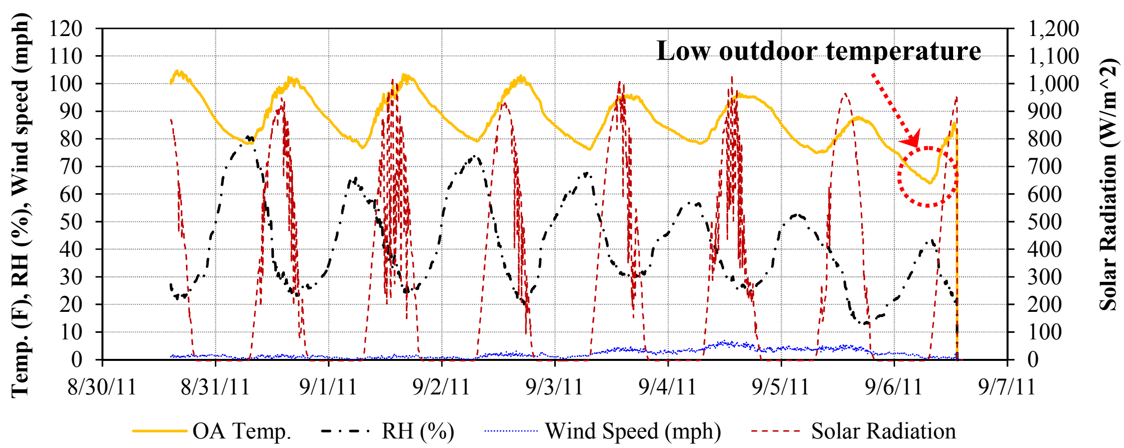


Figure 154: 15 Minute Electricity Use of the Case-Study Building for the Whole-Building and Major End-Uses (August 30 to September 6, 2011)

- Thermal comfort analysis using the PMV/PPD distribution chart

In this proposed method, the continuously measured indoor climate conditions are analyzed using the PMV/PPD distribution chart. The use of the PMV/PPD distribution chart allows the analysis of the measured four environmental variables (air temperature, humidity, mean radiant temperature, and air speed) along with the two surveyed personal variables (clothing and activity). One office was selected as an example to discuss the proposed approach.

Figure 155 shows the indoor climate conditions collected in one west-facing office on the second floor of the case-study building over one week from August 16 to 23, 2011, which are plotted onto the ASHRAE Standard 55-2010 PMV/PPD distribution plot. In this figure, the data are presented separately for the occupied and unoccupied periods during weekday business hours (i.e., 8 a.m. to 5 p.m.) as well as unoccupied periods during non-business hours. With the surveyed clothing (0.57 clo) and activity (1.0 met), the occupant in this office was predicted to experience cold thermal sensation with a very low median PMV (−1.25 PMV and 38% PPD). Thus, based on the PMV/PPD analysis with the surveyed clothing and activity, this office's thermal environments were observed to be outside of the comfort zone against the Computer Model Method's acceptable PMV range (i.e., ±0.5 PMV) in Section 5.2.1.2 of ASHRAE Standard 55-2004 and Standard 55-2010.

Generally, this result agrees with the findings from a graphical analysis using the psychrometric chart (Figure 146). Based on the analysis using the psychrometric chart, 94% of the observed thermal measurements during the occupied periods were outside of the summer comfort zone of the ASHRAE Standard 55-2004 and Standard 55-2010 (i.e., Graphic Comfort Zone Method's summer comfort zone in Section 5.2.1.1). The observed small differences[215] in the results between the PMV/PPD analysis method versus the comfort zone analysis method is partly because the surveyed activity level (i.e., 1.0 met) was lower than the activity level assumed in the ASHRAE Standard 55-2010 Comfort Zones (i.e., 1.1 met), and partly because the measured air speed was higher than 20 fpm, which is an air speed assumed in the ASHRAE Standard 55-2010 Comfort Zones. Therefore, the use of the PMV/PPD distribution chart would be more acceptable for the conditions with air speed over 20 fpm and for the measurements

[215] Based on the Graphic Comfort Zone Method (Section 5.2.1.1), about 6% of the observed thermal measurement during the occupied periods were inside the summer comfort zone, which complies with the ASHRAE Standard 55-2004 and Standard 55-2010. On the other hand, against the Computer Model Method (Section 5.2.1.2), this office's thermal environments were observed to be outside of the acceptable PMV range all the time.

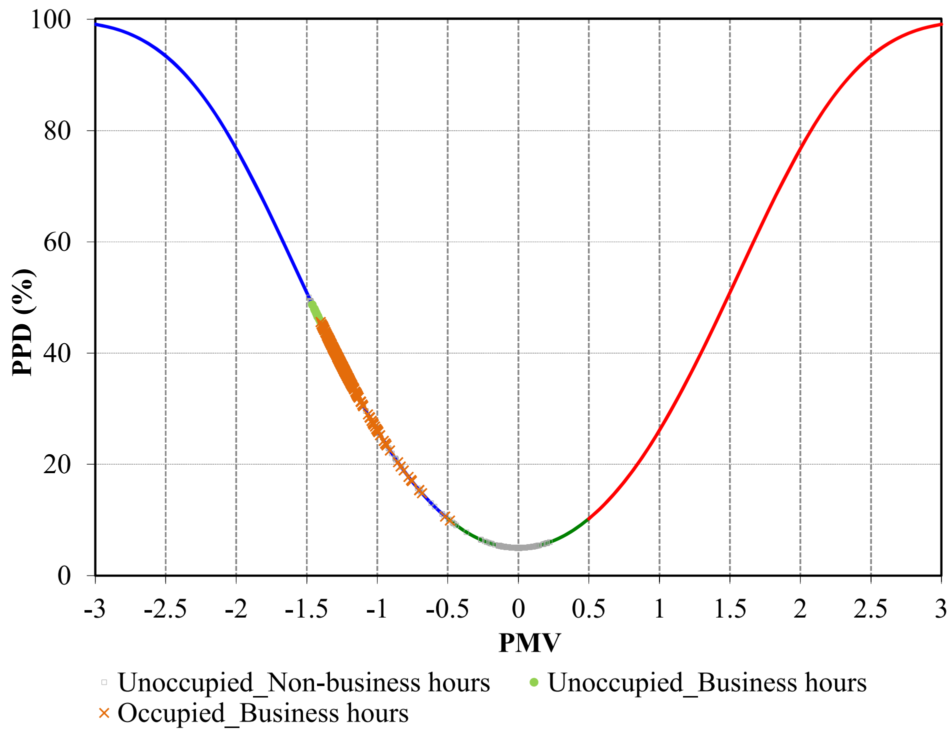


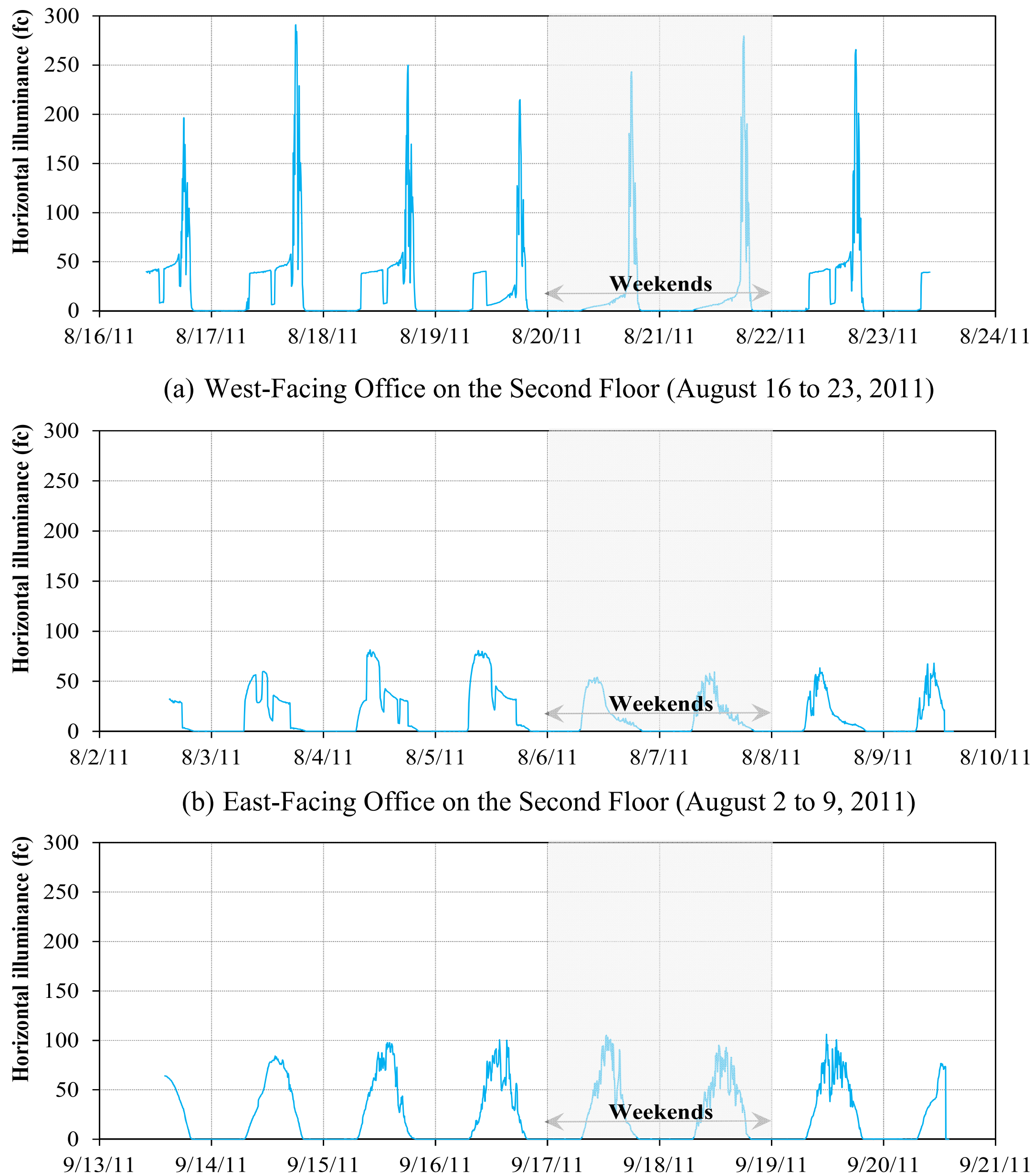
Figure 155: Measured Indoor Climate Conditions of One West-Facing Office on the Second Floor of the Case-Study Building on ASHRAE Standard 55-2010 PMV/PPD Distribution Plot (August 16 to 23, 2011)

where the clothing and activity were surveyed.

- Analysis of lighting performance metrics using the hourly profiles

In this proposed method, the lighting performance metrics are analyzed using the hourly profiles. As discussed above, the hourly profile is an effective way to review when and how often the abnormal behaviors occur if they are present. Of the eleven offices of a case-study building where the measurements were made over a one week period in each office, three offices were selected as examples to discuss the proposed approach.

Figures 156 and 157 show the 5 minute interval time-series plot and a time-of-day graphical display of the measured horizontal illuminance using a color-coded data points by occupancy (i.e., Occupied during business hours: orange, Unoccupied during business hours: green, Unoccupied during non-business hours: gray), respectively, for the three offices: (a) a west-facing office on the second floor (August 16 to 23, 2011); (b) an east-facing office on the second floor (August 2 to 9, 2011); and (c) a south-facing office on the sixth floor (September 13 to 20, 2011). Not surprisingly, it was observed that the time-of-day profile of the measured horizontal illuminance was affected by the orientation of the room. The peak horizontal illuminance occurred near noon in a south-facing office, while the peak illuminance occurred in the morning in an east-facing office; and in the late afternoon in a west-facing office. This confirms the limitation of spot measurements, which is the approach in the current version of the ASHRAE PMP lighting protocols. Thus, adequate advice about either when the lighting



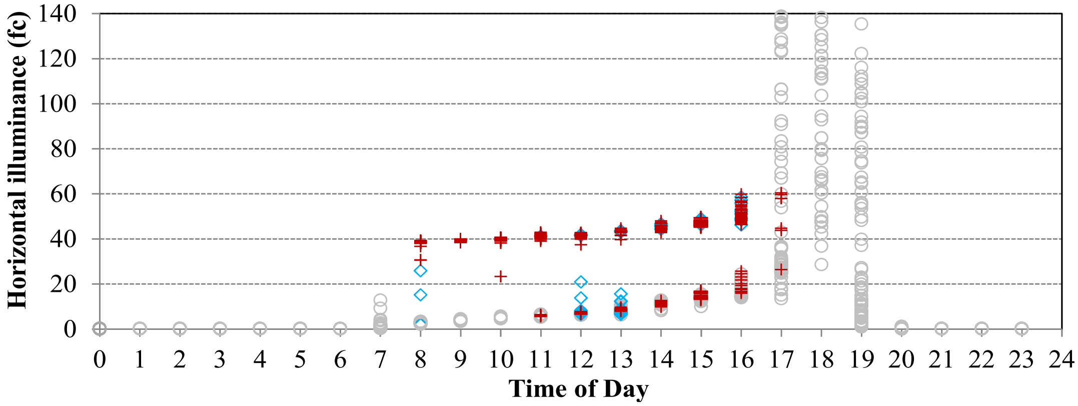
(a) West-Facing Office on the Second Floor (August 16 to 23, 2011)

(b) East-Facing Office on the Second Floor (August 2 to 9, 2011)

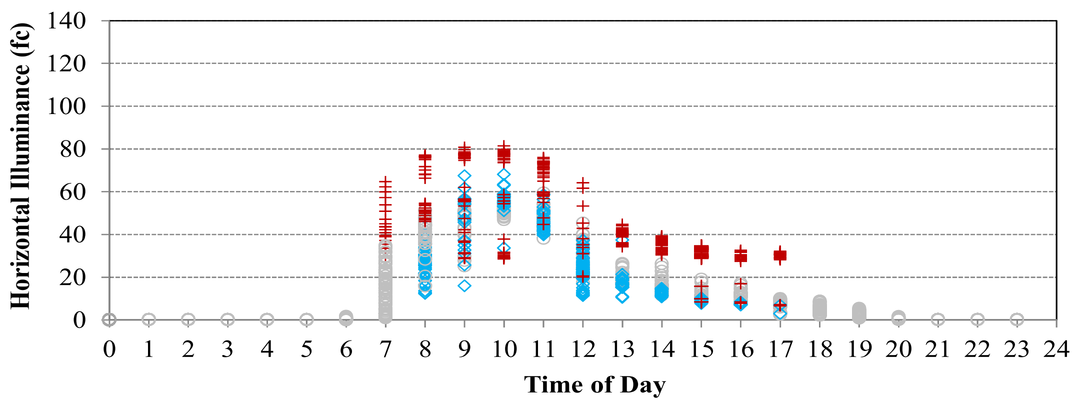
(c) South-Facing Office on the Sixth Floor (September 13 to 20, 2011)

Figure 156: 5 Minute Horizontal Illuminance

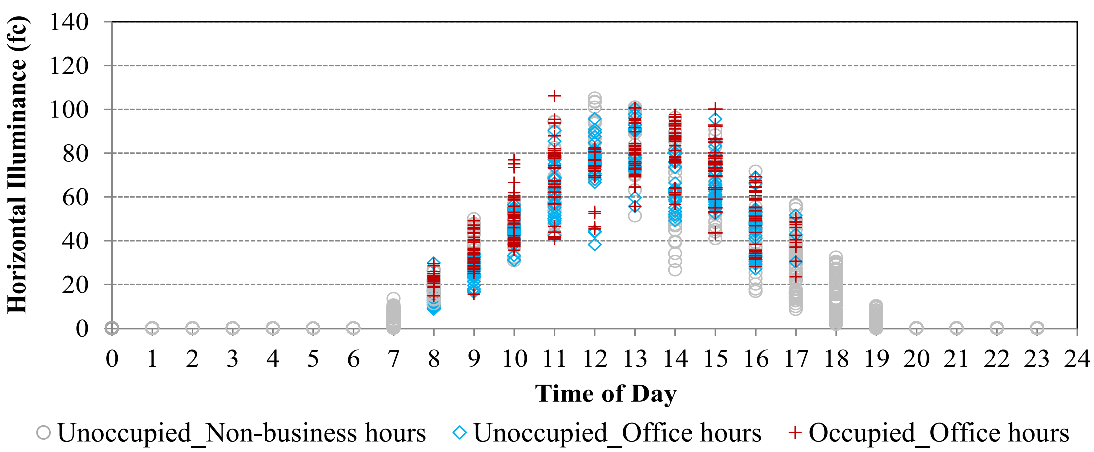
measurements should be performed for the different orientations of the perimeter office or how to perform the continuous lighting measurements needs to be addressed in the ASHRAE PMP.



(a) West-Facing Office on the Second Floor (August 16 to 23, 2011)



(b) East-Facing Office on the Second Floor (August 2 to 9, 2011)



(c) South-Facing Office on the Sixth Floor (September 13 to 20, 2011)

Figure 157: Hourly Profiles of Horizontal Illuminance

c) Comparison of the Proposed Approach Against the Existing Approach

When applying the same evaluation criteria (i.e., validity, reliability, and practicality) that were used to evaluate the existing ASHRAE PMP procedures[216] to the proposed approach, this new approach is expected to improve the reliability as well as the practicality of the ASHRAE PMP Intermediate and Advanced Level IEQ protocol with detailed procedures to characterize the building's IEQ performance using the proposed continuous monitoring system. Any increase in data collection efforts or costs that are necessary to perform this new approach can be seen as insignificant since the existing approach of the ASHRAE PMP IEQ protocols also require high data collection efforts, which accompanying high costs.

[216] The applicability of the three levels of measurement approaches in the ASHRAE PMP was examined in terms of validity, reliability and practicality of each level of the protocols based on a scale from 1 (very bad) to 5 (very good). Evaluation criteria were developed in three domains: validity, reliability and practicality, which were built upon the framework originally suggested by the Malmqvist and Glaumann (2006). Details are presented in Section 6.1.2.3.

CHAPTER VII

RECOMMENDATIONS FOR A NEW FIGURE-OF-MERIT RATING SYSTEM

This chapter presents the results of Phase III: Recommendations for a new figure-of-merit for rating a building's overall performance based on the ASHRAE PMP. Section 7.1 presents the new single figure-of-merit rating system based on above-average percentage scores or percentile rank of scores that are separately calculated for six performance areas (i.e., energy use, water use, thermal comfort, IAQ, lighting, and acoustics). The strengths and limitations of the proposed rating systems are discussed. Sections 7.2 and 7.3 discuss ideas for a future figure-of-merit rating system that can better represent the building's overall performance, including Predicted Percentage of Hours Dissatisfied (PPHD %) for IEQ instrumented measurements and cost. Section 7.4 provides a summary.

7.1. Proposed New Single Figure-Of-Merit Rating System

The proposed rating system linearly displays the combination of six figure-of-merits (FOMs), either above-average percentage scores or percentile rank of scores, calculated across all six performance areas (i.e., energy use, water use, thermal comfort, IAQ, lighting, and acoustics) using the results from the ASHRAE PMP Basic Level applications. A single FOM calculated by combining the six FOMs with assumed cost-based weighting factors is also presented in the rating system as "Combined." Following equations show the calculation procedures of each FOM based on above-average percentage scores (i.e., Eq. (7.1) for energy use; Eqs. (7.2) to (7.4) for water use; and Eqs. (7.5) and (7.6) for IEQ) and a combined single FOM based on both above-average percentage scores and percentile rank of scores (i.e., Eqs (7.7) to (7.11)).

The cost-based weighting factors were calculated using the three cost indices for energy, water, and IEQ of each year (i.e., measured energy cost index (ECI) ($/ft2.·yr), measured water cost index (WCI) ($/ft2.·yr), and measured IEQ productivity cost ($/ft2.·yr)). To calculate measured IEQ productivity cost, an average annual salary per person was assumed as $45,230/yr-person, which is the national mean annual salary for all occupations in May 2011 according to the U.S. Department of Labor (DOL) Bureau of Labor Statistics (BLS) national survey known as Occupational Employment and Wages (OEW) (BLS 2012). For the number of

$$\text{FOM } energy\,(\%) = \frac{\text{National Median Source EUI }\left(\frac{\text{kBtu}}{\text{sq.ft.}\cdot\text{yr}}\right) - \text{Meausred Source EUI }\left(\frac{\text{kBtu}}{\text{sq.ft.}\cdot\text{yr}}\right)}{\text{National Median Source EUI }\left(\frac{\text{kBtu}}{\text{sq.ft.}\cdot\text{yr}}\right)} \quad (7.1)$$

$$\text{FOM } water\,(\%) = \frac{\text{FOM } water, indoor\,(\%) - \text{FOM } water, landscape\,(\%)}{2} \quad (7.2)$$

where,

$$\text{FOM } water, indoor\,(\%) = \frac{\text{DOE FEMP Guideline Value }\left(\frac{\text{Gal}}{\text{employee}\cdot\text{day}}\right) - \text{Measured WUI Indoor }\left(\frac{\text{Gal}}{\text{employee}\cdot\text{day}}\right)}{\text{DOE FEMP Guideline Value }\left(\frac{\text{Gal}}{\text{employee}\cdot\text{day}}\right)} \quad (7.3)$$

$$\text{FOM } water, landscape\,(\%) = \frac{\text{DOE FEMP Guideline Value }\left(\frac{\text{Gal}}{\text{acre}\cdot\text{day}}\right) - \text{Meausred WUI Landscape }\left(\frac{\text{Gal}}{\text{acre}\cdot\text{day}}\right)}{\text{DOE FEMP Guideline Value }\left(\frac{\text{Gal}}{\text{acre}\cdot\text{day}}\right)} \quad (7.4)$$

$$\text{FOM } ieq\,(\%) = \frac{\text{FOM } tc\,(\%) + \text{FOM}iaq\,(\%) + \text{FOM}lighting\,(\%) + \text{FOM}acoustics(\%)}{4} \quad (7.5)$$

where,

$$\text{FOM } tc, iaq, lighting, acoustics\,(\%) = \frac{\text{Percentile of Satisfaction Against the CBE Benchmarks } - 50^{\text{th}} \text{ (Average Performance)}}{50^{\text{th}}} \quad (7.6)$$[217]

$$\text{FOM } combined\,(\%) = \frac{\text{FOM } energy\,(\%) \times \text{WF } energy + \text{FOM } water\,(\%) \times \text{WF } water + \text{FOM } ieq\,(\%) \times \text{WF } ieq}{\text{WF } energy + \text{WF } water + \text{WF } ieq} \quad (7.7)$$

where,

$$\text{WF } energy = \frac{\text{Measured ECI }\left(\frac{\text{US \$}}{\text{sq.ft.}\cdot\text{yr}}\right)}{\text{Measured ECI }\left(\frac{\text{US \$}}{\text{sq.ft.}\cdot\text{yr}}\right) + \text{Measured WCI }\left(\frac{\text{US \$}}{\text{sq.ft.}\cdot\text{yr}}\right) + \text{Measured IEQ Productivity Cost }\left(\frac{\text{US \$}}{\text{sq.ft.}\cdot\text{yr}}\right)} \quad (7.8)$$

$$\text{WF } water = \frac{\text{Measured WCI }\left(\frac{\text{US \$}}{\text{sq.ft.}\cdot\text{yr}}\right)}{\text{Measured ECI }\left(\frac{\text{US \$}}{\text{sq.ft.}\cdot\text{yr}}\right) + \text{Measured WCI }\left(\frac{\text{US \$}}{\text{sq.ft.}\cdot\text{yr}}\right) + \text{Measured IEQ Productivity Cost }\left(\frac{\text{US \$}}{\text{sq.ft.}\cdot\text{yr}}\right)} \quad (7.9)$$

$$\text{WF } ieq = \frac{\text{Measured IEQ Productivity Cost }\left(\frac{\text{US \$}}{\text{sq.ft.}\cdot\text{yr}}\right)}{\text{Measured ECI }\left(\frac{\text{US \$}}{\text{sq.ft.}\cdot\text{yr}}\right) + \text{Measured WCI }\left(\frac{\text{US \$}}{\text{sq.ft.}\cdot\text{yr}}\right) + \text{Measured IEQ Productivity Cost }\left(\frac{\text{US \$}}{\text{sq.ft.}\cdot\text{yr}}\right)} \quad (7.10)$$

$$\text{Measured IEQ Productivity Cost }\left(\frac{\text{US \$}}{\text{sq.ft.}\cdot\text{yr}}\right) = \frac{|\text{Productivity Change }(\%)| \times \text{Average Annual Salary }\left(\frac{\text{US \$}}{\text{yr}\cdot\text{person}}\right) \times \text{Number of Occupants}}{\text{Gross Floor Area of the Building (sq.ft.)}} \quad (7.11)$$

[217] A percentile against the CBE Benchmarks is based on 1-100 scale. A 50th percentile indicates average performance, and a lower number indicates a better performance.

occupants, 250 were used as a proxy for full-time employees of a total of the 323 occupants. Finally, to estimate the productivity change (%), the impact of IEQ satisfaction on overall productivity was assumed as ±10% (i.e., +10% increase for the 100th percentile of IEQ satisfaction, no change (0%) for the 50th percentile of IEQ satisfaction, and −10% decrease for the 0th percentile of IEQ satisfaction). Previous studies typically reported that about 5% to 15% changes in office worker performance are due to changes in environmental conditions (CIBSE 1999). Table 47 lists the calculated weighting factors and figure-of-merits based on above-average percentage scores or percentile rank of scores for 2010 and 2011.

Figure 158 shows the above-average percentage scores obtained from the case-study building. One of the strengths of the proposed rating system based on above-average percentage scores is that there are benchmarks (i.e., average performance scores) available for all six areas. In addition, the representation is simple and easy to understand, which is expected to allow high usability of the proposed rating system. However, the proposed system has a limitation that the metrics used to calculate the FOMs for energy (i.e., FOM_{energy}) and water (i.e., FOM_{water}) are different from the metrics used to calculate the FOM for IEQ (i.e., FOM_{ieq}). For calculating

Table 47: Calculated Weighting Factors and Figure-Of-Merits for 2010 and 2011[218]

		Above-Average Percentage Scores		Percentile Rank of Scores	
		2010	**2011**	**2010**	**2011**
FOM	Energy	3%	3%	52nd	52nd
	Water	-35%	-44%	-	-
	TC	74%	78%	87th	89th
	IAQ	68%	76%	84th	88th
	Lighting	94%	94%	97th	97th
	Acoustics	88%	84%	94th	92nd
	IEQ AVG.	81%	83%	91st	92nd
Meaured Cost Index (US$/sq.ft.-yr)	ECI	2.07	2.23	2.07	2.23
	WCI	0.14	0.15	0.14	0.15
	IEQ Cost	7.39	7.57	7.39	7.57
Weighting Factor	Energy	0.22	0.22	0.22	0.22
	Water	0.01	0.02	0.01	0.02
	IEQ	0.77	0.76	0.77	0.76
Combined FOM		**62%**	**63%**	**81st**	**82nd**

[218] To calculate a single FOM (i.e., combined) based on percentile rank of scores, the water performance was assumed as the 25th percentiles for both 2010 and 2011 since there are no benchmarks currently available for water performance.

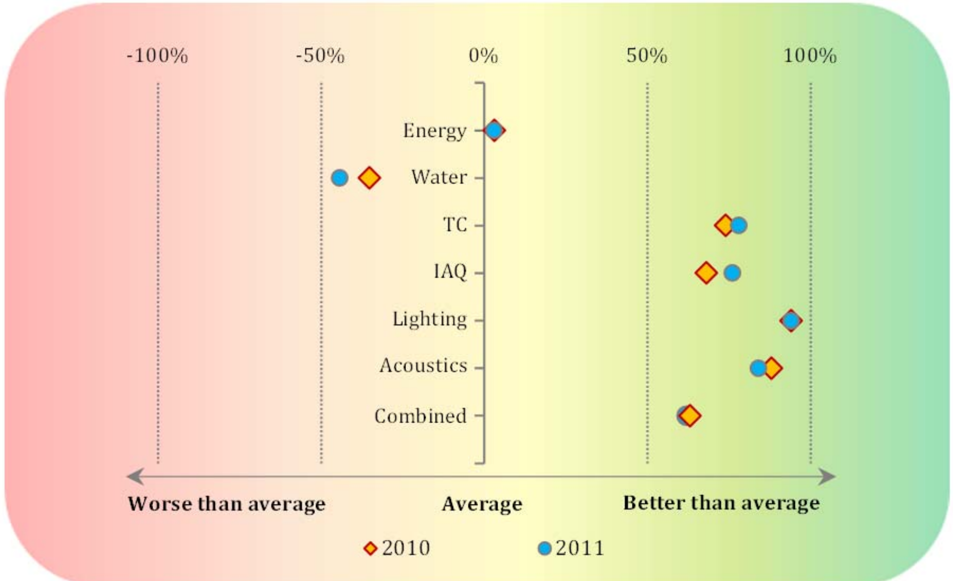


Figure 158: Single Figure-Of-Merit Representation Based on Above-Average Percentage Scores

FOM_{ieq}, since the percentiles are used, a full range of the proposed FOM_{ieq} scale is between −100% and 100%. On the other hand, for calculating FOM_{energy} and FOM_{water}, the source EUI (kBtu/sq.ft.·yr) and the WUI (gal/employee·day or gal/acre·day) were used, which resulted in a different full range of a scale of which low end is below −100% with a 100% high end of a scale. Another limitation of the proposed system is that the figure-of-merits for IEQ performance are determined based on the mean satisfaction scores of subjective assessment of IEQ performance, which do not consider objective IEQ assessments based on instrumented measures as well as frequency distributions of the surveyed IEQ satisfaction.

Next, Figure 159 shows the percentile ranks of scores obtained from the case-study building[219]. A rating system based on a percentile rank has been used to rate a building's energy performance, including: the U.S. EPA ENERGY STAR labeling program[220]. One of the

[219] To calculate a single FOM (i.e., combined) by combining the six FOMs with assumed cost-based weighting factors, the water performance was assumed as the 25th percentiles for both 2010 and 2011 since there are no benchmarks currently available for water performance.

[220] The U.S. EPA ENERGY STAR labeling program rates a buildings' energy performance on a scale of 1–100 against a peer group of facilities, with adjustments for climate, facility size, hours of operation, and the number of occupants. To obtain an ENERGY STAR Label, the users are required to enter 12 consecutive months of energy use data for all fuel types used in the building into the ENERGY STAR Portfolio Manager (EPA 2010b). Then the Portfolio Manager converts the annual site energy consumption of the building into the total equivalent source energy use using the national average source-site ratios. The peer group database for a comparison is derived from the U.S. DOE Energy Information

strengths of the proposed rating system based on percentile ranks of scores is that a uniform scale of 1–100[221] can be applied to all six areas, which is expected to allow high comparability between different performance areas over time. Another strength is that the representation is simple and easy to understand, which is expected to allow high usability. However, several limitations were found in the proposed rating system, including that there are no benchmarks currently available for water performance; and that the figure-of-merits for IEQ performance are determined based on the mean satisfaction scores of subjective assessment of IEQ performance.

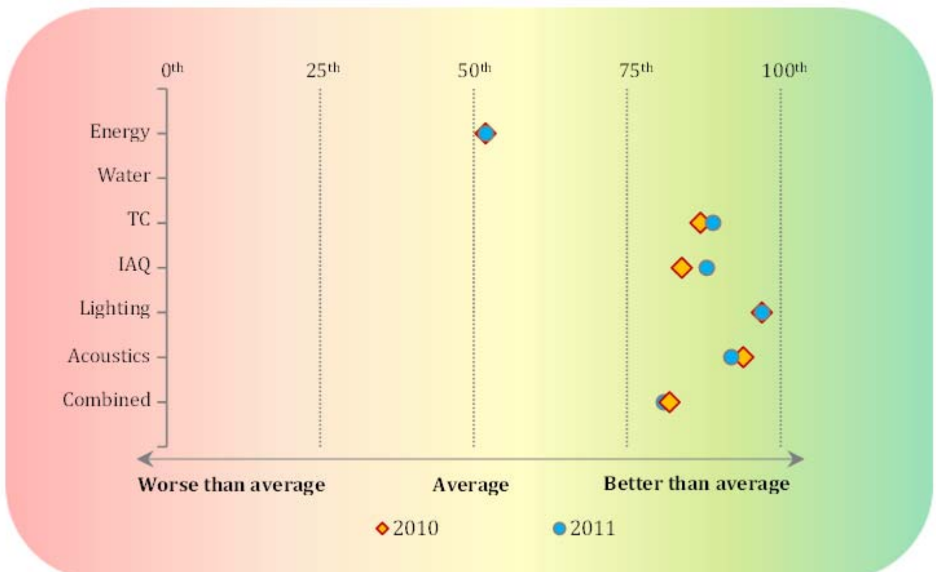


Figure 159: Single Figure-Of-Merit Representation Based on Percentile Ranks of Scores

Administration's (EIA) national survey known as Commercial Building Energy Consumption Survey (CBECS) (EIA 2003).

[221] A rating is based on 1-100 scale. A rating of 50 indicates average performance, and a higher number indicates a better performance.

7.2. Predicted Percentage of Hours Dissatisfied (PPHD %) for IEQ Instrumented Measurements

Unfortunately, the proposed rating system based on either above-average percentage scores or percentile rank of scores has some limitations. First, the proposed rating system does not include the results of instrumented measurements since the four IEQ figure-of-merits are determined from the IEQ satisfaction survey results. In addition, the rating system does not consider frequency distributions of the surveyed IEQ satisfaction since the IEQ figure-of-merits are determined using the mean satisfaction scores from the IEQ survey. It would be desirable for a future rating system to be determined based on the application of all the ASHRAE PMP procedures, including the instrumented measurements of the selected IEQ variables. However, currently, there are no metrics or figure-of-merits available that can be used to quantify IEQ performance based on instrumented measurements across all four areas (i.e., thermal comfort, IAQ, lighting, and acoustics) in a consistent way. Thus, this section discusses a new IEQ figure-of-merit that can be applied to all four IEQ areas, based on the Predicted Percentage of Hours Dissatisfied (PPHD %).

The PPHD rating is a percentage of hours that the measured IEQ performance data are within the acceptable comfort range defined in the appropriate benchmarking standards such as the ASHRAE Standard 55-2004 (ASHRAE 2004) and Standard 55-2010 (ASHRAE 2010c) for thermal comfort; the ASHRAE Standard 62.1-2007 (ASHRAE 2007b) and Standard 62.1-2010 (ASHRAE 2010d) for IAQ; the Table 3-9 in the ASHRAE PMP and the ISO Standard 8995:2002 (ISO 2002) for lighting; and the Table 3-10 in the ASHRAE PMP and the Swedish National Board of Health and Welfare (as cited in Kjellberg et al. 1997), and the Swedish Royal Board of Building (as cited in Kjellberg et al. 1997) for acoustics. As an example to show the proposed PPHD (%) rating, Figure 160 provides the PPHD (%) calculated using the data obtained from the eleven offices of the case-study building during the occupied hours. In this figure, the selected metrics for calculating the PPHD (%) are: predicted mean vote (PMV) for thermal comfort; CO_2 level for IAQ; horizontal illuminance for lighting; and A-weighted equivalent sound pressure levels (LAeq) for Acoustics.

The proposed PPHD (%) rating is applicable for all four IEQ areas if the appropriate benchmarks are available and is simple enough to be understood. If the measurements are performed in various locations of a building, the samples collected in different locations can be presented using a quartile analysis (i.e., a box and whisker plot) that has been commonly used in statistics (Emerson and Strenio 1983).

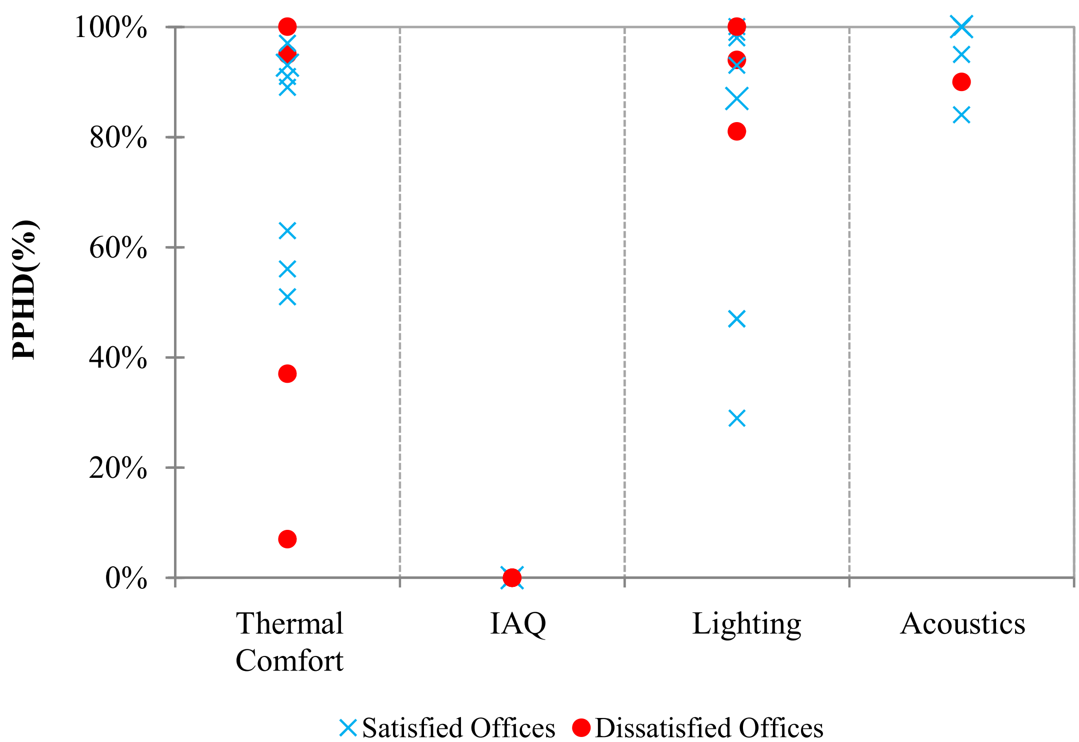


Figure 160: Predicted Percentage of Hours Dissatisfied (%) Rating for Continuously Measured IEQ Performance Data

7.3. Cost-Based Rating System

This section discusses a new procedure for a cost-based rating system to quantify a building's overall performance based on the application of the ASHRAE PMP. The major advantage of using cost-based metrics is its ease of understanding as well as its high impact on the decision making process. Not surprisingly, the energy and water use performance can be easily combined using a cost index, as shown in Figure 161. In this figure, the bar charts (left axis) show the annual average whole-building energy, water, sewer, and the total cost (thousands$/yr) before applying normalization by the gross floor area of the building. The line graphs (right axis) show the cost indices normalized by the gross floor area ($\$/ft^2 \cdot yr$) for energy, water, sewer and total costs.

To quantify the cost impact associated with the IEQ performance, productivity is one of the metrics that is applicable across all four IEQ areas. For example, there have been studies to access the productivity as a function of the measured thermal comfort metrics, including temperature (Seppänen et al. 2006; Niemelä et al. 2002) and PMV/PPD indices (Kosonen and Tan 2004). Once the changes in occupants' productivity is quantified as a function of the IEQ performance of a building, a cost impact of the changes in productivity can be estimated by multiplying it by the employees' salaries.

As an example, this study estimated the changes in productivity (i.e., relative performance) using the temperature data obtained from the eleven offices of the case-study building during the occupied hours, as shown in Figure 162 and Table 48. In this example, the equation proposed by Seppänen et al. (2006) [222] was used to estimate the changes in productivity (i.e., relative performance to the maximum value) of the elven offices. Not surprisingly, the estimated productivity showed a time-varying distribution (Figure 162(a)). Thus, using the average temperature of the eleven offices, the average productivity of each office was calculated (Figure 162 (b) and Table 48). Overall, it was observed that the average productivity of the eleven offices was 0.99, which is equivalent to 1% of productivity loss. A cost impact of the decreased productivity can be estimated by multiplying the calculated productivity loss (i.e., 1%) by the employees' salaries.

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[222] The relative performance was calculated using the equation proposed by Seppänen et al. (2006), which requires one input variable of room temperature in degrees Celsius: $P = 0.1647524 \times T - 0.0058274 \times T^2 + 0.0000623 \times T^3 - 0.4685328$, in which: P = productivity relative to maximum value; and T = room temperature (C).

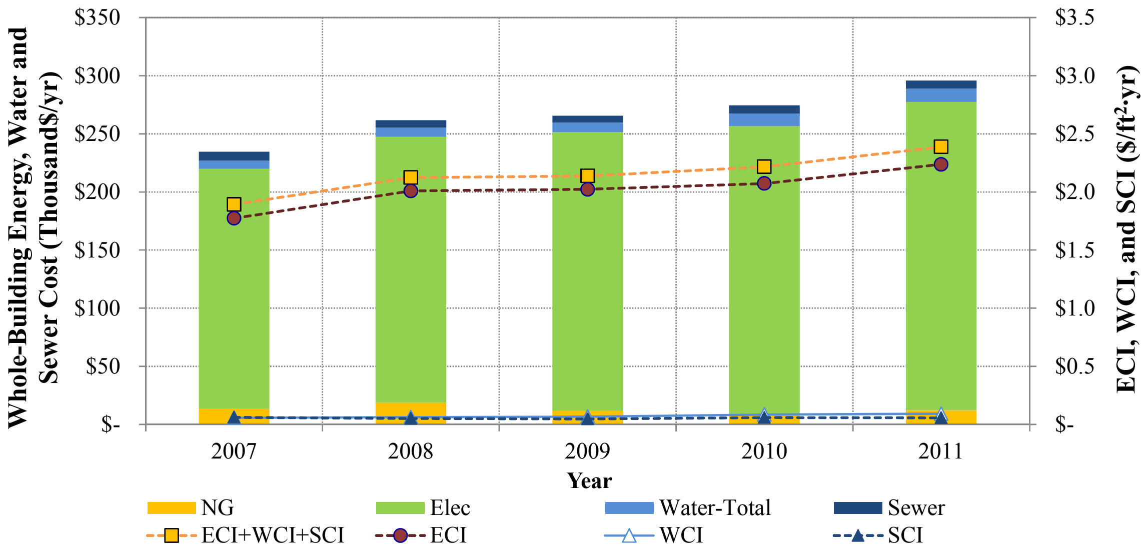
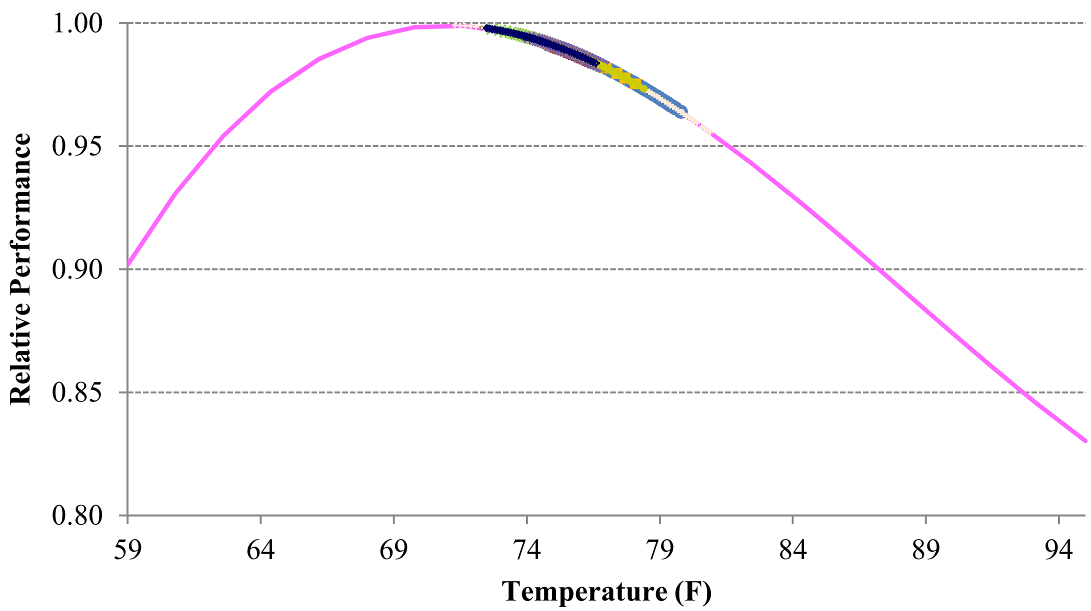
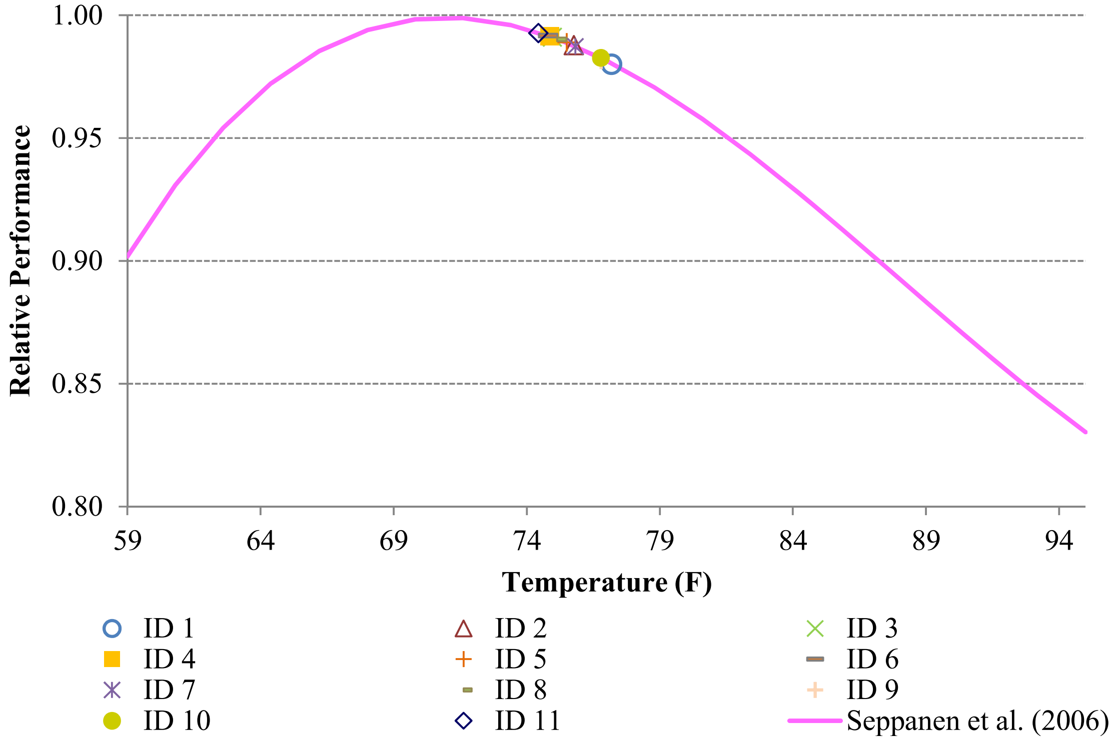


Figure 161: Annual Whole-Building Energy, Water and Sewer Cost (Left Axis) and Cost Indices for Energy, Water, and Sewer (Right Axis) of the Case-Study Building



(a) Time-Varying Distribution of Estimated Productivity

Figure 162: Relative Performance of Eleven Offices Associated with Temperature



(b) Average Productivity

Figure 162: Continued

Table 48: Relative Performance of Eleven Offices Associated with Temperature: Analysis for Average Productivity

	Average Temperature	Relative Performance
ID 1	77.2	0.98
ID 2	75.8	0.99
ID 3	75.0	0.99
ID 4	74.9	0.99
ID 5	75.5	0.99
ID 6	74.8	0.99
ID 7	75.8	0.99
ID 8	75.2	0.99
ID 9	76.8	0.98
ID 10	76.8	0.98
ID 11	74.4	0.99
AVG.	**75.6**	**0.99**

7.4. Summary of Recommendations for a New Figure-Of-Merit Rating System

Recommendations were developed for rating a building's overall performance based on the ASHRAE PMP Basic Level procedures, including the new single figure-of-merit rating system based on above-average percentage scores or percentile rank of scores. The proposed single rating system linearly displays the combination of six figure-of-merits, either above-average percentage scores or percentile ranks of scores, calculated across all six performance areas (i.e., energy use, water use, thermal comfort, IAQ, lighting, and acoustics) using the results from the ASHRAE PMP Basic Level applications. Finally, a single FOM was calculated by combining the six FOMs with assumed cost-based weighting factors and presented in the rating system. The strengths and limitations of the proposed rating systems are also discussed.

Next, since it would be desirable for a future rating system to be determined based on the application of all the ASHRAE PMP procedures, including the instrumented measurements of the selected IEQ variables, two ideas for a future figure-of-merit rating system were discussed, which can better represent the building's overall performance, including Predicted Percentage of Hours Dissatisfied (PPHD %) for IEQ instrumented measurements and a cost-based rating system. The PPHD rating is a percentage of hours that the measured IEQ performance data are within the acceptable comfort range defined in the appropriate benchmarking. The proposed PPHD (%) rating is applicable for all four IEQ areas if the appropriate benchmarks are available and is simple enough to be understood. The second procedure is a cost-based rating system. The major advantage of using cost-based metrics is its ease of understanding as well as its high impact on the decision making process.

CHAPTER VIII
SUMMARY AND FUTURE WORK

This chapter presents a summary of this study. To improve the applicability of the ASHRAE/CIBSE/USGBC Performance Measurement Protocols (PMP) for Commercial Buildings, this study developed and applied a field test to evaluate the ASHRAE PMP in a case-study office building in central Texas and developed the forty recommendations and the twelve new or modified approaches for the issues identified in the current version of the ASHRAE PMP. The application of the developed recommendations and the new or modified approaches to the future version of the ASHRAE PMP is expected to improve the applicability of the ASHRAE PMP in terms of validity, reliability, and practicality, which aligns the overall purpose of this study. Finally, this study developed a new single figure-of-merit rating system based on the ASHRAE PMP procedures. The developed rating system is expected to improve the usability of the protocols.

As the first integrated protocol on building performance measurement, the ASHRAE PMP accomplished its goal of providing a standardized set of protocols for measuring and comparing the overall performance of a building, including energy, water, thermal comfort, indoor air quality, lighting, and acoustics. However, several areas for improvement were identified. For example, conflicting results were observed from different metrics, procedures, or benchmarks provided in the ASHRAE PMP. In addition, limited guidelines are available for performing the measurements, including step-by-step protocols, easy-to-use instrumentation, equipment calibration, sampling methods, measurement location, and time of day for the measurements, data scan and collection intervals, etc. For some performance areas, the ASHRAE PMP also failed to provide detailed modeling techniques, graphical indices, uncertainty analysis, and reliable benchmarks. Lastly, practical issues were identified such as high cost requirements to apply the ASHRAE PMP and its time-intensive procedures.

All these observations noted throughout the entire research process are listed as the forty issues, including thirteen for energy use, five for water use, and twenty-two for IEQ protocols. For each of the forty issues identified, recommendations were developed. Finally, for the selected high-priority issues that need more detailed evidence-based recommendations, twelve new or modified approaches (i.e., two modified and three new approaches for energy; one new approach for water use; and six new approaches for IEQ protocols) were proposed and then evaluated against the existing procedures in the ASHRAE PMP. These include the developments of:

- **Modified Approach for Issue E-3:** Separate energy use indices for each energy source
- **Modified Approach for Issue E-7:** A 3-P multi-variable monthly energy use regression model including an occupancy variable
- **New Approach for Issue E-8:** An outlier detection method for the proposed monthly regression model
- **New Approach for Issue E-10**: Graphical analysis techniques of hourly energy use data using the three-dimensional, hourly profiles
- **New Approach for Issue E-12**: A method how to use chiller data to investigate a building's peak demand performance as well as chiller performance benchmarking methods
- **New Approach for Issue W-5**: A 3-P multi-variable monthly water use regression model for a weather-normalized comparison of measured water performance
- **New Approach for Issue IEQ-1**: A graphical index for surveyed IEQ satisfaction votes at the whole-building level
- **New Approach for Issue IEQ-9**: Step-by-step measurement protocols for IEQ spot measurements
- **New Approach for Issue IEQ-15**: A method how to use a vertical temperature profile to evaluate room air circulation
- **New Approach for Issue IEQ-17**: A real-time wireless IEQ monitoring system for the continuous IEQ measurements
- **New Approach for Issue IEQ-19**: A method how to use LCeq – LAeq difference as a low-cost alternative to estimate low frequency noise annoyance
- **New Approach for Issue IEQ-20**: A statistical analysis to decompose time-varying distribution of indices for benchmarking

This study was performed in three phases: Phase I: Field test of the ASHRAE PMP; Phase II: Proposed new or modified approaches to improve the ASHRAE PMP; and Phase III: Recommendations for a new figure-of-merit for rating a building's overall performance based on the multiple indices in the ASHRAE PMP. Sections 8.1 summarizes the results of Phase I and Phase II for each performance area, including: energy use, water use, and IEQ (i.e., thermal comfort, IAQ, lighting, and acoustics), respectively. Section 8.2 presents a summary of Phase III results. Lastly, Section 8.3 provides the recommendations for future research.

8.1. Summary of Phase I and Phase II Results

A field test of the ASHRAE PMP was developed[223] and applied to data taken from the case-study office building[224]. For each performance area of each level, the performance metrics required in the ASHRAE PMP were calculated and then compared with the appropriate benchmarks. As a result, a total of forty issues were identified, including thirteen for energy use, five for water use, and twenty-two for IEQ protocols. The problems and issues identified were listed. For each issue, recommendations were developed to improve the applicability of the ASHRAE PMP. For the selected issues, new or modified approaches were proposed, including: two modified and three new approaches for energy use; one new approach for water use; and six new approaches for IEQ protocols. The proposed approaches were then evaluated against the existing methods by using the validity, reliability, and practicality as the evaluation criteria.

8.1.1. *Energy Use*

8.1.1.1. Level I: Basic Level

At the Basic Level, an annual whole-building energy use index (EUI) and an energy cost index (ECI) were calculated using the monthly electric and natural gas utility bills for the case-study building. The calculated EUIs were then compared against two sources of benchmarking data: the 2007 ASHRAE Handbook HVAC Applications, Chapter 35-Energy Use and Management (ASHRAE 2007b) and the U.S. EPA ENERGY STAR ratings (EPA 2010b). During the process, four issues (i.e., Issue E-1 through Issue E-4) were identified. These issues along with the corresponding recommendations and the proposed new or modified approaches (if applicable) are included in the following discussion:

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[223] The protocols that were field tested under this study include all six performance areas (i.e., energy use, water use, thermal comfort, IAQ, lighting, and acoustics) for the Basic and Intermediate Levels. For the Advanced Level, water and acoustics protocols were not tested.

[224] The seven-story, case-study building is an office building in College Station, Texas. The building was constructed in 1992 and occupied by about 323 employees. The conditioned floor area of the building is 123,960 ft^2. The building is served by 17 single duct variable air volume (SDVAV) air handling units (AHUs) with variable frequency drives (VFDs) and two 100% outside air AHUs that provide the SDVAV units with conditioned outside air. The stand-alone thermal plant of the building has two 280-ton (3.36 MMBtu/h) centrifugal chillers and two 1.68 MMBtu/h hot water boilers with an input capacity of 2.10 MMBtu/h. The cooling loads of the case-study building are normally met by running one chiller.

- **Issue E-1**: Different benchmarking sources can yield very different results: i.e., worse than average performance against the ASHRAE benchmarks versus average performance against the ENERGY STAR Portfolio Manager benchmarks.
  Recommendation for Issue E-1: The ASHRAE PMP should provide users with a priority ranking of the different benchmarks.

- **Issue E-2**: Different energy performance metrics (i.e., EUI versus ECI) yield different results since the ECI is calculated using unit costs of energy, which were not fixed costs over time.
  Recommendation for Issue E-2: The ASHRAE PMP should provide advice to the user to help resolve the differences between two indices when different results arise.

- **Issue E-3:** The energy performance metrics required at the ASHRAE PMP Basic Level are total indices at the whole-building level, although the data were collected separately for each energy source.
  Recommendation for Issue E-3: It is recommended that calculations of energy performance metrics for each energy source be discussed in the ASHRAE PMP when the building consumes energy from two or more different energy sources.
  Modified Approach for Issue E-3: In the modified approach proposed in this study, the energy use and cost metrics were calculated separately for each energy source. Not surprisingly, at the case-study building, it was revealed that the use of the modified approach provided additional characterization of the building's energy performance, including an identification of: the areas where performance either improved or deteriorated; the contribution of different energy sources to the overall total energy use of a building; and the contribution of a demand charge to the overall energy cost index of a building.

- **Issue E-4**: The ASHRAE PMP suggests two different EUI calculation procedures that are based on different adjustment methods.

- **Recommendation for Issue E-4:** It would be an improvement for the ASHRAE PMP to mention the different adjustment methods (i.e., calendar month versus billing month) for the two EUI calculation methods[225].

8.1.1.2. Level II: Intermediate Level

At the Intermediate Level, monthly energy use and demand data as well as major end-use energy use were collected from a previously installed data logger in the thermal plant of the building (Kim and Haberl 2009) as well as monthly utility bills. Using the collected data, whole-building electricity, demand, and natural gas models were developed as a function of a single independent variable (i.e., outdoor temperature) for the years between 2007 and 2011. The ASHRAE Inverse Modeling Toolkit (IMT) (Kissock et al. 2004) was used to develop the models. Performance changes were then calculated against the baseline year for self-benchmarking. During the process, five issues (i.e., Issue E-5 through Issue E-9) were identified. These issues along with the corresponding recommendations and the proposed new or modified approaches (if applicable) are included in the following discussion:

- **Issue E-5**: The ASHRAE PMP does not provide advice about how to ensure a fair level of confidence in the calculated regression model as well as performance changes (i.e., savings). **Recommendation for Issue E-5:** The ASHRAE PMP should provide advice to the user as to how to ensure a fair level of confidence that the calculated model represents the candidate building and adequately tracks performance changes (i.e., savings). In this study, the Whole-Building Performance Path of the ASHRAE Guideline 14-2002 (ASHRAE 2002) was referenced in the entire calculation procedure to calculate the uncertainty of the regression models used in the self-benchmarking results.

- **Issue E-6**: The ASHRAE PMP does not provide advice about how to calculate a suitable outdoor temperature index for different types of energy use (i.e., electricity, peak demand, and natural gas use).

[225] Although no significant differences were revealed in the EUIs calculated using these two procedures in this study (i.e., resulting in a percentage error between -0.39% and 0.69%), some differences may be expected when the billing month is significantly different from the calendar month.

Recommendation for Issue E-6: The ASHRAE PMP should provide advice to the user as to how to calculate a suitable outdoor temperature index to calculate the ASHRAE IMT models for different types of energy use. In this study, a comparison of several outdoor temperature indices was performed for electricity, demand, and natural gas use models. Some differences were found in the calculated savings between the indices. However, for the case-study building, the differences were within the range of the model's uncertainties.

- **Issue E-7**: An issue was found that the instructions for calculating a monthly regression model in the current version of the ASHRAE PMP do not provide advice about how to model a building that has different operating modes for holidays.

  Recommendation for Issue E-7: It is recommended that the ASHRAE PMP provide a modeling method that can be used when the building has different operating modes for holidays to improve the accuracy of the regression model.

  Modified Approach for Issue E-7: In the modified approach proposed in this study, a combination three-parameter, change-point multi-variable regression (3-P MVR) was developed using outdoor temperature in a change-point model and the number of holidays as an additional independent variable. The results show that the use of the proposed 3P-MVR model improved the accuracy of the monthly 3-P cooling model, which under-predicted the monthly base-load consumption of the case-study building due to a different operating mode for holidays as well as the issue of a high net determination bias of the 3-P baseline model. For the case-study building, the modified approach improved the reliability of the ASHRAE PMP Intermediate Level energy protocol with a lower level of uncertainty in the estimated savings against the baseline year. Similar results are expected for other buildings with similar energy use profiles.

- **Issue E-8**: The ASHRAE PMP does not describe how to deal with outliers in the dataset when inverse regression models are used.

  Recommendation for Issue E-8: The ASHRAE PMP should provide advice to the user how to deal with outliers in the dataset when the IMT modes are applied as well as how to interpret the outliers to detect some potential operational problems in the building.

  New Approach for Issue E-8: In the new approach proposed in this study, this study compared two different methods to identify potential outliers. It was found that the use of

±1.5 CV-RMSE criteria of the calculated IMT 3-P cooling model was useful in detecting suspected outliers for 3-P cooling models compared to the method based on a quartile analysis[226]. The quartile method was found to be effective at detecting extreme outliers, but failed to account for a seasonal variation in peak demand[227]. In addition, it was found that monthly outliers can provide useful information that may be helpful to detect some operational problems in the building such as simultaneous operation of two chillers when only one chiller was needed.

- **Issue E-9**: The ASHRAE PMP does not provide any advice about end-use benchmarks or how to benchmark the calculated energy use indices from the end-use data against a reliable, external reference.

  Recommendation for Issue E-9: It is recommended that the ASHRAE PMP provide reliable, external reference that can be used to benchmark the calculated major end-use energy use indices for a broad range of commercial buildings.

8.1.1.3. Level III: Advanced Level

At the Advanced Level, daily or hourly energy use measurements for the whole-building and major end-uses were collected from a previously installed data logger in the thermal plant of the case-study building (Kim and Haberl 2009). Inverse regression models were then computed using daily electricity use, and a demand analysis was performed with hourly load profiles calculated using hourly or sub-hourly electricity use data. Performance changes were then calculated against the baseline year. During the process, four issues (i.e., Issue E-10 through Issue E-13) were identified. These issues along with the corresponding recommendations and the proposed new or modified approaches (if applicable) are included in the following discussion:

- **Issue E-10**: The ASHRAE PMP does not provide detailed techniques or data analysis procedures that show how to interpret and analyze data at the daily or hourly level.

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[226] In the quartile analysis, the data points beyond the 25th and 75th quartiles by one and a half times the interquartile range (IQR = 75th quartile – 25th quartile) were considered potential outliers, which is commonly used in statistics (Emerson and Strenio 1983).

[227] Winter peak demands that were higher than expected could not be detected since they were at similar levels to summer peak demands.

Recommendation for Issue E-10: The ASHRAE PMP should provide detailed techniques or procedures about how to interpret and analyze such high resolution data and references to related work.

New Approach for Issue E-10: In the new approach proposed in this study, this study displayed the hourly electricity usage profiles for the whole-building electricity use and other major electricity end-uses for each year as three dimensional surface plots, which is the graphical approach taken by Haberl et al. (1988a). The three-dimensional, hourly electricity usage profiles proved useful in revealing several interesting features that were not identified using time-series plots, such as a quick identification of load shapes of the whole-building electricity use and other major electricity end-uses separately for weekdays, weekends, and holidays.

- **Issue E-11**: The ASHRAE PMP does not provide details that are sufficient enough for the users to install and calibrate the equipment to take the measurements of daily or hourly energy use without referring to external documents, including the ASHRAE Guideline 14 (ASHRAE 2002) and CIBSE TM39 (CIBSE 2006b).

  Recommendation for Issue E-11: The ASHRAE PMP should provide details that are sufficient enough for the users to make the measurements without referencing other external documents to become more of a stand-alone document.

- **Issue E-12**: The ASHRAE PMP does not provide discussions about how to use chiller operation data to investigate a building's energy performance as well as how to evaluate the chiller performance data against external benchmarks.

  Recommendation for Issue E-12: It is recommended that the ASHRAE PMP includes a method about how to use hourly or sub-hourly chiller operation data to diagnose abnormal energy use behavior due to improper chiller operation. Since chillers are one of the largest energy consumers in a building in a cooling dominated climate, it would be also advisable for the ASHRAE PMP to include the procedures about how to evaluate measured chiller performance data against external benchmarks.

  New Approach for Issue E-12: In the new approach proposed in this study, this study examined classic methods used for chiller diagnosis that can detect the chiller's degraded performance over time by comparing the measured chiller performance data against the manufacturer's data[228] as well as the minimum efficiency requirements of the part load performance ratings (i.e., IPLV or NPLV) to comply with the ASHRAE Standard 90.1-2007 (ASHRAE 2007g) and Standard 90.1-2010 (ASHRAE 2010e). The results show that both methods are effective when used as simple indicators to estimate the need for improvement in chiller performance. In addition, this study revealed that the sub-hourly chiller electricity use data was helpful in diagnosing the causes of the observed abnormally whole-building high peak demand.

- **Issue E-13**: Different levels of the ASHRAE PMP procedures yield different performance evaluations of the same building. For example, slightly lower savings were indicated with the Advanced Level electric demand analysis using the maximum 90th percentile of the diversity factor compared to the electric demand savings calculated at the Intermediate Level based on monthly billed electric demand.
  Recommendation for Issue E-13: The ASHRAE PMP should provide advice to the user to help resolve the differences when different performance ratings arise from the application of different performance evaluation PMP levels to the same building.

8.1.2. *Water Use*

8.1.2.1. Level I: Basic Level

At the Basic Level, an annual total site water use index (WUI) and water cost index (WCI) were calculated using the monthly building and landscape water use utility bills for the case-study building. The calculated WUIs were then compared against the three sources of benchmarking data: the U.S. Department of Energy (DOE) Federal Energy Management Program (FEMP) Federal Water Use Indices (FEMP 2009), the Verein Deutscher Ingenieure (VDI, The Association of German Engineers) 3807 Part 3 (VDI 2000), and the Chartered Institution of Building Services Engineers (CIBSE) Guide G, Public Health Engineering (CIBSE 2004). During the process, three issues (i.e., Issue W-1 through Issue W-3) were identified. These issues along with the corresponding recommendations and the proposed new or modified approaches (if applicable) are included in the following discussion:

[228] For a comparison between years, thermodynamic chiller models were calculated using the simple chiller model developed under the ASHRAE Research Project RP-827 (Brandemuehl et al. 1996).

- **Issue W-1**: Several issues were found during the benchmarking procedures, including no benchmarks for buildings that have atypical spaces (i.e., office building with gymnasium shower facilities); and different performance ratings from different benchmarking sources.
  Recommendation for Issue W-1: The ASHRAE PMP should provide users with advice about how to adjust the benchmarks for buildings that have atypical spaces as well as advice about how to help resolve the differences when different performance ratings arise from different benchmarks (i.e., a priority ranking of the different referenced benchmarks).

- **Issue W-2:** The water performance metric required at the ASHRAE PMP Basic Level cannot be directly compared to the benchmark references provided in the PMP.
  Recommendation for Issue W-2: The ASHRAE PMP Basic Level water protocol should provide users with combined benchmarks that can be directly comparable to the required performance metrics without requiring sub-metering of end-uses.

- **Issue W-3:** There are no clear guidelines about how to estimate and track the number of occupants and/or irrigated landscape areas associated with a building.
  Recommendation for Issue W-3: The ASHRAE PMP should provide clear guidelines how to estimate occupants and/or irrigated landscape areas.

8.1.2.2. Level II: Intermediate Level

At the Intermediate Level, an annual and monthly water use index (WUI) were calculated separately for the total building (per gross floor area of a building and per number of occupants), landscape (per landscape area), and wastewater (per gross floor area of a building and per number of occupants). However, in the Section of Performance Evaluation/Benchmarking of the Intermediate Level water protocols, the ASHRAE PMP provides water savings strategies instead of detailed analysis techniques or modeling methods, which was one of the issues identified. Therefore, this study developed the procedures about how to calculate monthly water use regression models using outdoor temperature and precipitation amount/occurrence as independent variables based on a review of previous studies on the water use model at the municipal level. Self-reference comparisons were then performed between years since the ASHRAE PMP Intermediate Level water protocol does not provide any external-reference benchmarking data. During the process, two issues (i.e., Issue W-4 and Issue W-5) were identified. These issues along with the corresponding recommendations and the proposed new or modified approaches (if applicable) are included in the following discussion:

- **Issue W-4:** The ASHRAE PMP does not provide any external-reference benchmarking data for the Intermediate Level water performance metrics, but there are benchmarks available[229].
  Recommendation for Issue W-4: The ASHRAE PMP should provide users with external-reference benchmarks for the Intermediate Level water performance that are currently provided in the Basic Level water protocol in addition to self-reference comparisons.

- **Issue W-5:** There are few detailed analysis techniques or modeling methods to analyze and evaluate a building's water performance beyond a log of the calculated WUIs.
  Recommendation for Issue W-5: The ASHRAE PMP should provide detailed analysis techniques or modeling methods to analyze and evaluate water performance rather than water savings strategies.
  New Approach for Issue W-5: In the new approach proposed in this study, a combination three-parameter, change-point multi-variable regression (3-P MVR) model was developed using outdoor temperature and precipitation amount/occurrence as independent variables based on a review of previous studies on the water use model at the municipal level. It was found that both the monthly building water use and the landscape water use are dependent on outdoor temperature[230], and that an addition of a precipitation variable improved the model fit for the landscape water use[231]. Lastly, the monthly total site water use models (i.e., indoor and outdoor combined water use) were calculated using the outdoor temperature in a change-point model and precipitation as an additional independent variable. The savings were then computed against the baseline year 2008, and the usability of the proposed new approach (i.e., weather-normalized performance changes) was successfully demonstrated. Finally, the

[229] The ASHRAE PMP Basic Level benchmark data sets are provided separately for a building and landscape.
[230] For the building (i.e., indoor) water use models, it was found that there were no noticeable differences in the models obtained using the two different monthly outdoor temperature indices (T_{minmax} versus T_{max}). On the other hand, for the landscape (i.e., outdoor) water use models, it was found that the models with T_{max} had slightly better goodness-of-fit indicators compared to the models with T_{minmax}.
[231] The addition of a precipitation variable did not improve the model fit for the building water use, which was deemed reasonable for indoor water use models. On the other hand, for the landscape water use models, the use of a variable composed of the number of rainy days over 0.3 inches resulted in the best fit compared to the use of either total precipitation or number of rainy days over 0.1 inches.

generalized water use model at the building level is a 3-P cooling change-point model based on a single outdoor temperature variable for indoor building water use; and a 3-P MVR model based on an outdoor temperature in a change-point model and a precipitation variable as an additional independent variable if the water use of interest includes outdoor landscape water use. The use of the proposed approach is expected to improve the validity of the ASHRAE PMP Intermediate Level water protocol with an improved characterization of the building's water performance.

8.1.3. *IEQ (Thermal Comfort, IAQ, Lighting, and Acoustics)*

8.1.3.1. Level I: Basic Level

At the Basic Level, the occupant IEQ satisfaction survey and spot measurements of several IEQ parameters were performed. First, paper-based IEQ assessment questionnaire surveys were conducted using the survey tool developed by the CBE at the University of California, Berkeley for the summer (May 2010) and winter (February 2011) periods. Follow-up spot measurements of several IEQ parameters were then performed in June 2010 for 17 offices. The evaluation of the different IEQ performance metrics was performed by comparing the results to the appropriate benchmarks, including the CBE benchmarking scores for office buildings, the ASHRAE Standard 55-2004 (ASHRAE 2004) and Standard 55-2010 (ASHRAE 2010c), the ASHRAE Standard 62.1-2007 (ASHRAE 2007b) and Standard 62.1-2010 (ASHRAE 2010d), as well as the Table 3-9 and Table 3-10 in the ASHRAE PMP. During the process, ten issues (i.e., Issue IEQ-1 through Issue IEQ-10) were identified. These issues along with the corresponding recommendations and the proposed new or modified approaches (if applicable) are included in the following discussion:

- **Issue IEQ-1**: The ASHRAE PMP Basic Level IEQ protocol does not provide clear guidelines about how to display and interpret the results[232].

  Recommendation for Issue IEQ-1: The ASHRAE PMP Basic Level IEQ protocol should provide users with clear guidelines about how to display and interpret the results, including: a

[232] For example, the ASHRAE PMP IEQ protocol does not provide any advice about how to graphically represent the IEQ survey results and spot measurement results across an entire building; how to compare the results against the benchmarks (i.e., mean scores versus frequency distributions); or how to interpret the survey and spot measurement results of individual offices at the whole-building level.

graphical index that synthesizes the collected information across an entire building and a numerical ranking of the different indices (i.e., mean scores versus frequency distributions).

New Approach for Issue IEQ-1: In the new approach proposed in this study, a graphical index for displaying the IEQ survey results was created by mapping the occupant IEQ satisfaction votes on the floor plans of a building using a color-coded satisfaction scale (i.e., very satisfied: green, neutral: yellow, dissatisfied: red). This proposed new approach is expected to allow characterizing the measured occupants' IEQ satisfaction /dissatisfaction and self-reported productivity across an entire building at a single glance and correlate them with the orientation, geometry, or type of workspace (i.e., private or open office).

- **Issue IEQ-2**: Different results may be obtained from different benchmarking sources: i.e., better than average against the CBE benchmarks in all areas versus worse than average against the ASHRAE Standard 55-2004 and Standard 55-2010 for thermal comfort and sound privacy.

  Recommendation for Issue IEQ-2: The ASHRAE PMP Basic Level IEQ protocol should provide users with a priority ranking of the different guidelines and should provide advice to the user to help resolve the differences when different results arise from the different benchmarks.
- **Issue IEQ-3**: The ASHRAE PMP does not provide guidance about how to handle the discrepancies in the results between IEQ survey and spot measurements of the same space when they arise.

  Recommendation for Issue IEQ-3: The ASHRAE PMP Basic Level IEQ protocol should provide advice to the user about how to interpret the results when different results arise between subjective and instrumented measurements of the same space.

- **Issue IEQ-4:** Of the seven IEQ topics addressed in the CBE survey questions, three topics (i.e., office layout, office furnishing, and cleaning/maintenance) are beyond the scope of the current version of the ASHRAE PMP. Furthermore, the ASHRAE PMP does not provide guidance about what to do with this information.

  Recommendation for Issue IEQ-4: It is recommended for the ASHRAE PMP Basic Level IEQ protocol to determine the appropriateness of using a full set of the CBE survey questionnaire as one of the required performance metrics in the ASHRAE PMP.

- **<u>Issue IEQ-5:</u>** Although the CBE benchmark is fully satisfactory benchmarks covering a wide variety of buildings in different locations over a period of years, the benchmarking database for the subjective IEQ survey needs a fully accessible public domain benchmark database where all individual records are available for analysis, to supplement the current CBE benchmark, which only provides summary statistics.
  <u>Recommendation for Issue IEQ-5</u>: The ASHRAE PMP Basic Level IEQ protocol should provide a fully accessible public domain benchmark database to supplement the current CBE benchmarks.

- **<u>Issue IEQ-6:</u>** The ASHRAE PMP Basic Level IEQ protocol does not discuss the seasonal influence on an occupants' subjective IEQ assessment.
  <u>Recommendation for Issue IEQ-6:</u> It would be an improvement for the ASHRAE PMP Basic Level IEQ protocol to provide information about the seasonal influence on an occupants' subjective IEQ assessment and to provide advice about how to sample seasonality[233].

- **<u>Issue IEQ-7:</u>** The ASHRAE PMP Basic Level IEQ protocol does not apply a uniform set of rules on the use of spot measurements: i.e., optional for thermal comfort versus required for IAQ, lighting, and acoustics regardless of the results of the IEQ satisfaction survey.
  <u>Recommendation for Issue IEQ-7</u>: The ASHRAE PMP Basic Level IEQ protocol should provide a uniform set of rules to all four IEQ areas to be more consistent.

- **<u>Issue IEQ-8:</u>** The current version of the ASHRAE PMP does not provide any advice about how to reproduce dissatisfaction when spot measurements are performed[234].
  <u>Recommendation for Issue IEQ-8</u>: The ASHRAE PMP Basic Level IEQ protocol should consider providing advice about how to reproduce dissatisfaction reported in a survey when Basic Level spot measurements are used, or provide advice about how to collect and analyze dynamic measurements in light of rapidly evolving field instruments and data loggers.

[233] Although a seasonal influence on an occupants' subjective IEQ assessment was not confirmed in this study, some differences may result when a building has significantly different operating modes by season.
[234] In this study, of the six thermally-dissatisfied offices, three offices maintained similar thermal environments as the satisfied offices using personal fans and a small heater located under the desk. Thus, spot measurements could not confirm the complaints because there was no protocol to determine how the presence of portable heating/cooling equipment was to be accounted for.

- **Issue IEQ-9:** The ASHRAE PMP has no specific measurement protocol that can be used for IEQ spot measurements[235].

  Recommendation for Issue IEQ-9: It is recommended for the ASHRAE PMP Basic Level IEQ protocol provides a specific step-by-step measurement protocol that can be applied to overall IEQ spot measurements.

  New Approach for Issue IEQ-9: In the new approach proposed in this study, to accomplish uniformity, a specific IEQ spot measurement protocol for office spaces was developed and used with the corresponding data collection form. The proposed step-by-step protocol was found to help reduce the risk of misinterpretation.

- **Issue IEQ-10:** Each sub-chapter of the ASHRAE PMP Basic Level repeatedly asks the same descriptive information, which could be condensed into one section.

  Recommendation for Issue IEQ-10: It would be more efficient to use the ASHRAE PMP Basic Level protocol if it provided a combined set of questions related to the basic building and system characteristics that could be used by all six categories of the ASHRAE PMP and then referenced the set of questions in other section as needed.

8.1.3.2. Level II and III: Intermediate and Advanced Level

For the Intermediate and Advanced Level IEQ protocols, one field test that covered both levels was developed and applied to the case-study building since both levels require similar data collection efforts of several IEQ parameters. Of the IEQ performance metrics required at the Intermediate and Advanced Levels, the metrics measured at the case-study building are[236]: time-series measurements of four air temperatures (at 4, 24, 43, 66 inches above the floor), four globe temperatures (at 4, 24, 43, 66 inches above the floor), one humidity, and one air speed for thermal comfort; time-series measurements of CO_2, and TVOCs for IAQ; and detailed one-time illuminance and luminance measurements using HDR photography for lighting. For lighting and acoustics, the modified approaches were used based on the results of the Basic Level field test while also considering the significance as well as practicality of the measures (i.e., low

[235] Although the lighting and acoustics protocols provide some recommendations for spot measurements, they are general guidelines rather than detailed step-by-step instructions.
[236] The measurement selections and modified approaches were made based on the results of the Basic Level field test while also considering the significance as well as practical applicability of the measures (i.e., low availability and high cost requirements).

availability and high cost requirements), including time-series measurements of horizontal and vertical illuminance for lighting as well as time-series measurements of A-weighted and C-weighted sound pressure levels (SPL) and time-series measurements from an occupancy sensor. The measurements were made over a one week period in each of the eleven office spaces from July through September 2011 along with a concurrent 'right-now' thermal comfort occupant survey.

The evaluation of the different IEQ performance metrics was performed by comparing the measurement results to the appropriate benchmarks, including the ASHRAE Standard 55-2004 (ASHRAE 2004) and Standard 55-2010 (ASHRAE 2010c), the ASHRAE RP-884 database (de Dear 1998), the ASHRAE Standard 62.1-2007 (ASHRAE 2007b) and Standard 62.1-2010 (ASHRAE 2010d), the ISO Standard 8995:2002 (ISO 2002), the Swedish National Board of Health and Welfare (as cited in Kjellberg et al. 1997), and the Swedish Royal Board of Building (as cited in Kjellberg et al. 1997) as well as the Table 3-9 and Table 3-10 in the ASHRAE PMP. During the process, twelve issues (i.e., Issue IEQ-11 through Issue IEQ-22) were identified. These issues along with the corresponding recommendations and the proposed new or modified approaches (if applicable) are included in the following discussion:

- **Issue IEQ-11:** The current version of the ASHRAE PMP Intermediate and Advanced Level IEQ protocols does not provide enough details that are sufficient for the users to perform the measurements and compare the results against benchmarks without referencing other external documents.

  Recommendation for Issue IEQ-11: The ASHRAE PMP Intermediate and Advanced Level IEQ protocols need to become more than a combination of several standards for each performance category. The ASHRAE PMP also needs to provide details that are sufficient enough for the users to perform the measurements without having to reference other external documents.

- **Issue IEQ-12:** Newer editions of the benchmarking standards that supersede the referenced editions in the ASHRAE PMP are currently available. Comparisons between the different versions revealed a discrepancy in several of the referenced provisions, which may influence the benchmarking results.

Recommendation for Issue IEQ-12: It is recommended that the ASHRAE PMP Intermediate and Advanced Level IEQ protocols clarify which versions of benchmarking standards to be used when a new edition becomes available.

- **Issue IEQ-13:** No benchmarks are available regarding lower humidity limits although non-thermal comfort issues are recognized in the ASHRAE Standard 55-2004 and ASHRAE Standard 55-2010.
  Recommendation for Issue IEQ-13: The ASHRAE PMP IEQ protocols should consider providing reliable benchmarks for acceptable low humidity limits.

- **Issue IEQ-14:** No benchmarks are available about high illuminance limits although there were complaints about indoor lighting environments that are too bright in the survey at the case-study building.
  Recommendation for Issue IEQ-14: The ASHRAE PMP IEQ protocols should consider providing reliable benchmarks for acceptable high illuminance limits.

- **Issue IEQ-15:** At the case-study building, time-series measurements of CO_2 and VOCs could not reveal the issue related to the air stuffiness/staleness reported in the survey.
  Recommendation for Issue IEQ-15: It is recommended that the ASHRAE PMP Intermediate and Advanced Level IAQ protocols discuss how to use vertical temperature profiles of a room as a simple indicator to evaluate room air circulation.
  New Approach for Issue IEQ-15: In the new approach proposed in this study, a simple method was developed that can be used to diagnose air circulation problems within a room using median vertical temperature profiles from time-series measurements. As a result, for the two dissatisfied offices, hot air stratification was observed at 43 in. (1.1 m), possibly indicating poor air circulation in the two offices that might prevent the delivery of fresh air in the breathing zones. Thus the use of vertical temperature profiles was found to be an effective method to evaluate room air circulation which is related to the stuffiness and staleness of the room air.

- **Issue IEQ-16:** Some issues could not be verified using time-series measurements from the instrumentation cart, which most likely indicated individual differences in subjective preferences in the CBE's IEQ survey.
  Recommendation for Issue IEQ-16: The ASHRAE PMP IEQ protocols should provide advice to the users how to interpret person-to-person variations in the evaluations when different results arise between subjective and instrumented measurements in the same space.

- **Issue IEQ-17:** The ASHRAE PMP Intermediate and Advanced Level lighting and acoustics protocols do not require continuous measurements. However, large time-of-day variations in time-series measurements of lighting and acoustics performance metrics were observed in the case-study building used in this study.
  Recommendation for Issue IEQ-17: The ASHRAE PMP Intermediate and Advanced Level IEQ protocols should consider providing advice about how to collect and analyze dynamic or time-series measurements, or should adequately explain the limitations of spot measurements with advice about how to interpret the results when time-series measurements are not available.
  New Approach for Issue IEQ-17: In the new approach proposed in this study, a method how to collect and analyze the continuously measured IEQ performance data was discussed using a comprehensive IEQ continuous monitoring cart developed in this study. Based on a review of previous studies on building performance measurements as well as market research on measurement instruments, this study developed a comprehensive instrumentation cart to collect continuous, time-series data from selected IEQ-related parameters (i.e., four air temperatures, four globe temperatures, humidity, air speed, CO_2, total volatile organic compounds (TVOCs), horizontal and vertical illuminance, A-weighted and C-weighted sound pressure levels (SPL)), and occupancy. In addition, a real-time monitoring dashboard of the continuously monitored IEQ data was used to view the measurements via a wireless connection to the internet. The cart was used in eleven offices of the case-study building to demonstrate its usability. As a result, the use of the IEQ monitoring system was found to be an effective method to evaluate IEQ performance of a building, although several areas for

improvement were identified[237]. Finally, several methods of displaying and analyzing the collected data to maximize the information contained in the data were discussed.

- **Issue IEQ-18:** The ASHRAE PMP Intermediate and Advanced Level IEQ protocols do not provide guidelines about the location to perform field measurements[238].
  Recommendation for Issue IEQ-18: The ASHRAE PMP Intermediate and Advanced Level IEQ protocols should provide detailed continuous measurement protocols, including the location where to perform the measurements and advice about how to address asymmetric issues with the field measurements.

- **Issue IEQ-19:** The octave band measurements required at the Intermediate Level have low practical applicability (i.e., there are very few manufacturers who make the equipment, and the equipment has a high cost).
  Recommendation for Issue IEQ-19: It is recommended that the ASHRAE PMP Intermediate and Advanced Level acoustics protocols include the cost-effective method, proposed in this thesis to evaluate low frequency noise annoyance in the room as a low-cost alternative to the octave band frequency analysis that is currently specified.
  New Approach for Issue IEQ-19: In the new approach proposed in this study, the LCeq – LAeq difference was used to diagnose low frequency noise annoyance in the case-study building. It was found that the LCeq – LAeq difference can be regarded as a simple indicator to estimate low frequency noise annoyance when a full, octave band frequency analysis is not available. Such a measurement is also inexpensive and simple to perform.

- **Issue IEQ-20:** The ASHRAE PMP Intermediate and Advanced Level IEQ protocols do not provide clear guidelines about how to analyze the results of continuous, time-series measurements for benchmarking, although continuous measurements are required for thermal comfort and IAQ protocols.

[237] For example, the cart can be improved by using detachable or remote illuminance sensors located at the task using wireless devices.
[238] For example, the Advanced Level thermal comfort protocol suggests replacing the occupant's chair with the measurement cart and collecting data for several minutes. However, this suggestion is not always feasible for continuous measurements when the office is occupied and in use. In addition, the ASHRAE PMP Intermediate and Advanced Level IAQ protocols suggest measurements in representative spaces, which is open to self-interpretation as to exactly what a representative space is.

Recommendation for Issue IEQ-20: It is recommended that the ASHRAE PMP Intermediate and Advanced Level IEQ protocols include clear guidelines about how to analyze the results of continuous, time-series measurements for benchmarking.

New Approach for Issue IEQ-20: In the new approach proposed in this study, a statistical analysis was used to describe the time-varying distribution of indices: maximum, 95th, median, 5th, and minimum. The 95th and 5th percentiles were chosen to characterize extreme variations based on a ±5% deviation. The median was chosen as a convenient way to describe the average of skewed distributions using a single number for a comparison between locations, while also conveying information about that variation for half the measurement period.

- **Issue IEQ-21:** The ASHRAE PMP Intermediate Level IEQ protocols do not provide clear guidelines about how to display and interpret the results of a 'right-now' survey.

  Recommendation for Issue IEQ-21: The ASHRAE PMP Intermediate Level IEQ protocols should provide users with clear guidelines about how to display and interpret the results of a 'right-now' survey, including: a method about how to synthesize appropriate benchmarks; a ranking of the different indices (i.e., mean scores versus frequency distributions); and a method about how to analyze subjective responses with the concurrently measured physical indoor climate conditions.

- **Issue IEQ-22:** The existing ASHRAE RP-884 benchmark database has several limitations, including the fact that the database is based on relatively old data sets that were collected in the 1990's and that most data sets were collected in office buildings in several different countries.

  Recommendation for Issue IEQ-22: The ASHRAE PMP should note the limitations of the existing ASHRAE RP-884 database and should provide advice to the user to help resolve the issues when the appropriate benchmarks are not available.

8.2. Summary of Phase III Results

Recommendations were developed for rating a building's overall performance based on the ASHRAE PMP Basic Level procedures, including the new single figure-of-merit rating system based on above-average percentage scores or percentile rank of scores. The proposed single rating system linearly displays the combination of six figure-of-merits, either above-average percentage scores or percentile ranks of scores, calculated across all six performance areas (i.e., energy use, water use, thermal comfort, IAQ, lighting, and acoustics) using the results from the ASHRAE PMP Basic Level applications. Finally, a single FOM was calculated by combining the six FOMs with assumed cost-based weighting factors and presented in the rating system. The strengths and limitations of the proposed rating systems are also discussed.

Next, since it would be desirable for a future rating system to be determined based on the application of all the ASHRAE PMP procedures, including the instrumented measurements of the selected IEQ variables, two ideas for a future figure-of-merit rating system were discussed, which can better represent the building's overall performance, including Predicted Percentage of Hours Dissatisfied (PPHD %) for IEQ instrumented measurements and a cost-based rating system. The PPHD rating is a percentage of hours that the measured IEQ performance data are within the acceptable comfort range defined in the appropriate benchmarking. The proposed PPHD (%) rating is applicable for all four IEQ areas if the appropriate benchmarks are available and is simple enough to be understood. The second procedure is a cost-based rating system. The major advantage of using cost-based metrics is its ease of understanding as well as its high impact on the decision making process.

8.3. Recommendations for Future Research

In this study, the field test and the evaluations of the ASHRAE PMP are limited to the characteristics of the case-study building, a typical office building in central Texas. Since other buildings with different HVAC systems and other building characteristics in different climates may lead to different conclusions, it is recommended that the ASHRAE PMP be field tested using different building types in different climates.

In addition, although this study proposed recommendations for forty issues as well as the new or modified approaches for twelve selected issues, there were several issues that need more detailed recommendations, which will require additional effort and evidence. As a result, the following issues are recommended to be addressed in future research:

- **Recommended Future Research for Issue E-9**: It is recommended that research be performed to compile the existing reliable, external references, which can then be used to develop benchmarks for the major end-use energy uses in different buildings.
- **Recommended Future Research for Issue W-1:** It is recommended that research be performed to compile or reclassify the existing reliable, external references, which can then

be used to benchmark the water performance of buildings that have atypical spaces (i.e., office building with gymnasium shower facilities).

- **Recommended Future Research for Issue W-2:** It is recommended that research be performed to combine the ASHRAE PMP Basic Level water use intensity (WUI) benchmarks that are provided separately for the building and landscape, which can then be directly comparable to the required performance metrics without requiring sub-metering.
- **Recommended Future Research for Issue W-3:** It is recommended that research be performed into the methods used to estimate and track the number of occupants and/or landscape areas for the ASHRAE PMP Basic Level water protocols, which is expected to improve the reliability of the existing ASHRAE PMP Basic Level water protocols.
- **Recommended Future Research for Issue W-5:** It is recommended that research be performed into detailed analysis techniques or modeling method to analyze and evaluate daily water performance at the building level, which may include time lag effect of precipitation on the daily water consumption.
- **Recommended Future Research for Issue IEQ-13:** It is recommended that research be performed to review the existing studies that examined the impact of low humidity levels on occupants' health, comfort, or productivity, which is expected to provide reliable benchmarks for acceptable low humidity limits.
- **Recommended Future Research for Issue IEQ-14:** It is recommended that research be performed to review the existing studies that examined the impact of high illuminance levels on occupants' health, comfort, or productivity, which is expected to provide reliable benchmarks for acceptable high illuminance limits.
- **Recommended Future Research for Issue IEQ-17:** It is recommended that research be performed into other potential graphical signatures of the continuously measured time-series IEQ performance data (i.e., small variations versus large variations in the measured sound pressure levels) and their statistical decomposition methods, which can maximize the information contained in the data. It is also recommended that research be performed into a cost-effective IEQ monitoring system for the continuous IEQ measurements, which will have a major impact when applying the ASHRAE PMP to a large fraction of the existing building stock.

- **<u>Recommended Future Research for Issue IEQ-18:</u>** It is recommended that research be performed into field-testing asymmetric issues with IEQ field measurements, which is expected to provide clear guidelines about where and/or how to perform the measurements.
- **<u>Recommended Future Research for Issue IEQ-22:</u>** It is recommended that research to be performed to update the existing ASHRAE RP-884 benchmark database, which is expected to provide more recent and more extensive benchmarking database for thermal comfort 'right-now' surveys.

Finally, to improve the usability of the ASHRAE PMP, there is a need for a new comprehensive, figure-of-merit labeling system or methodology that covers all aspects of a building's overall performance. This study developed recommendations for rating a building's overall performance based on the ASHRAE PMP Basic Level procedures, including a single figure-of-merit rating system based on above-average percentage scores or percentile rank of scores using the ASHRAE PMP Basic Level results. However, several limitations were found in the proposed rating system, including that there are no benchmarks currently available for water performance. In addition, it would be desirable for a future rating system to be developed based on the application of all the ASHRAE PMP procedures at all levels, including instrumented measurements of the selected IEQ variables. To accomplish this, the following future research areas are identified:

- **<u>Recommended Future Research for a Single FOM Rating System</u>**: It is recommended that research be performed to review and compile the existing reliable, external references to develop the percentile distributions of a building's water performance, which can then be used to for the rating system developed in this study based on percentile rank of scores. It is also recommended that research be performed to examine the weighting factors of energy, water, and IEQ that are needed to calculate a single FOM score. Finally, research is recommended on a method how to apply the calculated, single FOM score to determine the compliance of a building with the AHSRAE PMP.
- **<u>Recommended Future Research for PPHD(%) Rating</u>**: It is recommended that research be performed to examine the acceptable Predicted Percentage of Hours Dissatisfied (PPHD(%)) (i.e., the percentage of hours that the measured IEQ performance data are outside of an acceptable comfort range). Such research can be used to benchmark the calculated PPHD(%) ratings.

- **<u>Recommended Future Research for Cost-Based Rating System</u>**: It is recommended that research to be performed to review the existing studies that have analyzed the productivity as a function of the measured IEQ performance metrics, which is expected to be used to quantify the impact of IEQ performance on occupants' productivity and consequently on the cost (i.e., consequences of poor IEQ conditions).

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APPENDIX A
QUESTIONNAIRES AND SURVEY FORMS

This appendix presents the questionnaires and survey forms used in the measurements, including: Texas A&M University Institutional Review Board (IRB) approval memos (A-1), a questionnaire used for the IEQ satisfaction survey (A-2), contact letters for the IEQ satisfaction survey (A-3), a questionnaire used for thermal comfort 'right-now' survey (A-4), and a survey form used for IEQ spot measurement (A-5).

A.1 Texas A&M University Institutional Review Board (IRB) Approval Memos

A.2 IEQ Satisfaction Survey Questionnaire

A.3 Contact Letters for the IEQ Satisfaction Survey

A.4 Thermal Comfort 'Right-Now' Survey Questionnaire

A.5 IEQ Spot Measurement Survey Form

A.1 Institutional Review Board (IRB) Approval Memos

TEXAS A&M UNIVERSITY
DIVISION OF RESEARCH AND GRADUATE STUDIES - OFFICE OF RESEARCH COMPLIANCE

1186 TAMU, General Services Complex
College Station, TX 77843-1186
750 Agronomy Road, #3500

979.458.1467
FAX 979.862.3176
http://researchcompliance.tamu.edu

Human Subjects Protection Program — Institutional Review Board

	DATE:	08-Mar-2010
MEMORANDUM		
	TO:	KIM, HYOJIN 77843-3578
	FROM:	Office of Research Compliance Institutional Review Board
	SUBJECT:	Initial Review

Protocol Number:	2010-0126
Title:	Methodology for Rating a Building's Overall Performance Based on ASHRAE/CIBSE/USGBC Performance Measurement Protocols for Commercial Buildings
Review Category:	Exempt from IRB Review

It has been determined that the referenced protocol application meets the criteria for exemption and no further review is required. However, any amendment or modification to the protocol must be reported to the IRB and reviewed before being implemented to ensure the protocol still meets the criteria for exemption.

This determination was based on the following Code of Federal Regulations:
(http://www.hhs.gov/ohrp/humansubjects/guidance/45cfr46.htm)

45 CFR 46.101(b)(2) Research involving the use of educational tests (cognitive, diagnostic, aptitude, achievement), survey procedures, interview procedures, or observation of public behavior, unless: (a) information obtained is recorded in such a manner that human subjects can be identified, directly or through identifiers linked to the subjects; and (b) any disclosure of the human subjects' responses outside the research could reasonably place the subjects at risk of criminal or civil liability or be damaging to the subjects' financial standing, employability, or reputation.

Provisions:

This electronic document provides notification of the review results by the Institutional Review Board.

TEXAS A&M UNIVERSITY
DIVISION OF RESEARCH AND GRADUATE STUDIES - OFFICE OF RESEARCH COMPLIANCE

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Human Subjects Protection Program

Institutional Review Board

	DATE:	23-Apr-2010
MEMORANDUM		
	TO:	KIM, HYOJIN 77843-3578
	FROM:	Office of Research Compliance Institutional Review Board
	SUBJECT:	Amendment

Protocol Number:	2010-0126
Title:	Methodology for Rating a Building's Overall Performance Based on ASHRAE/CIBSE/USGBC Performance Measurement Protocols for Commercial Buildings
Review Category:	Exempt from IRB Review

It has been determined that the referenced protocol application meets the criteria for exemption and no further review is required. However, any amendment or modification to the protocol must be reported to the IRB and reviewed before being implemented to ensure the protocol still meets the criteria for exemption.

This determination was based on the following Code of Federal Regulations:
(http://www.hhs.gov/ohrp/humansubjects/guidance/45cfr46.htm)

45 CFR 46.101(b)(2) Research involving the use of educational tests (cognitive, diagnostic, aptitude, achievement), survey procedures, interview procedures, or observation of public behavior, unless: (a) information obtained is recorded in such a manner that human subjects can be identified, directly or through identifiers linked to the subjects; and (b) any disclosure of the human subjects' responses outside the research could reasonably place the subjects at risk of criminal or civil liability or be damaging to the subjects' financial standing, employability, or reputation.

Provisions:	Questions added to questionnaire.

This electronic document provides notification of the review results by the Institutional Review Board.

A.2 IEQ Satisfaction Survey Questionnaire

ID: ☐☐☐☐
(Please do not fill out this area.)

John B. Connally Building
Indoor Environmental Quality (IEQ) Assessment Survey[1]

Any information provided by the John B. Connally building and the occupants are completely confidential, and no individual will be identified.

1. Name: ____
2. Office Room No.: ________________________________
3. Survey Date/Time: ____/____/2010 ____:____ am/pm

1. Personal Workspace Description

1. Which of the following best describes your personal workspace?
   - ☐ Enclosed office, private
   - ☐ Enclosed office, shared with other people
   - ☐ Cubicles with high partitions (about five or more feet high)
   - ☐ Cubicles with low partitions (lower than five feet high)
   - ☐ Workspace in open office with no partitions (just desks)
   - ☐ Other: ________________________________

2. Personal Workspace Location

1. On which floor is your workspace located? ________ Floor

2. In which area of the building is your workspace located?
   - ☐ South ☐ North ☐ East
   - ☐ West ☐ Core ☐ Don't know

3. To which direction do the windows closest to your workspace face?
   - ☐ South ☐ North ☐ East
   - ☐ West ☐ No windows ☐ Don't know

4. Are you near an exterior wall (within 15 feet)?
   - ☐ Yes ☐ No

5. Are you near a window (within 15 feet)?
   - ☐ Yes ☐ No

[1] This form is originally from the University of California, Berkeley's Center for the Built Environment IEQ survey that is copyrighted by the Regents of the University of California and reproduced with permission (April 12, 2010).

1

ID:
(Please do not fill out this area.)

3. Office Layout

1. How satisfied are you with the amount of space available for individual work and storage? Please mark a (√) on the box below.

Very Satisfied

3	2	1	0	-1	-2	-3

Very Dissatisfied

If you voted on the satisfied side (3, 2, 1, & 0), please go to the next question 2. If you voted on the dissatisfied side (-1, -2, -3), please answer the following question.

1-1. You have said that you are dissatisfied with the amount of space available for individual work and storage. Which of the following contribute to your dissatisfaction? (Check all that apply)

- ☐ Amount of work surface area
- ☐ Total area of work station
- ☐ Available filing and storage space
- ☐ Available space for personal items
- ☐ Space for meeting with other people
- ☐ Other: ____________________

2. How satisfied are you with the level of visual privacy?

Very Satisfied

3	2	1	0	-1	-2	-3

Very Dissatisfied

If you voted on the satisfied side (3, 2, 1, & 0), please go to the next question 3. If you voted on the dissatisfied side (-1, -2, -3), please answer the following question.

2-1. You have said that you are dissatisfied with the level of visual privacy. Which of the following contribute to your dissatisfaction? (Check all that apply)

- ☐ High density: too little space separating people
- ☐ Partitions or walls are too low or transparent
- ☐ People can easily see in through exterior windows
- ☐ Too many people walking in my work area
- ☐ Other: ____________________

3. How satisfied are you with ease of interaction with co-workers?

Very Satisfied

3	2	1	0	-1	-2	-3

Very Dissatisfied

If you voted on the satisfied side (3, 2, 1, & 0), please go to the next question 4. If you voted on the dissatisfied side (-1, -2, -3), please answer the following question.

3-1. You have said that you are dissatisfied with the ease of interaction with co-workers. Which of the following contribute to your dissatisfaction? (Check all that apply)

- ☐ My work station in not near my co-workers
- ☐ My work station is difficult to find or out of the way
- ☐ Conversations are discouraged because the noise is distracting to others
- ☐ There are no spaces (i.e., break rooms) to casually interact with co-workers
- ☐ There are few organized opportunities to interact with co-workers
- ☐ Other: ____________________

4. Overall, does the office layout enhance or interfere with your ability to get your job done?

Enhances

3	2	1	0	-1	-2	-3

Interferes

ID:

(Please do not fill out this area.)

5. Please describe any other issues related to the office layout that are important to you.

____

____

____

4. Office Furnishings

1. How satisfied are you with the comfort of your office furnishings (chair, desk, computer, equipment, etc)?

Very Satisfied	3	2	1	0	-1	-2	-3	Very Dissatisfied

2. How satisfied are you with your ability to adjust your furniture to meet your needs?

Very Satisfied	3	2	1	0	-1	-2	-3	Very Dissatisfied

3. How satisfied are you with the colors and textures of flooring, furniture and surface finishes?

Very Satisfied	3	2	1	0	-1	-2	-3	Very Dissatisfied

4. Do your office furnishings enhance or interfere with your ability to get your job done?

Enhances	3	2	1	0	-1	-2	-3	Interferes

5. Please describe any other issues related to the office furnishings that are important to you.

____

____

____

ID:

(Please do not fill out this area.)

5. Thermal Comfort

1. Which of the following do you personally adjust or control in your workspace? (Check all that apply)

- ☐ Window blinds or shades
- ☐ Operable window
- ☐ Thermostat
- ☐ Portable heater
- ☐ Permanent heater
- ☐ Room air-conditioning unit
- ☐ Portable fan
- ☐ Ceiling fan
- ☐ Adjustable air vent in wall or ceiling
- ☐ Adjustable floor air vent (diffuser)
- ☐ Door to interior space
- ☐ Door to exterior space
- ☐ None of the above
- ☐ Other: ______________________

2. How satisfied are you with the temperature in your workspace?

Very Satisfied	3	2	1	0	-1	-2	-3	Very Dissatisfied

<u>If you voted on the satisfied side (3, 2, 1, & 0), please go to the next question 3. If you voted on the dissatisfied side (-1, -2, -3), please answer the following questions.</u>

2-1. You have said that you are dissatisfied with the temperature in your workspace. Which of the following contribute to your dissatisfaction?

In warm/hot weather, the temperature in my workspace is: (Check all that apply)

- ☐ Often too hot
- ☐ Often too cold

In cool/cold weather, the temperature in my workspace is: (Check all that apply)

- ☐ Often too hot
- ☐ Often too cold

2-2. When is this most often a problem? (Check all that apply)

- ☐ Morning (before 11am)
- ☐ Mid-day (11am – 2 pm)
- ☐ Afternoon (2 pm – 5pm)
- ☐ Evening (after 5 pm)
- ☐ Weekends/holidays
- ☐ Monday mornings
- ☐ No particular time
- ☐ Other: ______________________

2-3. How would you best describe the source of this discomfort? (Check all that apply)

- ☐ Humidity too high (damp)
- ☐ Humidity too low (dry)
- ☐ Air movement too high
- ☐ Air movement too low
- ☐ Incoming sun
- ☐ Heat from office equipment
- ☐ Drafts from windows
- ☐ Drafts from vents
- ☐ My area is hotter/colder than other areas
- ☐ Thermostat is inaccessible
- ☐ Thermostat is adjusted by other people
- ☐ Clothing policy is not flexible
- ☐ Hot/cold surrounding surfaces (floor, ceiling, walls or windows)
- ☐ Heating/cooling system does not respond quickly enough to the thermostat
- ☐ Other: ______________________________

2-4. Please describe any other issues related to being too hot or too cold in your workspace.

____

____

____

3. Overall, does your thermal comfort in your workspace enhance or interfere with your ability to get your job done?

Enhances	3	2	1	0	-1	-2	-3	Interferes

ID:
(Please do not fill out this area.)

6. Air Quality

1. How satisfied are you with the air quality in your workspace (i.e., stuffy/stale air, cleanliness, odors)?

Very Satisfied | 3 | 2 | 1 | 0 | -1 | -2 | -3 | Very Dissatisfied

If you voted on the satisfied side (3, 2, 1, & 0), please go to the next question 2. If you voted on the dissatisfied side (-1, -2, -3), please answer the following questions.

1-1. You have said that you are dissatisfied with the air quality in your workspace. Please rate the level of each of the following problems:

Air is stuffy/stale:

Minor problem | 3 | 2 | 1 | 0 | -1 | -2 | -3 | Major problem

OR, if it's **Not a problem**, please check ☐

Air is not clean:

Minor problem | 3 | 2 | 1 | 0 | -1 | -2 | -3 | Major problem

OR, if it's **Not a problem**, please check ☐

Air smells bad (odors):

Minor problem | 3 | 2 | 1 | 0 | -1 | -2 | -3 | Major problem

OR, if it's **Not a problem**, please check ☐

1-2. If there is an odor problem, which of the following contribute to this problem? (Check all that apply)

☐ Tobacco smoke
☐ Printers
☐ Carpet or furniture
☐ Perfume
☐ Outside sources (car exhaust, smog)
☐ Photocopiers
☐ Food
☐ Other people
☐ Cleaning products
☐ Other: ____________________

1-3. Please describe any other issues related to the air quality in your workspace that are important to you.

____

____

____

2. Overall, does the air quality in your workspace enhance or interfere with your ability to get your job done?

Enhances | 3 | 2 | 1 | 0 | -1 | -2 | -3 | Interferes

ID: ☐☐☐☐
(Please do not fill out this area.)

7. Lighting

1. Which of the following controls do you have over the lighting in your workspace? (Check all that apply)

- ☐ Light switch
- ☐ Light dimmer
- ☐ Window blinds or shades
- ☐ Desk (task) light
- ☐ None of the above
- ☐ Other: ____________________

2. How satisfied are you with the amount of light in your workspace?

Very Satisfied	3	2	1	0	-1	-2	-3	Very Dissatisfied

3. How satisfied are you with the visual comfort of the lighting in your workspace (i.e., glare, reflections, and contrast)?

Very Satisfied	3	2	1	0	-1	-2	-3	Very Dissatisfied

If you voted on the satisfied side (3, 2, 1, & 0) *for both question 2 and question 3*, please go to the next question 4. If you voted on the dissatisfied side (-1, -2, -3) *for either question 1 or 2*, please answer the following questions.

3-1. You have said that you are dissatisfied with the lighting in your workspace. Which of the following contribute to your dissatisfaction? (Check all that apply)

- ☐ Too dark
- ☐ Electric lighting flickers
- ☐ Too bright
- ☐ Electric lighting is an undesirable color
- ☐ Not enough daylight
- ☐ No task lighting
- ☐ Too much daylight
- ☐ Reflections in the computer screen
- ☐ Not enough electric lighting
- ☐ Shadows on the workspace
- ☐ Too much electric lighting
- ☐ Other: ____________________

3-2. Please describe any other issues related to lighting in your workspace that are important to you.

____

____

____

4. Overall, does the lighting quality enhance or interfere with your ability to get your job done?

Enhances	3	2	1	0	-1	-2	-3	Interferes

ID:
(Please do not fill out this area.)

8. Acoustic Quality

1. How satisfied are you with the noise level in your workspace?

Very Satisfied	3	2	1	0	-1	-2	-3	Very Dissatisfied

2. How satisfied are you with the sound privacy in your workspace (ability to have conversations without your neighbors overhearing and vice versa)?

Very Satisfied	3	2	1	0	-1	-2	-3	Very Dissatisfied

<u>If you voted on the satisfied side (3, 2, 1, & 0) *for both question 1 and question 2*, please go to the next question 3. If you voted on the dissatisfied side (-1, -2, -3) *for either question 1 or 2*, please answer the following questions.</u>

2-1. You have said that you are dissatisfied with the acoustics in your workspace. Which of the following contribute to your dissatisfaction? (Check all that apply)

- ☐ Office equipment noise
- ☐ Office lighting noise
- ☐ Outdoor traffic noise
- ☐ Other outdoor noise
- ☐ People talking on the phone
- ☐ People talking in neighboring areas
- ☐ People overhearing my private conversations
- ☐ Telephones ringing
- ☐ Mechanical (heating, cooling and ventilation systems) noise
- ☐ Excessive echoing of voices or other sounds
- ☐ Other: ____________________________

2-2. Please describe any other issues related to acoustics in your workspace that are important to you.

____

____

____

3. Overall, does the acoustic quality in your workspace enhance or interfere with your ability to get your job done?

Enhances	3	2	1	0	-1	-2	-3	Interferes

ID:
(Please do not fill out this area.)

9. Cleanliness and Maintenance

1. How satisfied are you with general cleanliness of the overall building?

Very Satisfied | 3 | 2 | 1 | 0 | -1 | -2 | -3 | Very Dissatisfied

2. How satisfied are you with cleaning service provided for your workspace?

Very Satisfied | 3 | 2 | 1 | 0 | -1 | -2 | -3 | Very Dissatisfied

If you voted on the satisfied side (3, 2, 1, & 0), please go to the next question 3. If you voted on the dissatisfied side (-1, -2, -3), please answer the following questions.

2-1. You have said that you are dissatisfied with the cleaning service provided for your workspace. How often do you have significant problems?

- ☐ Always
- ☐ Often
- ☐ Sometimes
- ☐ Rarely
- ☐ Never
- ☐ Don't know/No opinion

2-2. Which of the following contribute to your dissatisfaction? (Check all that apply)

- ☐ Surface dust on work surfaces close to you
- ☐ Surface dust on other surfaces you might touch
- ☐ Surface dust on surfaces difficult to reach
- ☐ Spills and debris
- ☐ Dirty floors
- ☐ Trash cans are not emptied overnight
- ☐ Trash cans get too full during the day
- ☐ Trash cans are a significant source of odor
- ☐ Other: ____________________________

2-3. Please describe any other issues related to cleaning and maintenances that are important to you.

____

____

____

3. How satisfied are you with general maintenance of the building?

Very Satisfied | 3 | 2 | 1 | 0 | -1 | -2 | -3 | Very Dissatisfied

4. Does the cleanliness and maintenance of this building enhance or interfere with your ability to get your job done?

Enhances | 3 | 2 | 1 | 0 | -1 | -2 | -3 | Interferes

ID: ☐☐☐☐
(Please do not fill out this area.)

10. Building Features

1. Considering energy use, how efficiently is this building performing in your opinion?

Very efficient	3	2	1	0	-1	-2	-3	Not at all energy efficient

Comments: ____

____

2. For each of the building features listed below, please indicate how satisfied you are with the effectiveness of that feature:

Thermostats:

Very Satisfied	3	2	1	0	-1	-2	-3	Very Dissatisfied

☐ I have no experience with it.

Comments: ____

____

Light switches:

Very Satisfied	3	2	1	0	-1	-2	-3	Very Dissatisfied

☐ I have no experience with it.

Comments: ____

____

Window blinds:

Very Satisfied	3	2	1	0	-1	-2	-3	Very Dissatisfied

☐ I have no experience with it.

Comments: ____

____

3. How well informed do you feel about using the above mentioned features in this building?

Very well	3	2	1	0	-1	-2	-3	Not well informed

4. Please describe any other issues related to the design and operation of the above mentioned features that are important to you.

____

____

____

____

ID:

(Please do not fill out this area.)

11. General Comments

1. All things considered, how satisfied are you with your personal workspace?

Very Satisfied | 3 | 2 | 1 | 0 | -1 | -2 | -3 | Very Dissatisfied

2. Please estimate how your productivity is increased or decreased by the environmental conditions in this building (e.g., thermal, lighting, acoustics, cleanliness):

Increased | 20% | 10% | 5% | 0% | -5% | -10% | -20% | Decreased

3. How satisfied are you with the building overall?

Very Satisfied | 3 | 2 | 1 | 0 | -1 | -2 | -3 | Very Dissatisfied

4. Any additional comments or recommendations about your personal workspace or building overall?

____

____

____

12. Background

1. How many years have you worked in this building?
   - ☐ Less than 1 year
   - ☐ 1-2 years
   - ☐ 3-5 years
   - ☐ More than 5 years

2. How long have you been working at your present workspace?
   - ☐ Less than 3 months
   - ☐ 4-6 months
   - ☐ 7-12 months
   - ☐ More than 1 year

3. In a typical week, how many hours do you spend in your workspace?
   - ☐ Less than 10 hours
   - ☐ 11-30 hours
   - ☐ More than 30 hours

4. How would you describe the work you do?
   - ☐ Administrative support
   - ☐ Technical
   - ☐ Professional
   - ☐ Managerial/supervisory
   - ☐ Other

5. What is your age?
   - ☐ 30 or under
   - ☐ 31-50
   - ☐ Over 50

6. What is your gender?
   - ☐ Female
   - ☐ Male

There will be follow-up spot measurements of several IEQ-related parameters in several office spaces, including temperature, humidity, air velocity, CO_2 level, illuminance level and sound level. The procedures will take about 15-25 minutes. Would you allow me to conduct this follow-up measurement in your office if you're asked?

☐ **Yes** ☐ **No**

If yes, please indicate your preferred contact method and the corresponding information:

1) Email: __________ 2) Phone: __________ 3) Direct Visit to the Office __________.

Thank you for participating in this Survey!

A.3 Contact Letters for IEQ Satisfaction Survey

College of Architecture
Department of Architecture

Hyojin Kim
Ph.D. Student, Department of Architecture

TEXAS A&M UNIVERSITY

April, 2010

Dear occupant in John B. Connally Building:

We would like to invite you to participate in the John Connally Building's Indoor Environmental Quality (IEQ) Assessment survey. The survey questions consist of evaluation of seven indoor environmental quality topics, including office layout, office furnishings, thermal comfort, air quality, lighting, acoustics, and clean/maintenance, with the background survey.

The questionnaire should take 10 to 15 minutes to complete. All survey responses will remain confidential, and participants will remain anonymous and will only be identified as an assigned ID code in data analysis. Only the principal investigator and authorized personnel have the participants' names/office number linked to the identification number.

The results of this study will be a part of Ms. Hyojin Kim's Ph.D. study to test the *ASHRAE[1]/CIBSE[2]/USGBC[3] Performance Measurement Protocols (PMP) for Commercial Buildings,* which is a new protocol for measuring a building's overall performance, including energy use, water use, and indoor environmental quality. This study is expected to contribute to the verification of green building technologies and practices, which includes all aspects of energy, water, and IEQ performance.

Your voluntary participation is important. If you have any questions or comments about this study, please feel free to contact Ms. Kim by email hyojinkim@tees.tamus.edu or 979-862-6415.

Thank you very much for participating in this survey.

Sincerely,

Hyojin Kim
Ph.D. Student, Department of Architecture

Jeff S. Haberl (Supervisor)
Professor, Department of Architecture

[1] American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., Atlanta, Georgia.
[2] Chartered Institute of Building Services Engineers, London, England.
[3] U.S. Green Building Council, Washington, D.C.

WERC Rm#053A
3137 TAMU
College Station, TX 77843-3581

Tel. 979.862.6415
hyojinkim@tees.tamus.edu

College of Architecture
Department of Architecture

Hyojin Kim
Ph.D. Candidate, Department of Architecture

February, 2011

Dear occupant in John B. Connally Building:

We would like to invite you to participate in the second round of John Connally Building's Indoor Environmental Quality (IEQ) Assessment survey. This second survey is intended to observe changes in the building's IEQ performance that may be seasonal. You are asked to answer the same questionnaire as the one employed in the previous survey last summer. The survey questions consist of evaluation of seven indoor environmental quality topics, including office layout, office furnishings, thermal comfort, air quality, lighting, acoustics, and clean/maintenance, with the background survey.

The questionnaire should take 10 to 15 minutes to complete. All survey responses will remain confidential, and participants will remain anonymous and will only be identified as an assigned ID code in data analysis. Only the principal investigator and authorized personnel have the participants' names/office number linked to the identification number.

The results of this study will be a part of Ms. Hyojin Kim's Ph.D. study to test the *ASHRAE[1]/CIBSE[2]/USGBC[3] Performance Measurement Protocols (PMP) for Commercial Buildings,* which is a new protocol for measuring a building's overall performance, including energy use, water use, and indoor environmental quality. This study is expected to contribute to the verification of green building technologies and practices, which includes all aspects of energy, water, and IEQ performance.

Your voluntary participation is important. If you have any questions or comments about this study, please feel free to contact Ms. Kim by email hyojinkim@tees.tamus.edu or 979-458-1014.

Thank you very much for participating in this survey.

Sincerely,

Hyojin Kim	Jeff S. Haberl (Supervisor)
Ph.D. Candidate, Department of Architecture	Professor, Department of Architecture

[1] American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., Atlanta, Georgia.
[2] Chartered Institute of Building Services Engineers, London, England.
[3] U.S. Green Building Council, Washington, D.C.

WERC Rm#053B
3137 TAMU
College Station, TX 77843-3581

Tel. 979.458.1014
hyojinkim@tees.tamus.edu

A.4 Thermal Comfort 'Right-Now' Survey Questionnaire

Date:_______________ **ID:** ☐☐☐☐

Time:__________am/pm (Please do not fill out ID.)

Right-Now Thermal Comfort Survey

A. Thermal Environment.

Please mark a (√) on the scale and box below at the place that best represents how you feel **at this moment** about the thermal environment of your office.

1. Please rate your **right-now** thermal sensation and comfort. You may mark in an appropriate place between two categories, if you wish.

Cold | Cool | Slightly cool | Neutral | Slightly warm | Warm | Hot

Very comfortable | Comfortable | Just comfortable | Just uncomfortable | Uncomfortable | Very uncomfortable

2. Is the **thermal environment** of your office acceptable to you **right now**?
☐ acceptable ☐ not acceptable

3. **Right now**, would you prefer to be:
☐ warmer ☐ no change ☐ cooler

4. **Right now**, would you prefer:
☐ more air movement ☐ no change ☐ less air movement

5. **Today**, have you operated shades/blinds/fans?
☐ yes ☐ no

B. Clothing and activity.

Please mark a (√) on the box below that best represents the clothing/activity that you are **currently** wearing/performing.

	Trousers, short-sleeve shirt
	Trousers, long-sleeve shirt
	Trousers, long-sleeve shirt, suit jacket
	Trousers, long-sleeve shirt, suit jacket, vest, T-shirt
	Trousers, long-sleeve shirt, long-sleeve sweater, T-shirt
	Trousers, long-sleeve shirt, long-sleeve sweater, T-shirt, long underwear bottoms
	Knee-length skirt, short-sleeve shirt (sandals)
	Knee-length skirt, long-sleeve shirt, full slip
	Knee-length skirt, long-sleeve shirt, half slip, long-sleeve sweater
	Knee-length skirt, long-sleeve shirt, half slip, suit jacket
	Ankle-length skirt, long-sleeve shirt, suit jacket
	Long-sleeve coveralls, T-shirt
	Overalls, long-sleeve shirt, T-shirt
	Insulated coveralls, long-sleeve thermal underwear tops and bottoms

	Seated, reading, or writing
	Typing
	Filing, seated
	Filing, standing
	Walking about
	Lifting/packing

A.5 IEQ Spot Measurement Survey Form

IEQ Spot Measurement: Office Spaces		**Surveyor's Name**	**ID**
Date	**Time**	**Sky Condition**	**Room No.**
Total Number of Occupants	**Occupancy at the Time of Measurement**	**Thermostat Availability**	**Thermostat Setting**
Ceiling Lamp Type	**Task Lamp Type**	**All Sound Producing Equipments at the Time of Measurement**	
Sketch of a Simple Floor Plan of the Space (including windows, doors, furniture, luminaries, and occupant normal location)			

Spot Measurements							
Position No.		**1**		**2**		**3**	
Temp. (F)							
RH (%)							
Globe Temp. (F)							
Air Velocity (fpm)							
CO_2 (ppm)							
Lighting (fc)	Horizontal						
	Vertical						
SPL (dBA)							

Reflectance			
Wall	Floor	Ceiling	
Occupants' Clothing			
Group 1	Group 2	Group 3	Group 4
Occupants' Main Activity			
Group 1	Group 2	Group 3	Group 4

Note	

APPENDIX B
MARKET RESEARCH ON IEQ INSTRUMENTS

To select the appropriate sensors for the IEQ continuous monitoring cart, a survey was performed on the currently available equipment on the market. This appendix presents a summary table of the survey, including: sensor type, accuracy, resolution, response time, power consumption, measurement range, and cost information.

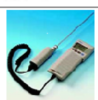
B.1 Instruments for Thermal Comfort: Temperature, RH, and Air Speed

B.2 Instruments for IAQ: CO_2, VOCs, and PM

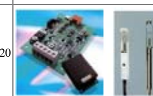
B.3 Instruments for Lighting: Illuminance and Luminance

B.4 Instruments for Acoustics: Sound Level Meter and Calibrator

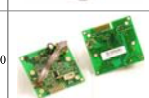
B.1 Instruments for Thermal Comfort: Temperature, RH, and Air Speed

Corporation	Name of Instruments	Model No.	Sensor Type	Accuracy	Resolution	Response Time	Power Consumption	Measurement Range	$ per	Image	Comments	Website
A. Temp./RH Sensors and Loggers												
Onset	HOBO XT temperature logger with external sensor	HOBO XT and TMCx-1T	Thermistor					5°C to +37°C, -37°C to +46°C, -39°C to +123°C	$99		Stores up to 1800 measurements TMCx-1T thermistor calbe: need an adapter for old-style temperature sensors (TMCx-1T-Adapter: $15)	www.onsetcomp.com
	HOBO-Temp./RH/Light/External	U12-012	10 K Thermistor	±0.7°F at 77°F (Temp.) / ±2.5% from 10 to 90% (RH) / 2 mV ± 2.5% of absolute reading (External Input)		6 min to 90% at 2.2 mph air flow (Temp.) / 1min (RH)		−4 -158°F (Temp.) / 5 - 95% (RH) / 1 -3,000 fc (Lighting) / 0 -2.5 VDC (External Input)	$130			
	HOBO-Temp./RH/2 External	U12-013	10 K Thermistor	±0.7°F at 77°F (Temp.) / ±2.5% from 10 to 90% (RH) / 2 mV ± 2.5% of absolute reading (External Input)		6 min to 90% at 2.2 mph air flow (Temp.) / 1min (RH)		−4 -158°F (Temp.) / 5- 95% (RH) / 0 -2.5 VDC (External Input)	$130		Two external channel	
	HOBO® "J,K,S,T Thermocouple" Data Logger with TC6-T (Type T 6 ft Beaded Thermocouple)	U12-014 & TC6-T	T-type thermocouple	T type: ±1.5°C (±2.7°F)				T type: -200 to 100 °C (-328° to 212°F)	$125 (Logger) + $19 (Thermocouple)		J, K, S, T thermocouple recordings; Automatic cold-junction compensation; Needs type T subminiature thermocouple connector ($9); TCW100-T (Type T 100 ft Thermocouple Wire): $59	
	HOBO LCD-Temp./RH	U14-001	Thermistor	±0.36°F from 32 to 122°F (Temp.) / ±2.5% from 10 to 90% (RH)		15 min to 90% at 2.2 mph air flow (Temp.) / 2min (RH)		−4 -122°F (Temp.) / 0 - 100% (RH)	$209		LCD display	
Lascar Electronics	USB High Accuracy Temp RH Data Logger	EL-USB-2+		±0.3°C (±0.6°F) / :±2.0% RH (20 to 80% RH)				: -35°C to 80°C (-31°F to 176°F) / : 0 to 100% RH	$110		32,758 Total Readings/Samples (16,382 Temperature and 16,382 Humidity Readings) / 103mm x 26.4mm (4.06" x 1.04")	http://www.lascarelectronics.com/temperaturedatalogger.php?location=us&datalogger=378
	USB Temperature Humidity LCD Data Logger	EL-USB-2-LCD		±0.5°C (±1.0°F) / ±3.0 %RH (20 to 80 %RH				: -35°C to 80°C (-31°F to 176°F) / : 0 to 100% RH	$97		32,758 Total Readings/Samples (16,382 Temperature and 16,382 Humidity Readings) / LCD display	http://www.lascarelectronics.com/temperaturedatalogger.php?location=us&datalogger=375
Vaisala	HMI 41 humidity and temperature indicator & HMP 42 Humidity and temperature probe	HMI 42 & HMP 42	PT 100 IEC 751 class B HUMICAP thin-film polymer sensor	±0.2°C / ±2.0 %RH (0 to 90 %RH) & ±3.0 %RH (90 to 100 %RH)		30 s (90%)		: -40°C to 100°C / : 0 to 100% RH	$1,120 (Indicator)+$350 (probe)		1500mm (59.1") spiral cable; thinnest probe (4mm (0.16") diameter) / Steel grid and membrane filter for sensor protection / data logging of 200 readings	http://www.vaisala.com/instruments/products/dc-hmi41.html
	Humidity and Temperature Transmitters	HMD 60Y	Pt 1000 IEC 751 class B; Vaisala HUMICAP® 180 capacitive thin-film polymer sensor	± 0.2°C at 20°C (Temp); ±2%RH (0...90%)			10 mA (typical) at 24 VAC	−4 -176°F (-20°C to 80°C) / 0 -100% RH	$500		2-wire, 4 to 20 mA output	http://www.vaisala.com/instruments/products/hf-hmdw6070.html

Corporation	Name of Instruments	Model No.	Sensor Type	Accuracy	Resolution	Response Time	Power Consumption	Measurement Range	$ per	Image	Comments	Website
A. Temp./RH Sensors and Loggers ***(Continued)***												
Vaisala	Vaisala Humidity and Temperature Probe	HMP45A	Pt 1000 IEC 751 class B; Vaisala HUMICAP® 180 capacitive thin-film polymer sensor	±0.2°C at 20°C (Temp); ±2% RH (0 to 90% Relative Humidity)		15 s (RH)	< 4mA	−39.2°C to +60°C / 0.8 - 100% RH	$595		Sensor protection: 0.2 µm Teflon membrane filter (par no. 2787HM)	http://www.vaisala.com/weather/products/qmh101-102.html
	Vaisala Temperature and RH sensor	HMP50-L	1000 Ω PRT, DIN 43760B; Vaisala INTERCAP®	±0.3°C at 0°C (Temp); ±3% RH (0 to 90% Relative Humidity)		15 s (RH)		−40°C to +60°C / 0 - 98% RH	$425			
T&D Corporation	TR-72U Thermo Recorders-with TR-3100 Temp./RH Sensor	TR-72U & TR-3110	Thermistor / Macromolecular Humidity Sensor	±0.3°C from 0 to 50°C (Temp.)/ ±5%RH at 50%RH (RH)				0 -50°C (Temp.)/ 10 - 95% (RH)	$300 (Logger)+$95 (sensor)		Made in Japan/ LCD display	http://www.tandd.com/
B. External Temperature Sensor for Globe Temperature												
Onset	TMC1-HD: Air/Water/Soil Temp Sensor (1' cable)	TMC1-HD	Thermistor	±0.45°F at 68°F		3 min to 90% at 2.2 mph air flow (Temp.)		−40 -212°F (Temp.in Air)	$29		Compatible w/ HOBO U12 series	www.onsetcomp.com
T&D Corporation (JAPAN)	TR0106: TPE Resin-Shielded Sensor for Globe Temp. (0.6 m)	TR-0106	Thermistor	±0.3°C (-20 to 80°C) and ±0.5°C(-40 to -20°C / 80 to 110°C)				−40 -110°C (Temp.)			Compatible w/ TR-72U	http://www.tandd.com/
	38mm-Diameter Ping-pong Ball Painted Gray with the TR-0106 Sensor		Thermistor								Photo: TR 0106 sensor and black ping-pong ball	
Omega	T type thermocouple Wire Special Limits of Error	GG-T-20-SLE-1000	T type thermocouple	±0.5°C (0.4%) or higher			No	−0 -350°C (Temp.)	$0.43/ ft.		1000 ft., Type T, 20 AWG, Fiberglass Insulated Thermocouple Wire, Special Limits of Error	http://www.omega.com/pptst/SLE_Wire.html
Campbell	T type thermocouple	105E-L	T type thermocouple				No	−270 -400°C (Temp.)	$1.03/ ft.			
C. Surface Temperature Meter												
Rayteck	Raytek Infrared Thermometer MT-4	MT-4		±2% or ±3.5°F (greater one) (30 to 525°F) and ±5°F (0 to 30°F)		500 mSec		0 -750°F (Temp.)	$105		Instant readings / Laser point	www.raytek.com

Corporation	Name of Instruments	Model No.	Sensor Type	Accuracy	Resolution	Response Time	Power Consumption	Measurement Range	$ per	Image	Comments	Website
D. Air Velocity Transducers and Meters												
Testo	Testo 416: Vane Anemometer with Cabled Telescopic Vane Probe	Testo 416		±(40 fpm +1.5% of rdg.)				118 to 8,000 fpm	$640		Calculate cfm	http://www.testo.us/online/abaxx-?$part=PORTAL.USA.ProductCategoryDesk&$event=show-from-menu&categoryid=2734742
TSI Incorporated	Model 8455 Air Velocity Transducer	8455	Protected probe tip (8455)	±2% of reading at 68.0-82.4°F (20 to 26°C), ±0.5% of full scale of selected range	0.07% of selected full scale	0.2 seconds		25 to 200 ~ 10,000 fpm (0.125 to 1.0 ~ 50 m/s), selectable	$775		Fast response time / Wide range of measurement applications	http://www.tsi.com/en-1033/products/2336/air_velocity_transducers/14014/8455.aspx
TSI Incorporated	Model 8475 Air Velocity Transducer	8475	Omnidirectional probe tip (8475)	±3% of reading at 68.0-82.4°F (20 to 26°C), ±1% of full scale of selected range	0.07% of selected full scale	5.0 seconds		10 to 100 ~ 500 fpm (0.05 to 0.5 ~ 2.54 m/s), selectable	$1,375		Accurate at low velocities from 10 to 100 ft/min	http://www.tsi.com/en-1033/models/14018/8475.aspx
Kanomax	Airflow Transducer Model 6312 + Probe (0941 or 0942)	6312		±30 fpm (0.15 m/s)				20 to 394 fpm (0.1 to 2.0 m/s)	$520			http://www.kanomax-usa.com/anemometer/6312/6312.html
Kanomax	Airflow Transducer Model 6332 + Probe (0964-01/02)	6332	Omni-directional (Needle)	± (3% of reading + 0.1) m/s; ±30 fpm (20 – 1000 fpm)		3.0 seconds	Approx. 2.0W	20 – 10000 fpm (0.1 – 50 m/s)	$790			http://www.kanomax-usa.com/anemometer/6332/6332.html
Kestrel	Kestrel® 3000 Pocket Wind Meter	Kestrel®		Larger than ±3% (Wind Speed)/ ±1.8°F (Temp.)/ ±3.0%RH (RH)		1 sec.		59 to 7877 fpm (Wind Speed)/-20 to 158 °F (Temp.)/ 5 to 95 % (RH)	$149		Measure Temp./RH. Calculate Wind Chill/Heat Index/Dew Point.	http://www.nkhome.com/ww/selector/

B.2 Instruments for IAQ: CO_2, VOCs, and PM

Corporation	Name of Instruments	Model No.	Sensor Type	Accuracy	Resolution	Response Time	Power Consumption	Measurement Range	$ per	Image	Comments	Website
A. CO_2 Sensors and Meters												
Telaire	Telaire 7001 CO2 Sensor	TEL-7001	Dual Beam Absorption Infrared™ / Sample method:Diffusion or flow through (50 - 100 ml/min)	±50 ppm or ±5% reading up to 5,000 ppm / ± 2°F (± 1°C)	±1 ppm / ± 0.1°F	<60 seconds to 90% of step change /20~30min temp.		0 to 10,000 ppm, 32°F to 122°F display / 0 to 4,000 ppm, 32°F to 104°F voltage output	$465		4 AA batteries (80 h) /HOBO CABLE-CO2 ($29)	http://www.onsetcomp.com/products/sensors/tel-7001
	Telaire Ventostat 8002	Ventostat 8002	Single Beam Absorption Infraredd™ / Sample method:Diffusion	±100 ppm or ±7% reading		<60 second	1.75 VA average, 2.75 VA peak	0 to 10,000 ppm	$299			http://www.gesensing.com/products/telaireco2sensorswallmount.htm
	Telaire Airestat CO2 Temperature Transmitter	T5001	Non-dispersive infrared (NDIR), gold plated optics, (with Telaire's patented ABC Logic self calibration algorithm) /NTC 20k thermistor	±75 ppm at 72 F or ±10% reading		3 to 5 minutes for 90% step change	1.75 VA average, 2.75 VA peak	0 to 2,000 ppm	$241		Diffusion sampling	http://www.gesensing.com/products/telairet5000.htm?bc=bc_ge_telaire
SenseAir® (Sweden)	pSense-RH Portable CO2 Meter	pSense-RH	Non-dispersive infrared (NDIR) technology with gold plated optical cell / Gas sampling method:Diffusion	±30 ppm ±5% of reading (0 ~ 5000 ppm) / ±0.6C/±0.9F, ±3% RH (10 ~ 90 %)		about 30 seconds		0-5000 ppm / 14~140F (-10~60C) / 0~99.9%	$ 460 / $ 500 (with data logger kit, including adapter)		CO2, Temp and RH% /4 AA batteries 24 hours or adapter / weighted average (8 hours, 15 min)	http://www.senseair.se/includes/products/psense_rh.php
Vaisala	Vaisala GMM112 Carbon Dioxide Module	GMM112	silicon based NDIR sensor	± (2.5 % of range + 3 % of reading)		1 min		0 … 2000 ppm, 0 … 5000 ppm			24 VDC/VAC power supply / Outputs 4 ... 20 mA, 0 ... 10 V	http://www.vaisala.com/instruments/products/gmm112.html
	Vaisala GMP343 Carbon Dioxide Sen	GMP343	Single-beam, dual-wavelength CO2 / Sample method:Diffusion or flow through (10l/min)	0 ... 1000 ppm: ±(3 ppm + 1 % of reading) 0 ... 2000 ppm : ±(5 ppm + 2 % of reading)		2~80 seconds		0~1000 ppm, 0~2000 ppm, 0~3000 ppm, 0~4000 ppm, 0~5000 ppm, 0~2 %	$2,640		Voltage output:range 0 ... 2.5 V, 0 ... 5 V / Current output: range 4 ... 20 mA	http://www.vaisala.com/instruments/products/gmp343.html#tab2Cont
SenseAir® (Sweden)	K-22 LO CO2 Sensor 0-2,000ppm	K22-LO	non-dispersive infrared (NDIR) waveguide technology with ABC long term drift compensation / Gas sampling method:Diffusion	± 75 ppm + 5% of measured value				0 to 2000 ppm	$100		0 to 5V = 0 to 2 000 ppm	http://www.co2meter.com/collections/co2-sensors/products/k-22-lo-co2-sensor-module
	K-30 CO2 Sensor 0-10,000ppm	K-30	non-dispersive infrared (NDIR) waveguide technology with ABC automatic background calibration algorithm/ Gas sampling method:Diffusion	± 30 ppm ± 5 % of measured value		20 seconds diffusion time		0 – 2,000 ppm analog output / 0-10,000 ppm (custom configuration required)	$125 / $175 (with USB)		Linear Conversion Range: 1 - 4 VDC for 0 - 5 000 ppmvol., with 0,5 VDC used as FAULT status signal	http://www.co2meter.com/collections/co2-sensors/products/k-30-co2-sensor-module

Corporation	Name of Instruments	Model No.	Sensor Type	Accuracy	Resolution	Response Time	Power Consumption	Measurement Range	$ per	Image	Comments	Website
B. Other IAQ Sensors and Meters, including CO, VOCs, PM												
Lascar Electronics	USB Carbon Monoxide Data Logger	EL-USB-CO		± 6% of Reading		1 Minute (90%)		0 to 10,000 ppm CO	$96		32,510 Samples/Readings	http://www.lascarelectronics.com/temperaturedatalogger.php?location=us&datalogger=104
ECO SENSORS, INC.	VOC GAS SENSOR Model C-21	ECOC21-000				Within one minute		50-100 ppm for most solvent based VOCs	$326		HMOS (heated metal oxide semiconductor) sensor / AC adapter 0-2 volt output	http://www.ecosensors.com/c21.html
RAE Systems	ppbRAE 3000 VOC Detector Monitors	ppbRAE Plus Model PGM-7340				< 3sec		1 ppb to 9,999 ppm	$6,325		Photo-isonisation sensor with super bright 10.6eV / 6 month data logging (1 min-interval)	http://raesystems.thomasnet.com/item/pid-2/ppbrae-3000-monitor/pn-2511?&seo=110&plpver=1001
RAE Systems	ppbRAE Plus VOC Detector Monitors	ppbRAE Plus Model PGM-7240				< 5sec		1 ppb to 2,000 ppm	$6,870		Photo-isonisation sensor with super bright 10.6eV / optional data logging of 267 hours (1 min-interval)	http://raesystems.thomasnet.com/item/pid-2/ppbrae-plus-monitors-pgm-7240-/item-6961?&seo=110&plpver=1001
Photovac.Inc	Photovac 2020 ComboPro	2020ComboPRO				< 3sec		0.1 to 10,000ppm	$2,495		Photo-isonisation sensor with super bright 10.6eV / datalogging of 200 hours (1 min-interval)	http://www.photovac.com/2020ComboPRO.aspx
TSI Incorporated	TSI DustTrak™ 8520 Aerosol Particulate Monitor	Model 8520		±0.1% of reading or ±0.001 mg/m3, whichever is greater				0.001 to 100 mg/m3 (Calibrated to ISO 12103-1, A1 test dust)			Measure particle concentrations corresponding to PM10, PM2.5, PM1.0 / Battery-operated (16 hours) with a built-in data logger (21 days of logging once/minute)	http://www.tsi.com/en-1033/products/14000/dusttrak%E2%84%A2_aerosol_monitors.aspx
TSI Incorporated	TSI DUSTTRAK™ II Aerosol Monitor	Model 8530/8531		±0.1% of reading or 0.001 mg/m3, whichever is greater				Model 8530=0.001 to 150 mg/m3 / Model 8531=0.001 to 400 mg/m3	$322 per week / $918 per month		Measure particle concentrations corresponding to PM10, PM2.5, PM1.0 / Battery-operated (12 hours) with a built-in data logger (45 days of logging once/minute)	http://www.tsi.com/en-1033/products/14000/dusttrak%E2%84%A2_aerosol_monitors.aspx

B.3 Instruments for Lighting: Illuminance and Luminance

Corporation	Name of Instruments	Model No.	Sensor Type	Accuracy	Resolution	Response Time	Power Consumption	Measurement Range	$ per	Image	Comments	Website
A. Illuminance and Luminance Sensors and Meters												
Konica Minolta	T-10/ T-10M Illuminance Meter	T-10 /T-10M		V(λ) within 8% (f1') ±2% ±1digit of displayed value				0.01 to 299,900 lx, (0.001 to 29,990 fcd)	$940 / $1213		T-10: Standard receptro head / T10M: Mini receptor head for small spaces	http://www.konicaminolta.com/instruments/products/light/illuminance-meter/t10/index.html
Extech Instruments	Extech HD450-NIST Heavy Duty Datalogging Light Meter with NIST Certificate	HD450NIST		± 5% rdg				0 to 400,000 LUX	$325		16,000 continuous readings; 99 selected readings (manual)	http://extechinstruments.com/instruments/product.asp?catid=10&prodid=57
	EasyView Light Meter with Memory: Model EA33	Model EA33		Vλ function (f'1 ≤6%) ± (3% rdg + 5 digits)				0 to 999,900 LUX (3 range)	$260		50 selected readings (manual)	http://extechinstruments.com/instruments/product.asp?catid=10&prodid=63
Li-cor	LI-210 Photometric Sensor	LI-210SA		CIE curve within ± 5%		10 µS			$ 420 (BNC Connector) / $480 (Millivolt Adapter)		Accessaries: 2290 Millivolt Adapter 604 Ohms ($40)/ 2003S Mounting and Leveling Fixture ($52)/ Cosine Correction	http://www.licor.com/env/Products/Sensors/210/li210_description.jsp
	LI-250A Light Meter	LI-250A		25°C: Typically ± 0.4% of reading ± 3 digits on the least significant digit displayed (all ranges). 0 – 55°C: Typically ± 0.6% of reading ± 3 digits on the least significant digit displayed (all ranges).		10 µS			$675			http://www.licor.com/env/Products/Sensors/250A/li250A_introduction.jsp
Konica Minolta	LS-100 Luminance Meter	LS-100		V(λ) within 8% (f1') 0.001 to 0.999cd/m2 (or fL): ±2% ±2 digits of displayed value 1.000cd/m2 (or fL) or greater: ±2% ±1 digit of displayed value				FAST: 0.001 to 299,900cd/m2 (0.001 to 87,530fL) SLOW: 0.001 to 49,990cd/m2 (0.001 to 14,590fL)	$3,302		1° angle of measurement	http://www.konicaminolta.com/instruments/products/light/luminance-meter/ls100-ls110/index.html
	LS-110 Luminance Meter	LS-110		V(λ) within 8% (f1') 0.01 to 9.99cd/m2 (or fL): ±2% ±2 digits of displayed value 10.00cd/m2 (or fL) or greater: ±2% ±1 digit of displayed value				FAST: 0.01 to 999,900cd/m2 (0.01 to 291,800fL) SLOW: 0.01 to 499,900cd/m2 (0.01 to 145,900fL)	$3,302		1/3° narrow angle of measurement (perfect for smaller surface)	http://www.konicaminolta.com/instruments/products/light/luminance-meter/ls100-ls110/index.html

B.4 Instruments for Acoustics: Sound Level Meter and Calibrator

Corporation	Name of Instruments	Model No.	Sensor Type	Accuracy	Resolution	Response Time	Power Consumption	Measurement Range	$ per	Image	Comments	Website
A. Sound Pressure Level Meters and Calibrators												
Pacific Sensor Technologies	PST-C320 Sound Level Meter	C320		±1.5dB(ref 94dB@1KHz)		Fast/slow response time		30-130 db	$256 (325 AUD)		IEC 651 Type 2 / A&C weighting / AC/DC Output /External Power	https://www.pacificsensortech.com.au/product/86/PST-C320-Sound-Level-Meter.html
	PST-C322 Sound Level Data Logger	C322		:t 1.5dB(ret 94dB@1KHz		Fast/slow response time		30-130 db	$345 (437 AUD)		IEC 651 Type 2 / A&C weighting / AC/DC Output /External Power / 32,000 RecordsDatalogger	https://www.pacificsensortech.com.au/product/169/PST-C322-Sound-Level-Data-Logger.html
	PST-C326 Sound Level Calibrator	C326		Understated reference environment conditions (23C 50%RH 101.325 kpa) +/- 0.5dB				94dB / 114dB	$276 (350 AUD)		94/114dB models 1kHz sine wave	https://www.pacificsensortech.com.au/product/6/PST-C326-Sound-Level-Calibrator.html
Brüel & Kjær Sound & Vibration (Denmark)	2240 Integrating-averaging Sound Level Meter	Type 2240		ANSI S1.4 Type 1 (0.1 dB resolution)		Fast		30 – 140 dB	around $1,500		ANSI S1.4 Type 1 / LAeq, LAFmax, LCpeak and LAF / Measurement times between 1 s and 60 min / NOISE FLOOR < 22 dB	http://www.bksv.com/Products/SoundLevelMeters/BasicSoundLevelMeters/2240SoundLevelMeter.aspx
	2250 Light	Type 2250		ANSI S1.4 Type 1		Fast		16.4 - 140 dB	around $3,500		ANSI S1.4 Type 1 / Laeq, Ocatave, 1/3 Octave	http://www.bksv.com/Products/SoundLevelMeters/AdvancedSoundLevelMeters/2250Light.aspx
Testo	testo 815	815		±1.0dB with 0.1dB resolution				32 - 130 dB	$423		ANSI S1.4 Type 2 / A&C weighting/ Battery operated (70h) / Time weighting	http://www.testo.us/online/abaxx-?$part=PORTAL.USA.ProductCategoryDesk.active-area.catalog.ProductDetail.details.technical%20data
	testo 816	816		±1.0dB with 0.1dB resolution				30 - 130 dB	$811		A&C weighting/ Battery operated (50h) / Power supply/ AC/DC output: DC 10 mV/dB	http://www.testo.us/online/abaxx-?$part=PORTAL.USA.SectorDesk&$event=show-from-menu&categoryid=2734238
01dB-METRAVIB (France)	SOLO Sound Level Meter (SLM)	SOLO SLM		ANSI S1.4 Type 1				30-137 dB(A)	$6,000 / $360 month (Rent)		ANSI S1.4 Type 1 / Laeq, Ocatave, 1/3 Octave	http://www.01db-metravib.com/environment.13/products.16/sound-level-meters.187/?L=1
	Blue SOLO	Blue SOLO		ANSI S1.4 Type 1				20-137 dB(A) / class 1; 30-137 dB(A) / Class 2			ANSI S1.4 Type 1 / Laeq, Ocatave, 1/3 Octave	http://www.01db-metravib.com/environment.13/products.16/sound-level-meters.187/?L=1

Corporation	Name of Instruments	Model No.	Sensor Type	Accuracy	Resolution	Response Time	Power Consumption	Measurement Range	$ per	Image	Comments	Website
A. Sound Pressure Level Meters and Calibrators *(Continued)*												
TES	TES-1350 Sound Level Meter (Discontinued)	1350		±2dB	0.1 db	Fast/slow response time		35-100 db; 65-130 db	$216		IEC 651 Type2; Electret condenser microphone; 31.5Hz to 8KHz;	http://www.tes-meter.com/tes1350.htm
Extech	Extech 407730 Digital Sound Level Meter	407730		±2dB accuracy	0.1 db	Fast: 125 milliseconds / Slow: 1 second		40-130 db	$89		A&C weighting / Battery operated (30 h) / AC analog output: 0.707Vrms at Full Scale	http://www.instrumart.com/Product.aspx?ProductID=24235&gclid=CM-fxrbv85oCFRYiagodFH66eQ
	Extech 407740 Sound Level Meter	407740		±1.5dB at 1KHz (94dB)	0.1 db	Fast: 200 milliseconds / Slow: 500 milliseconds		30-130 db	$249		ANSI S1.4 Type 2 /A&C weighting / 9VBattery operated / Output AC: 0.5Vrms at FS, DC: 0.3 to 1.3VDC, 10mV/dB	http://www.instrumart.com/Product.aspx?ProductID=25212
	Extech 407764 Datalogging Sound Level Meter	407764		±1.5dB	0.1 db	Fast: 125 milliseconds / Slow: 1 second		30-130 db	$599		ANSI S1.4 Type 2 / A&C weighting / 128,000 records / 9VBattery operated / Output AC: 0.707Vrms at FS, DC: 0.3 to 1.3VDC, 10mV/dB / AC adapter	http://www.instrumart.com/Product.aspx?ProductID=25214
	Extech 407780 Integrating Sound Level Datalogger	407780		±1.5dB	0.1 db	Fast: 125 milliseconds / Slow: 1 second		30-130 db	$1,124		ANSI S1.4 Type 2 / A&C weighting / 128,000 records / Battery operated / Output AC: 2Vrms at FS, DC: 0.3 to 1.3VDC, 10mV/dB / AC adapter/SPL, SEL, Lmax/Lmin and Leq	http://www.extech.com/instruments/product.asp?catid=18&prodid=243
	Extech 407790 Real Time Octave Band Analyzer	407790		±1.5dB (ref 94dB @1kHz)	0.1 db	Fast/slow response time		30-130 db	$3,599		ANSI S1.4 Type 2 / A&C&P weighting, Ocatave, 1/3 Octave / 10,000 records / Battery operated (2h) / Output AC: 2Vrms at FS, DC: 0.3 to 1.3VDC, 10mV/dB / AC adapter	http://www.instrumart.com/Product.aspx?ProductID=24273
	Extech 407744/407766 Sound Calibrator	407744 (94dB) /407766 (94/114dB)		Accuracy of 5% (frequency) and ±0.5dB at 94 dB (±0.8dB at 114dB)				94dB / 114dB	$299		94/114dB models 1kHz sine wave	http://www.instrumart.com/Product.aspx?ProductID=24285

APPENDIX C
CALIBRATION OF MEASURING INSTRUMENTS

This appendix presents the detailed calibration/verification procedures and results for the devices used in a comprehensive instrumentation cart developed in this study with the exception of the two new sensors calibrated by the manufacturer[239]. The instruments calibrated in this study include T-type thermocouples (C-1), and T-type thermocouples inside radiation shields for air temperatures (C-2), T-type thermocouples inside 38 mm-diameter table tennis balls painted gray for globe temperatures (C-3), Vaisala HMP45A humidity and temperature probe (C-4), Telaire 7001 CO_2 sensor (C-5), Licor LI-210 photometric sensors (C-6), and Extech 407780 and TES 1350 sound level meters (C-7).

C.1 T-Type Thermocouples

C.2 T-Type Thermocouples inside Radiation Shields for Air Temperatures

C.3 T-Type Thermocouples inside 38 mm-Diameter Table Tennis Balls Painted Gray for Globe Temperatures

C.4 Vaisala HMP45A Humidity and Temperature Probe

C.5 Telaire 7001 CO_2 Sensor

C.6 Licor LI-210 Photometric Sensors

C.7 Extech 407780 and TES 1350 Sound Level Meters

[239] This study did not perform an additional calibration for the two new sensors calibrated by the manufacturer, including TSI 8455 air velocity transducer for air velocity; and Eco Sensors VOC gas sensor C‑21 for VOCs level. To calibrate thermal anemometers (i.e., the probe of TSI 8455), a special wind tunnel facility that can be operated at a fixed air velocity and temperature is required. The basic mechanism is a comparison of the readings with a reference air velocity measured using the NIST-calibrated anemometers. The VOC gas sensor can be calibrated against a known concentration of gas mixture. The calibration can be performed by flowing gas to the sensor without cooling the sensor.

C.1 T-Type Thermocouples

To accomplish a calibration of T-type thermocouples for air and globe temperatures, two standards were referenced: the American Society for Testing and Materials (ASTM) Standards E77-07 (2007a) and E220-07a (2007b). The basic calibration mechanism used in this study is a comparison of the thermocouple readings against the readings of reference thermometers, including the ASTM certified liquid-in-glass thermometers and the calibrated Resistance Temperature Detector (RTD) temperature sensors, under controlled temperature environments (i.e., cold temperature mode, room temperature mode, and hot temperature mode). The RTD sensors were calibrated first against the ASTM certified liquid-in-glass thermometers under controlled temperature environments, including an ice point (Figure C-1).

To create controlled temperature environments, the thermocouples and reference thermometers were immersed in distilled water inside a glass container. The container was then placed inside a refrigerator, as shown in Figure C-2. For a cold temperature mode, the refrigerator was on, while for room temperature and hot temperature modes, the refrigerator was off. For a hot temperature mode, a 60W incandescent lamp was additionally used to produce heat inside the refrigerator. To maintain uniform thermal environments inside the refrigerator, a small fan was run during the procedures.

Figures C-3 and C-4 show the calibration results of the two RTD sensors, including a comparison of the RTD temperature readings against the reference temperatures before and after calibration as well as the residual plots before and after calibration. Figures C-5 through C-15 show the calibration results of the ten thermocouples, including an overall comparison of the temperature readings of all ten thermocouples against the reference temperatures that varied between 40 F and 95 F (Figure C-5); and individual residual plots of the ten thermocouples (Figures C-6 to C-15).

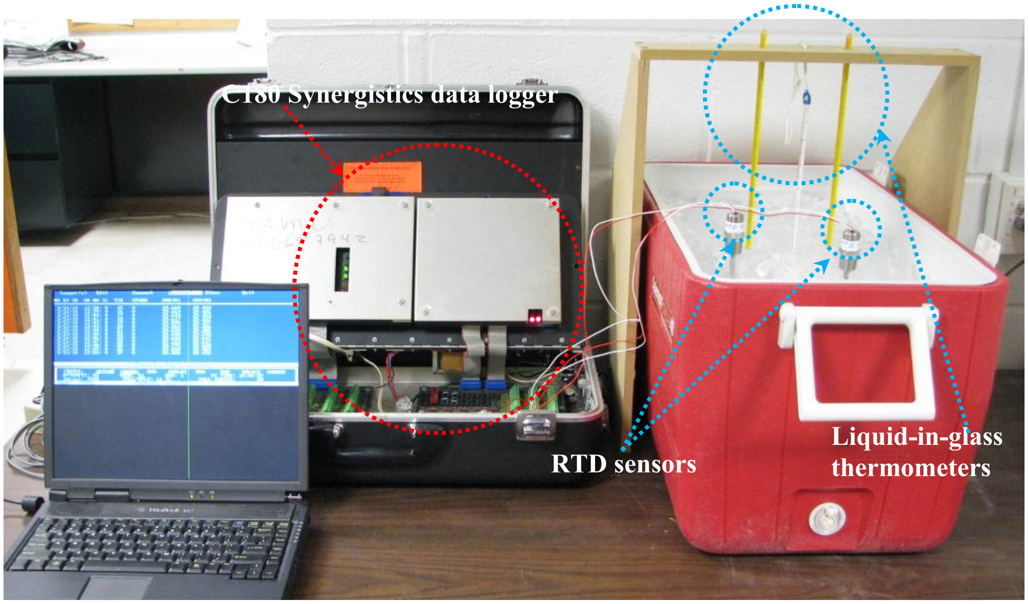


Figure C-1: Experimental Setting for the Calibration of the Two RTD Sensors against the Three ASTM Certified Liquid-In-Glass Thermometers for an Ice Point Test

60W incandescent lamp heat source

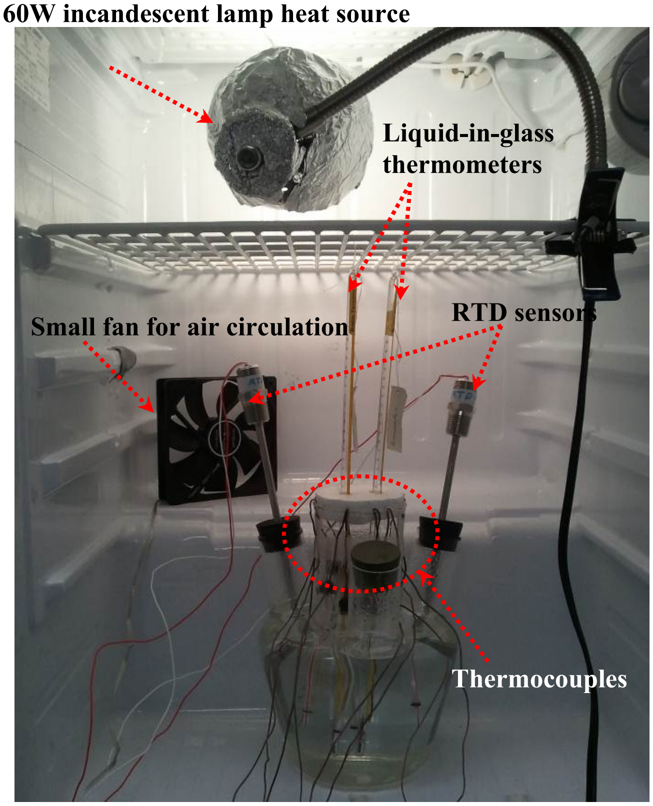
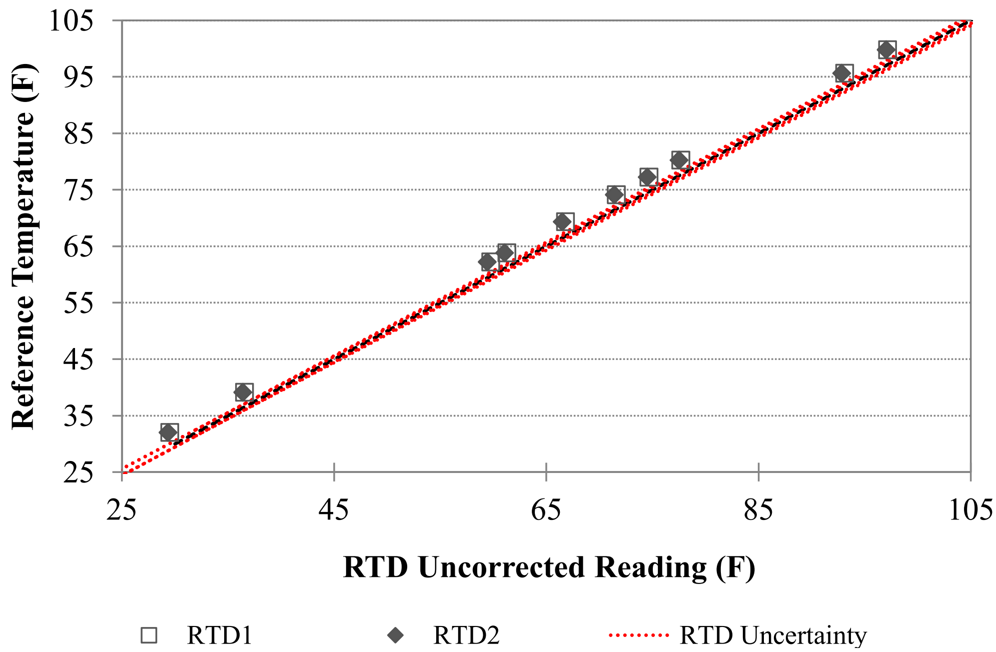
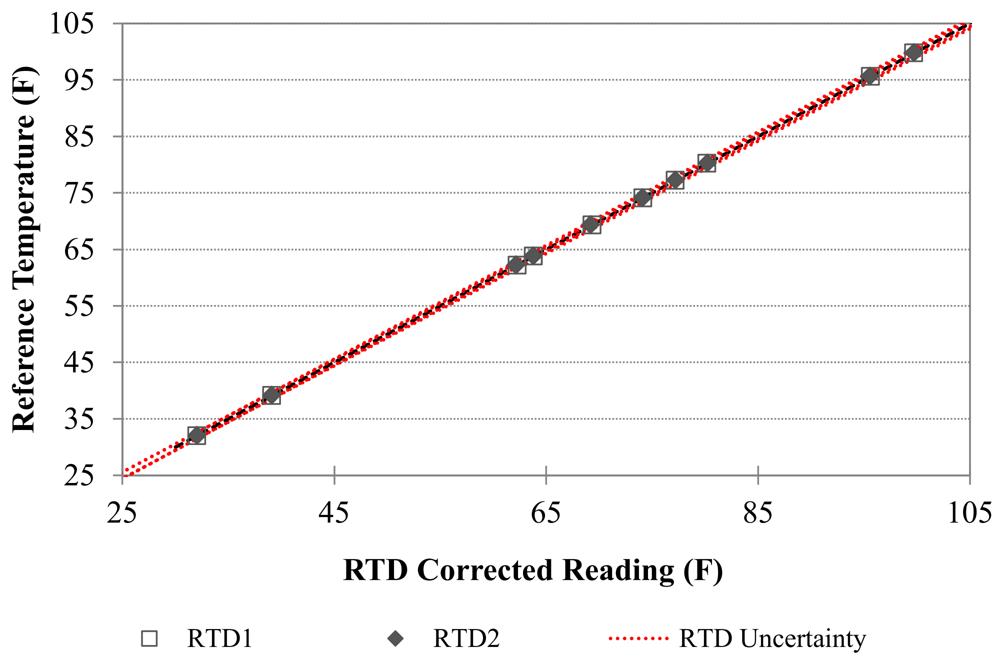


Figure C-2: Experimental Setting for the Calibration of the Ten Thermocouples against the Two ASTM Certified Liquid-In-Glass Thermometers as well as the Two Calibrated RTD Sensors

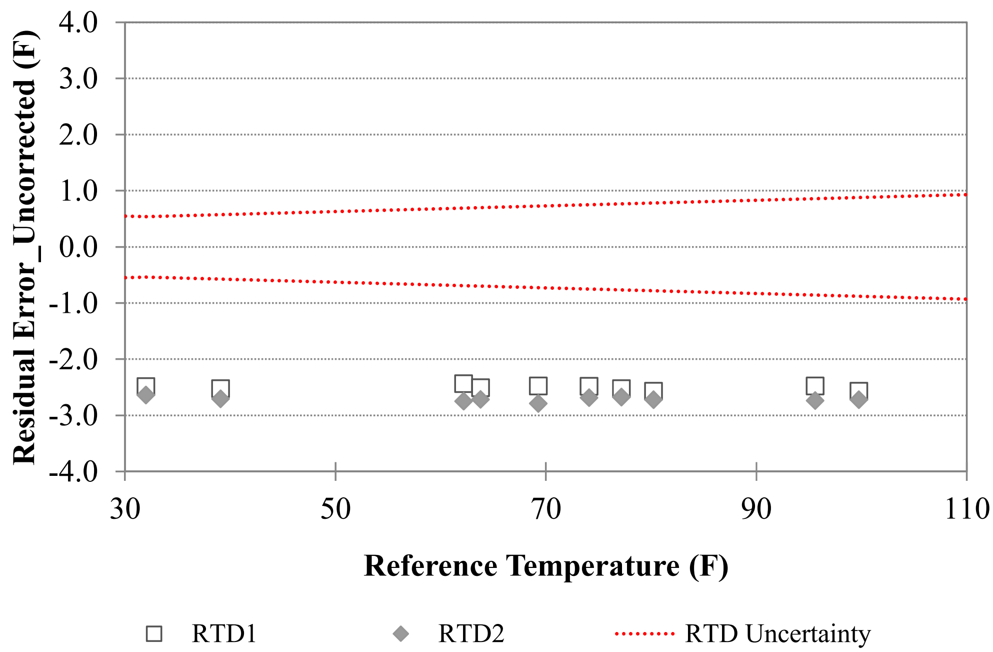


(a) Uncorrected Comparison (Before Calibration)

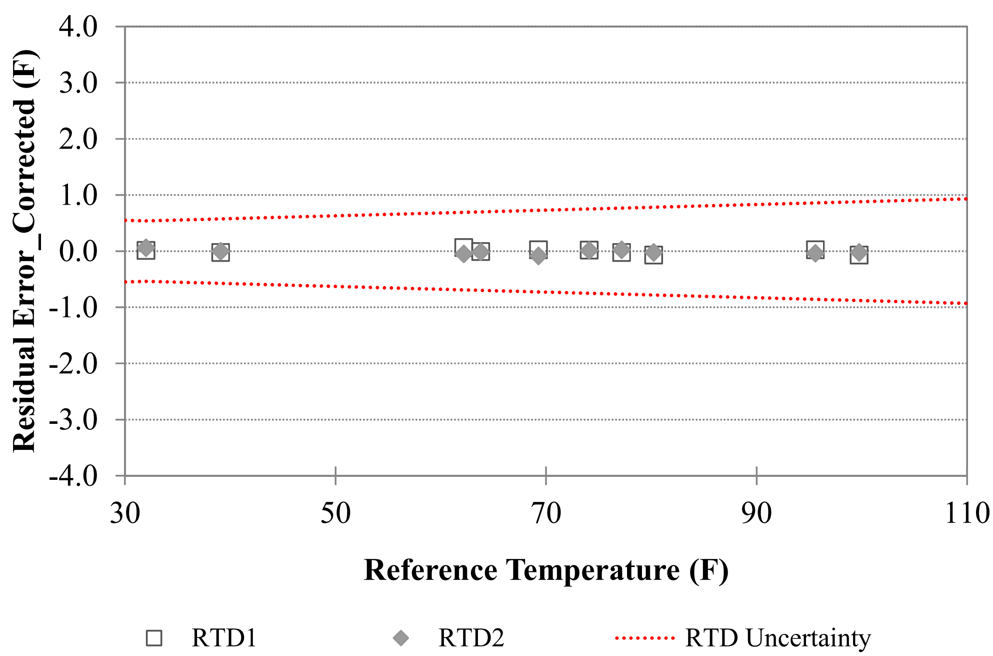


(b) Corrected Comparison (After Calibration)

Figure C-3: Comparison of the RTD Temperature Readings against the Reference Temperatures from 32 F to 100 F



(a) Uncorrected Residuals (Before Calibration)



(b) Corrected Residuals (After Calibration)

Figure C-4: RTD Temperature Residual Plot with the Manufacturer Specified Sensor Accuracy

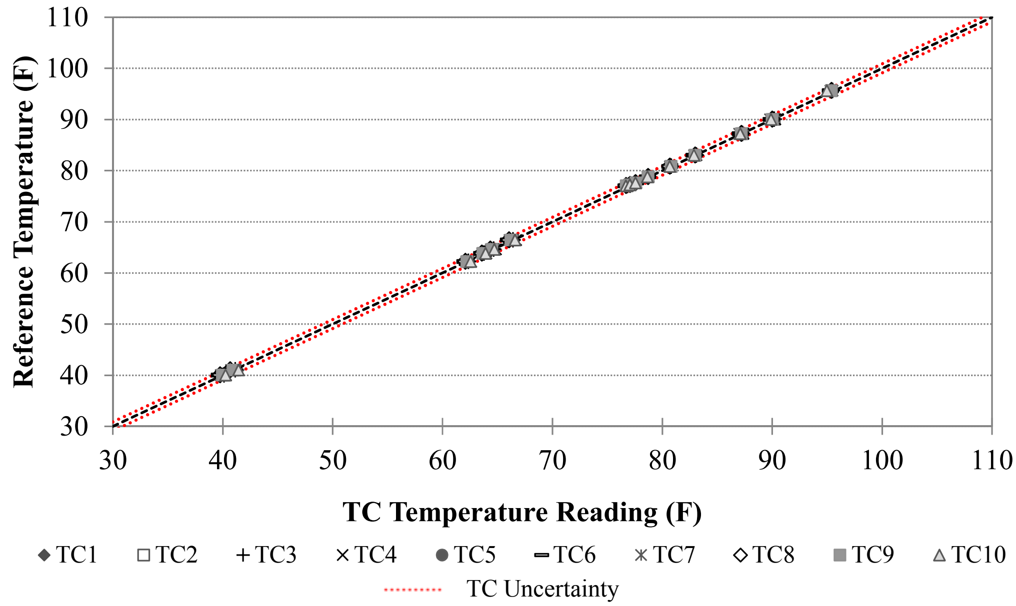


Figure C-5: Comparison of the Temperature Readings of the Ten Thermocouples (TC) against the Reference Temperatures from 40 F to 95 F

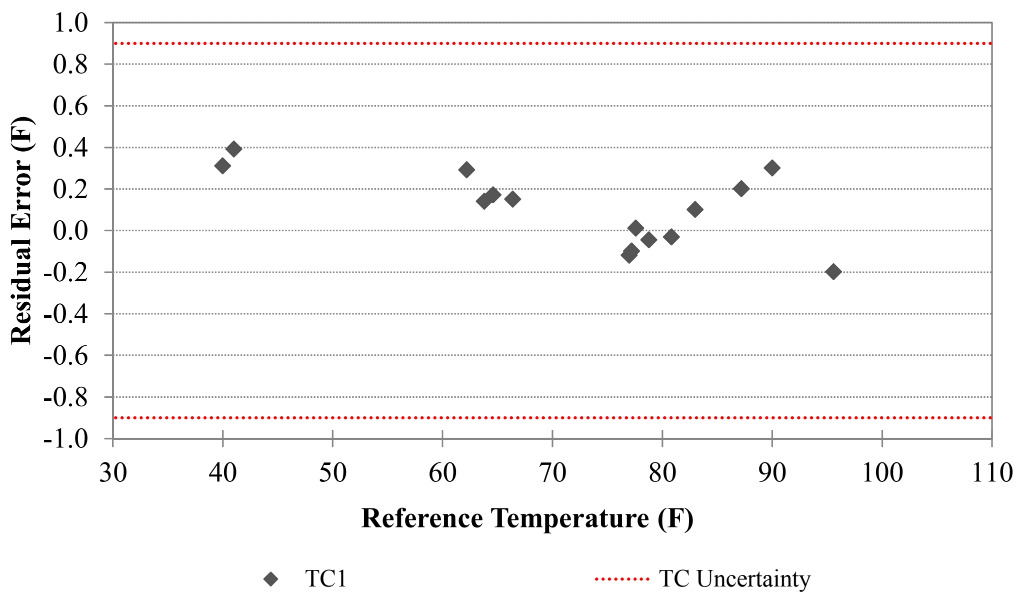


Figure C-6: Residual Plot of Thermocouple No.1 (TC1) with the Manufacturer Specified Sensor Accuracy (±0.9 F)

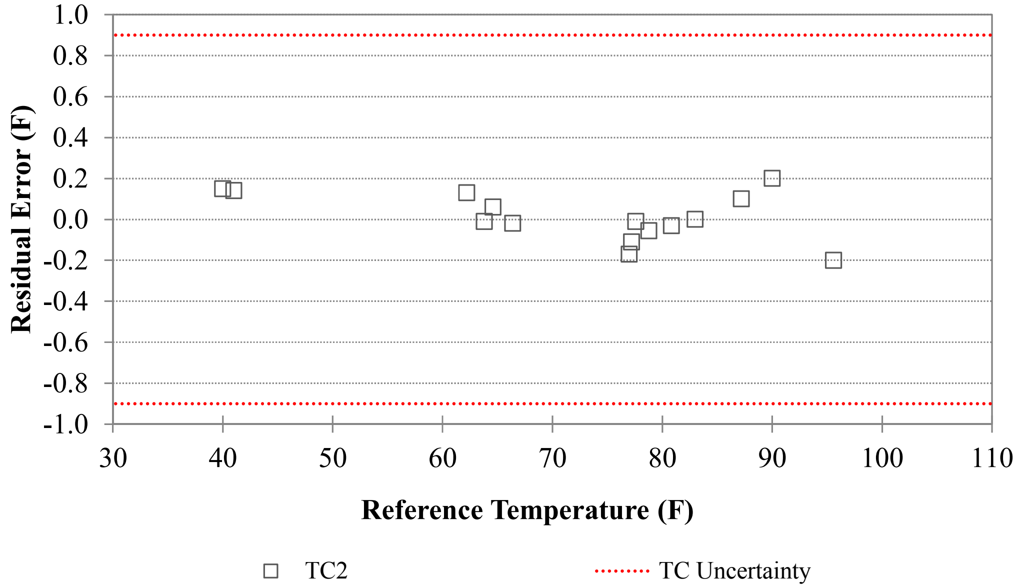


Figure C-7: Residual Plot of Thermocouple No.2 (TC2) with the Manufacturer Specified Sensor Accuracy (±0.9 F)

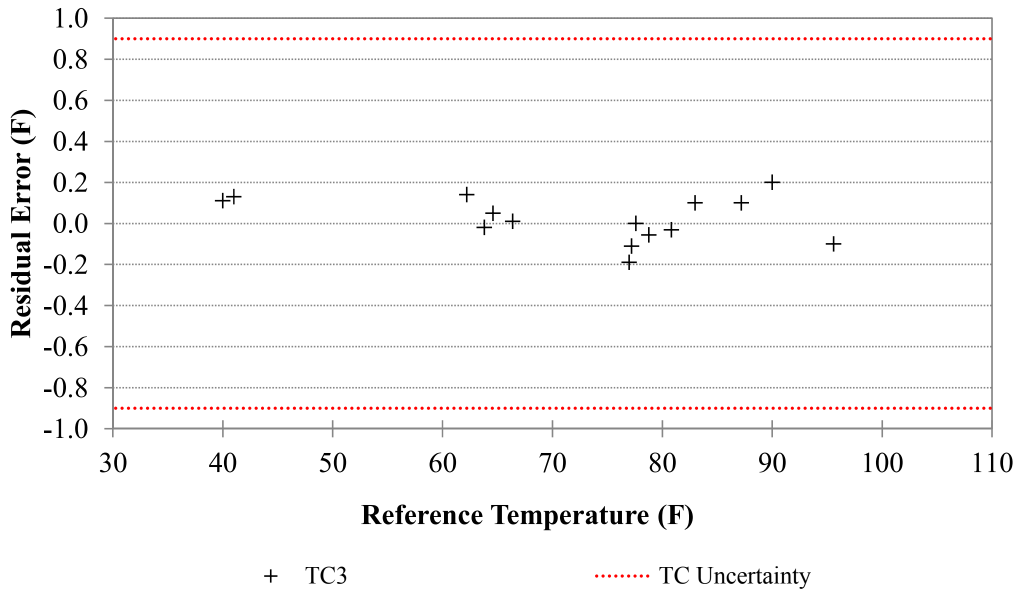


Figure C-8: Residual Plot of Thermocouple No.3 (TC3) with the Manufacturer Specified Sensor Accuracy (±0.9 F)

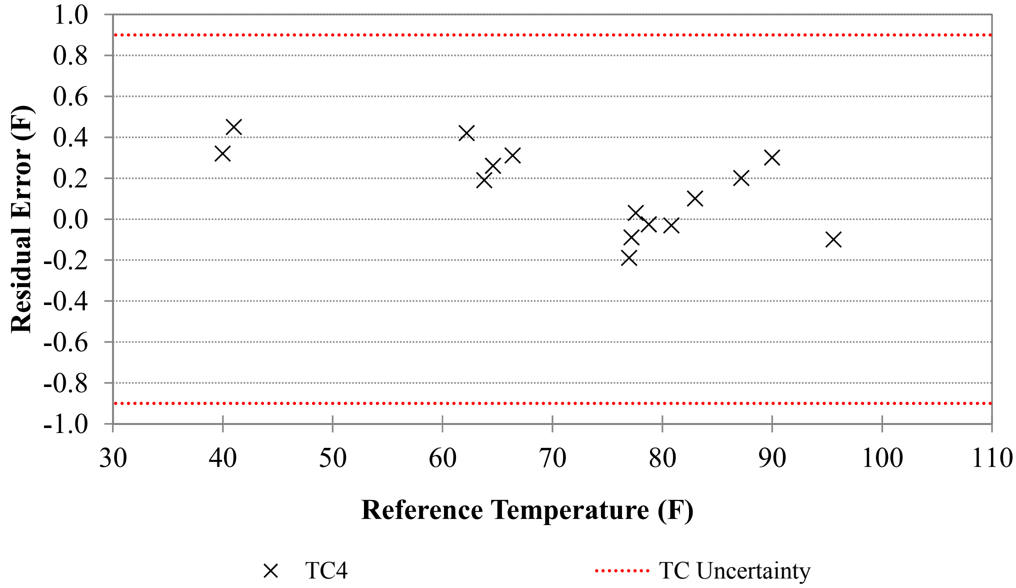


Figure C-9: Residual Plot of Thermocouple No.4 (TC4) with the Manufacturer Specified Sensor Accuracy (±0.9 F)

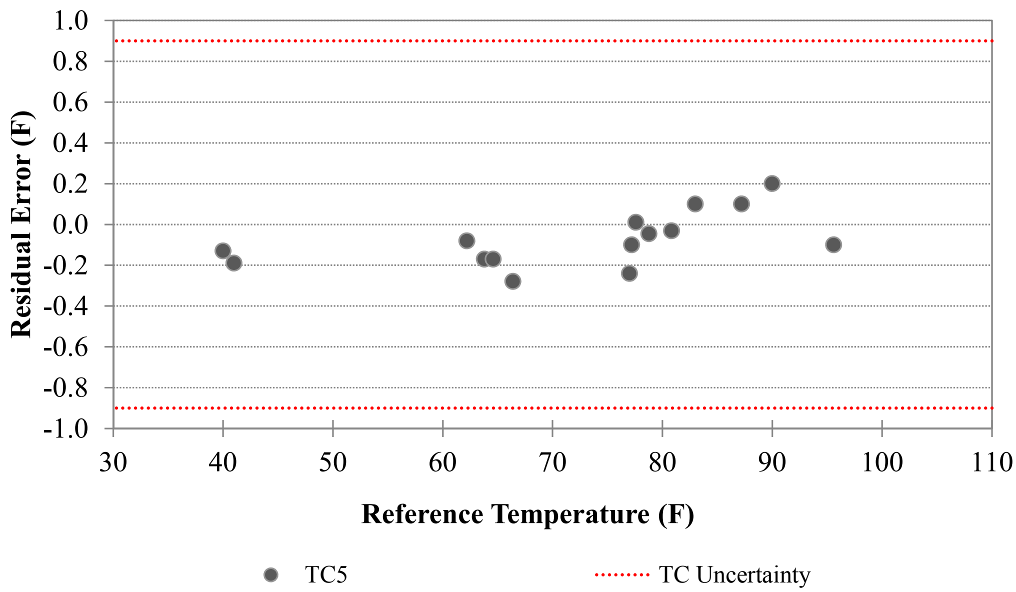


Figure C-10: Residual Plot of Thermocouple No.5 (TC5) with the Manufacturer Specified Sensor Accuracy (±0.9 F)

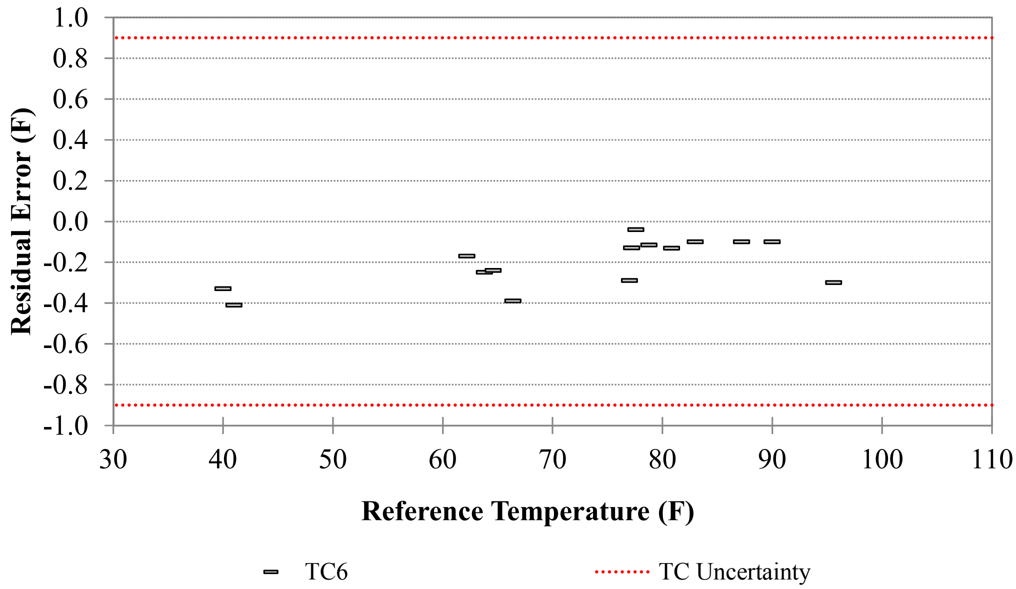


Figure C-11: Residual Plot of Thermocouple No.6 (TC6) with the Manufacturer Specified Sensor Accuracy (±0.9 F)

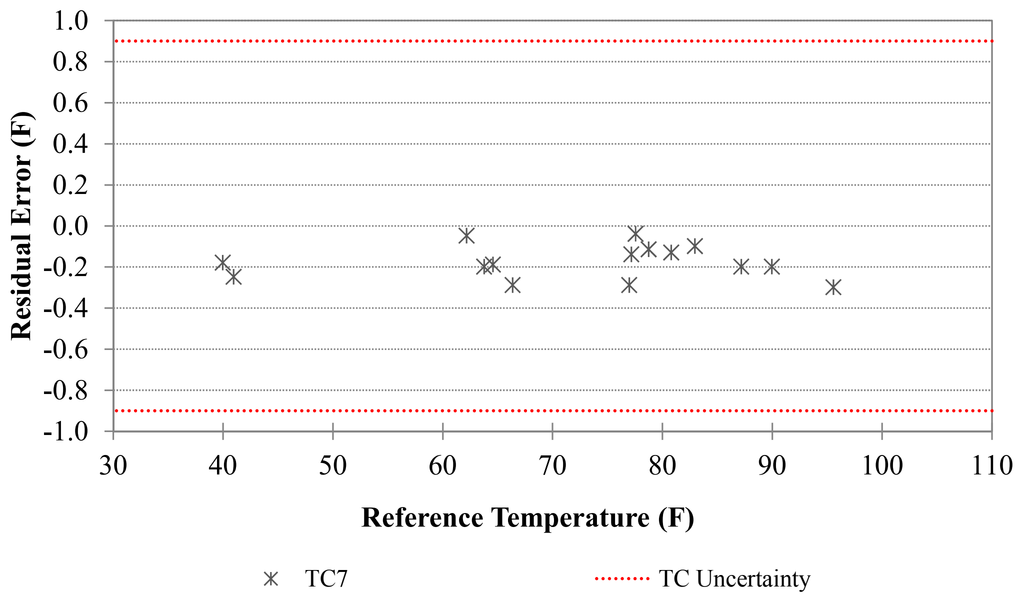


Figure C-12: Residual Plot of Thermocouple No.7 (TC7) with the Manufacturer Specified Sensor Accuracy (±0.9 F)

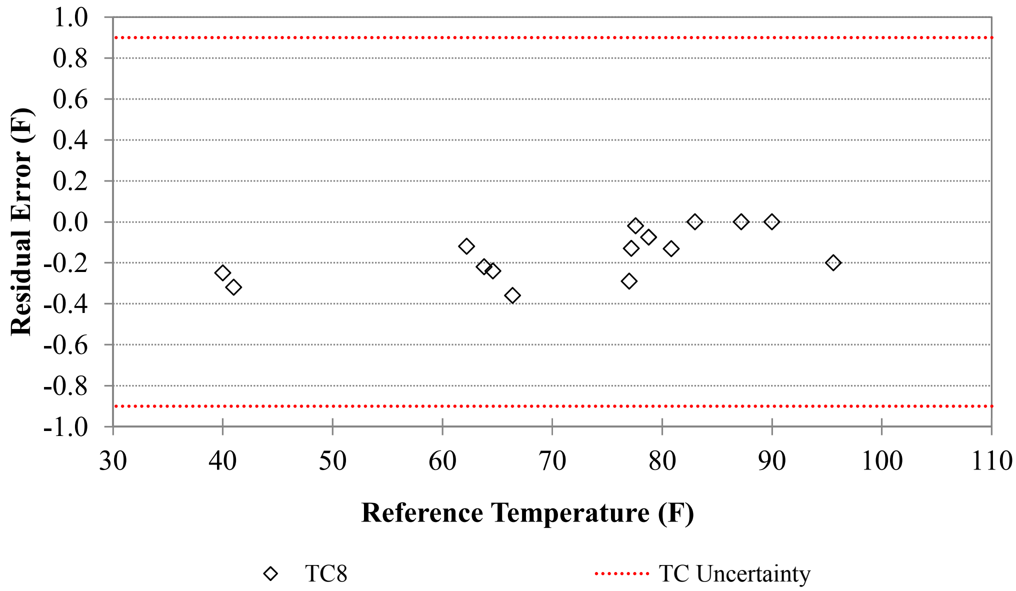


Figure C-13: Residual Plot of Thermocouple No.8 (TC8) with the Manufacturer Specified Sensor Accuracy (±0.9 F)

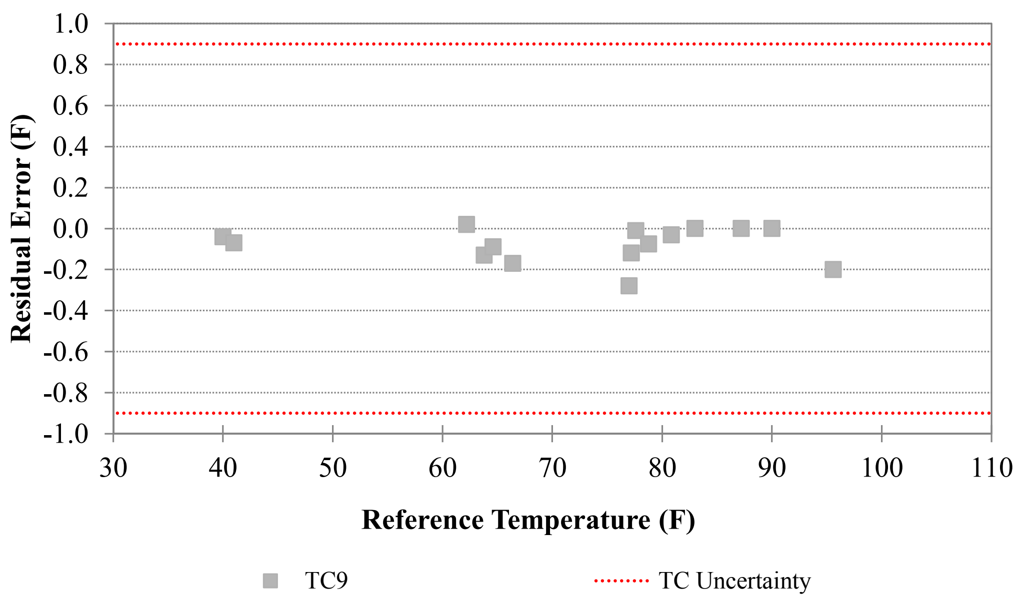


Figure C-14: Residual Plot of Thermocouple No.9 (TC9) with the Manufacturer Specified Sensor Accuracy (±0.9 F)

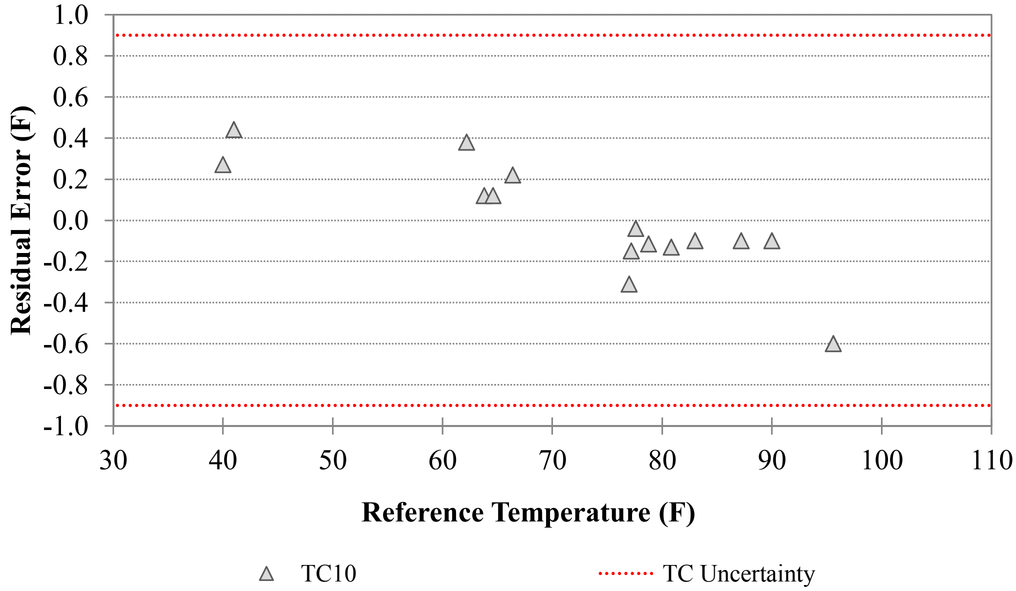


Figure C-15: Residual Plot of Thermocouple No.10 (TC10) with the Manufacturer Specified Sensor Accuracy (±0.9 F)

C.2 T-Type Thermocouples inside Radiation Shields for Air Temperatures

To accomplish a calibration of T-type thermocouples inside radiation shields for air temperatures, the basic calibration mechanism used in this study is a comparison of the shielded thermocouple readings against the readings of unshielded thermocouples, under controlled temperature environments (i.e., cold temperature mode, room temperature mode, and hot temperature mode). To create controlled temperature environments, the thermocouples and reference thermometers were placed inside a glass container. The container was then placed inside a refrigerator. For a cold temperature mode, the refrigerator was on, while for room temperature and hot temperature modes, the refrigerator was off. For a hot temperature mode, a 60W incandescent lamp was additionally used to produce heat inside the refrigerator. To maintain uniform thermal environments inside the refrigerator, a small fan was run during the procedures. Figures C-16 shows an overall comparison of the temperature readings of the four shielded thermocouples (TC1, TC3, TC5, and TC7) against the reference temperatures (i.e., unshielded thermocouples) that varied between 37 F and 97 F. Figures C-17 through C-20 present individual residual plots of the four shielded thermocouples.

In addition to an analysis of residual variation, sixteen test sets were designed to compare the response time of the four thermocouples (i.e., TC1, TC3, TC5, and TC7) with and without shields against the response time of the two reference thermocouples that were unshielded (Table C-1). Figures C-21 to C-24 present the results for each test condition, including room temperature to cold temperature (Figure C-21); cold temperature to room temperature (Figure C-22); room temperature to hot temperature (Figure C-23); and hot temperature to room temperature (Figure C-24). Finally, the response time was calculated (Table C-2). The response times of the shielded thermocouples were found to be two to three times longer than the response times of the two reference thermocouples without shields. It was also observed that for all test conditions, the temperature difference of the tested thermocouples with shields versus the reference thermocouples without shields became within the range of uncertainties after 10 minutes.

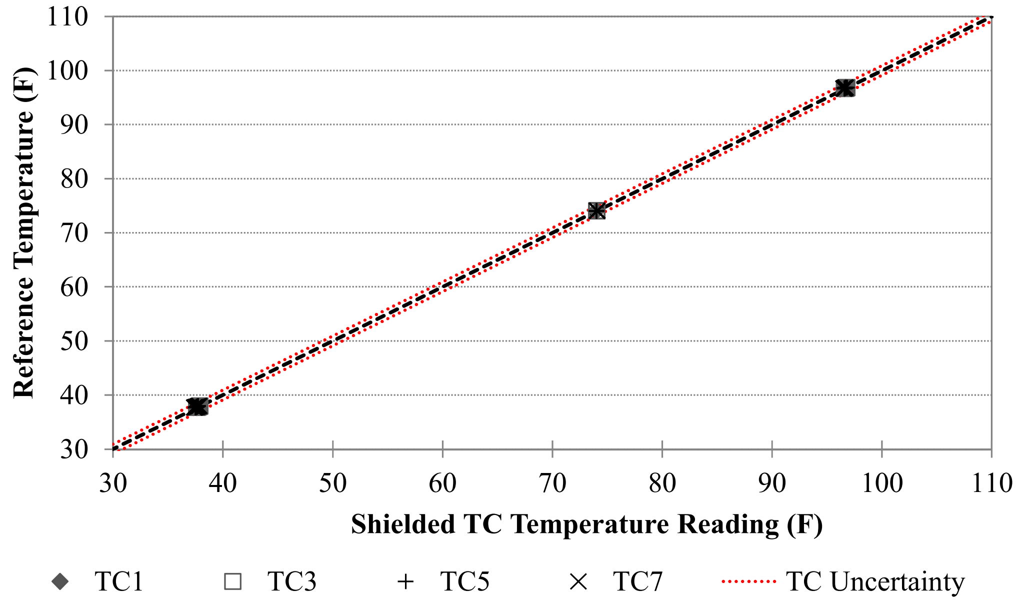


Figure C-16: Comparison of the Temperature Readings of the Four Shielded Thermocouples (TC1, TC3, TC5, and TC7) against the Reference Temperatures (i.e., Unshielded Thermocouples) from 37 F to 97 F

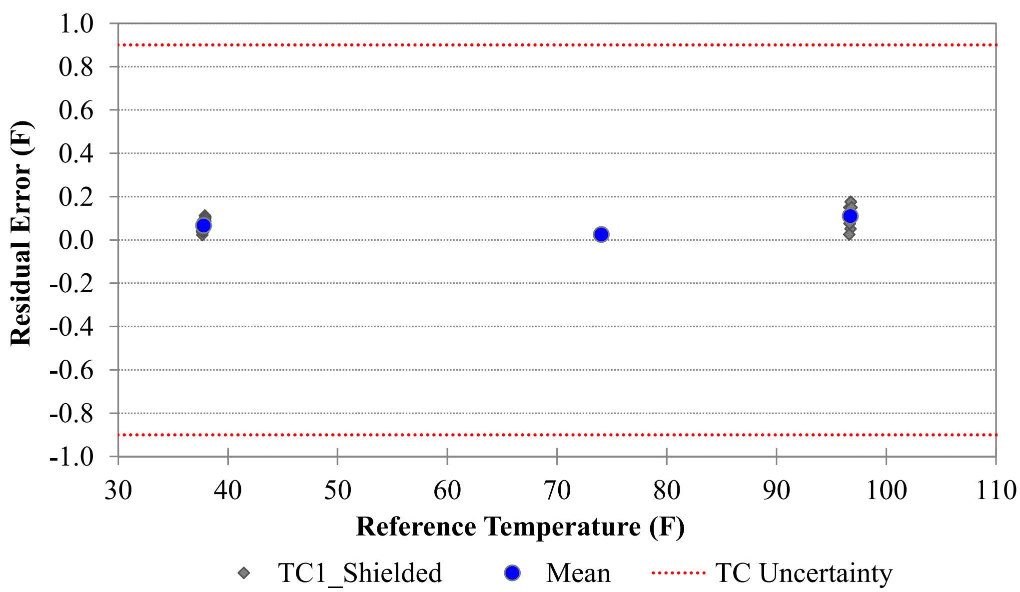


Figure C-17: Residual Plot of the Shielded Thermocouple No.1 (TC1_Shielded) with the Manufacturer Specified Sensor Accuracy (±0.9 F)

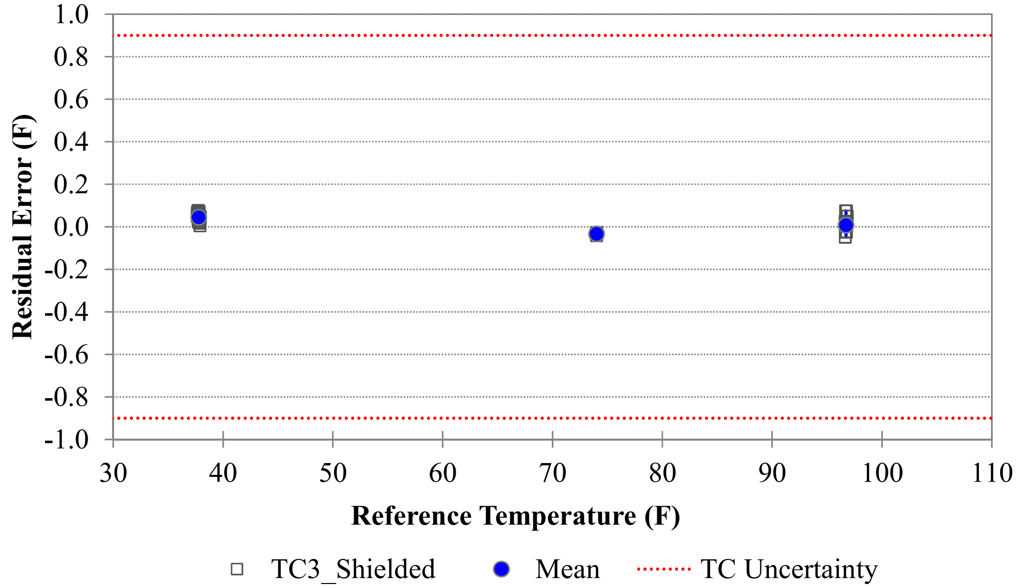


Figure C-18: Residual Plot of the Shielded Thermocouple No.3 (TC3_Shielded) with the Manufacturer Specified Sensor Accuracy (±0.9 F)

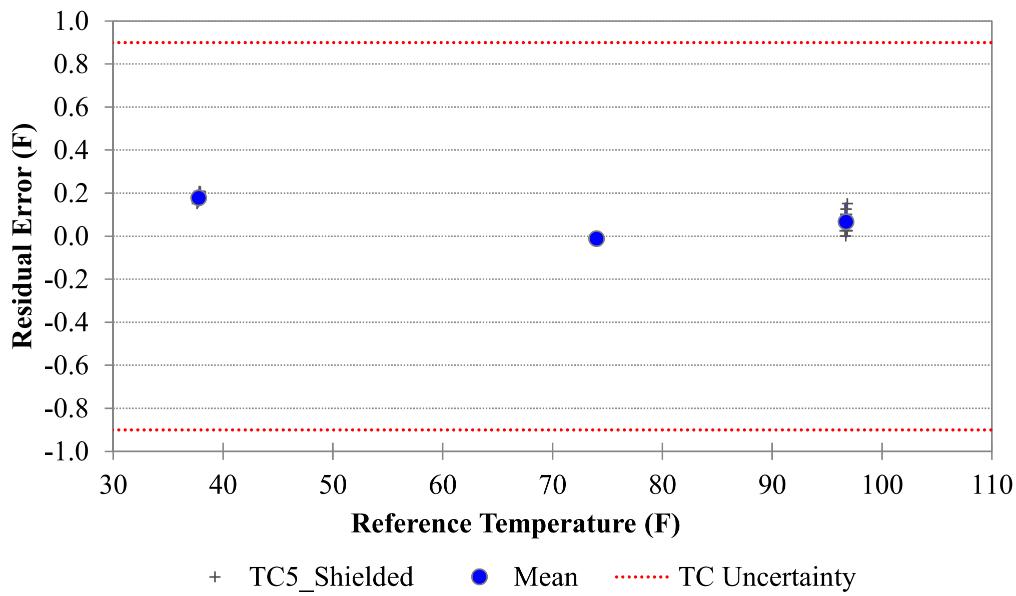


Figure C-19: Residual Plot of the Shielded Thermocouple No.5 (TC5_Shielded) with the Manufacturer Specified Sensor Accuracy (±0.9 F)

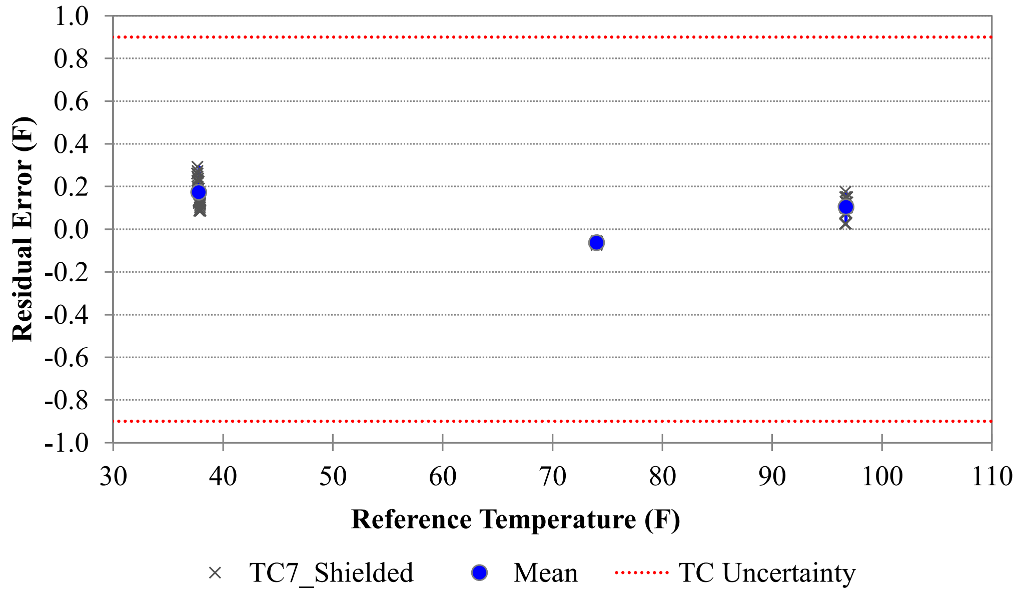
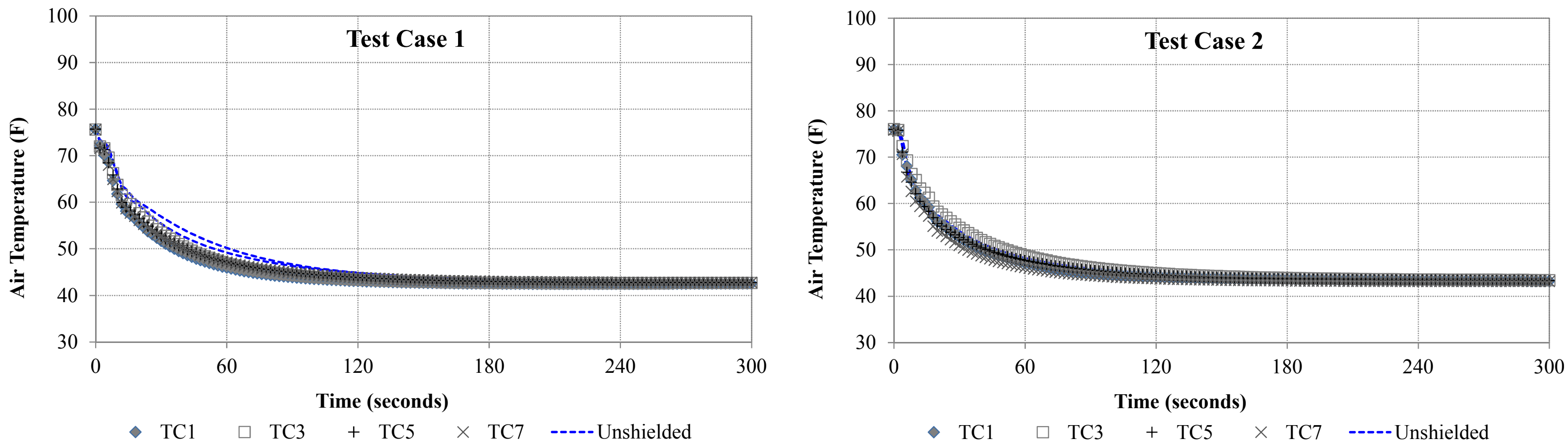


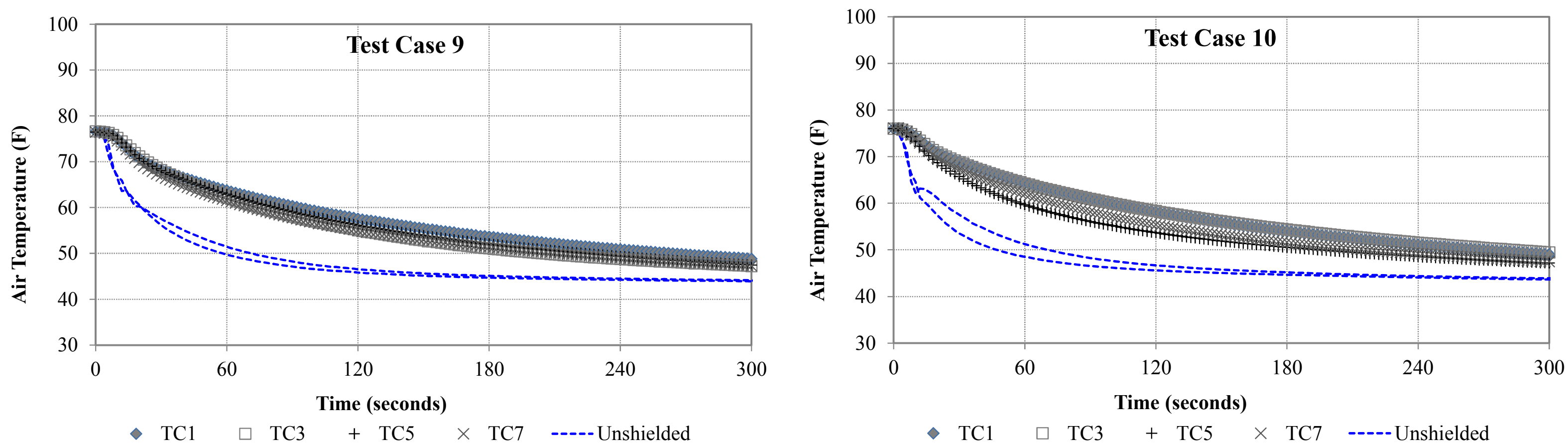
Figure C-20: Residual Plot of the Shielded Thermocouple No.7 (TC7_Shielded) with the Manufacturer Specified Sensor Accuracy (±0.9 F)

Table C-1: Test Sets Designed to Compare the Response Time of the Thermocouples with and without Shields

Test Set No.	Test Conditions				Data Collection Settings		Initial Temp., Ti (F)	Final Temp., Tf (F)
	Radiation Shields		Temperature Exposure		Collecttion Interval	Number of Readings		
	Tested TC (TC1, 3, 5, 7)	Reference TC	From	To				
Set 1	No shields	No shields	Room Temp.	Cold Temp.	2 sec	300	75.6	41.0
Set 2	No shields	No shields	Room Temp.	Cold Temp.	2 sec	300	76.0	41.9
Set 3	No shields	No shields	Cold Temp.	Room Temp.	2 sec	300	42.4	75.8
Set 4	No shields	No shields	Cold Temp.	Room Temp.	2 sec	300	42.6	75.9
Set 5	No shields	No shields	Room Temp.	Hot Temp.	2 sec	300	77.0	90.3
Set 6	No shields	No shields	Room Temp.	Hot Temp.	2 sec	300	76.8	90.2
Set 7	No shields	No shields	Hot Temp.	Room Temp.	2 sec	300	90.1	76.9
Set 8	No shields	No shields	Hot Temp.	Room Temp.	2 sec	300	90.1	77.2
Set 9	Shields	No shields	Room Temp.	Cold Temp.	2 sec	300	76.5	41.8
Set 10	Shields	No shields	Room Temp.	Cold Temp.	2 sec	300	76.0	42.3
Set 11	Shields	No shields	Cold Temp.	Room Temp.	2 sec	300	42.9	75.7
Set 12	Shields	No shields	Cold Temp.	Room Temp.	2 sec	300	43.3	76.2
Set 13	Shields	No shields	Room Temp.	Hot Temp.	2 sec	300	75.1	95.8
Set 14	Shields	No shields	Room Temp.	Hot Temp.	2 sec	300	77.0	90.6
Set 15	Shields	No shields	Hot Temp.	Room Temp.	2 sec	300	93.3	74.8
Set 16	Shields	No shields	Hot Temp.	Room Temp.	2 sec	300	95.2	75.6

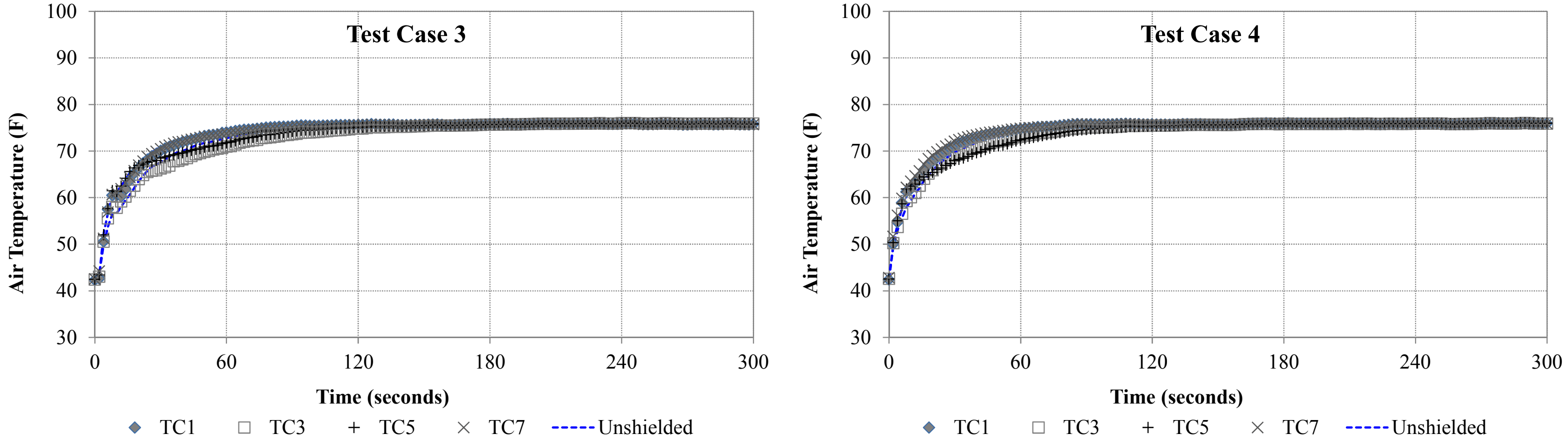


(a) Tested Thermocouples (TC1, TC3, TC5, TC7) without Shields

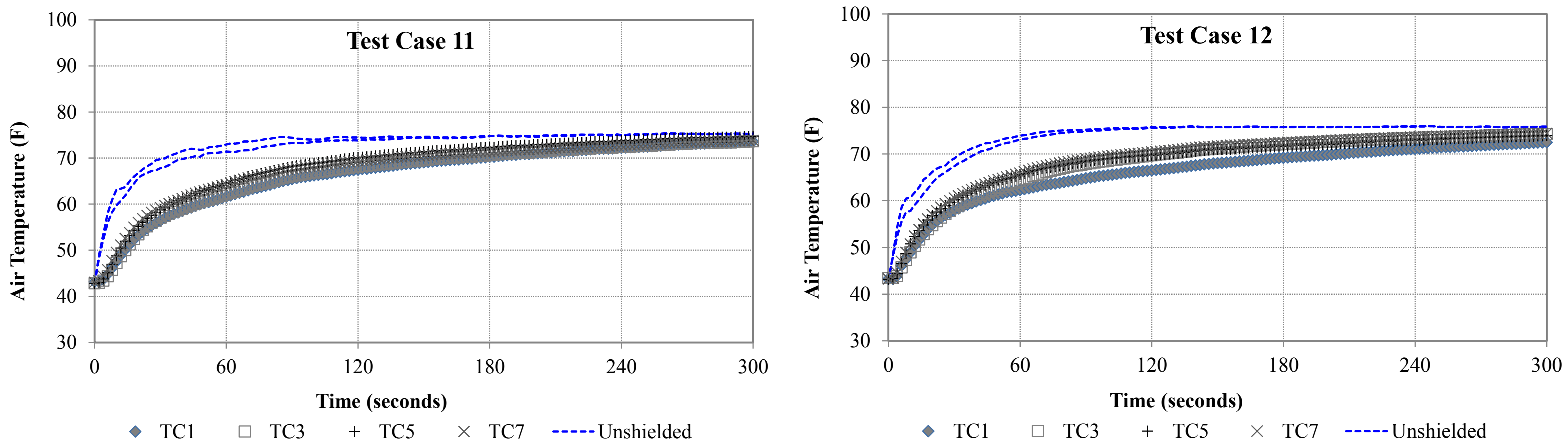


(b) Tested Thermocouples with Shields

Figure C-21: Response Time Testing Results of the Four Thermocouples (i.e., TC1, TC3, TC5, and TC7) against the Two Unshielded Reference Thermocouples: Room Temperature to Cold Temperature

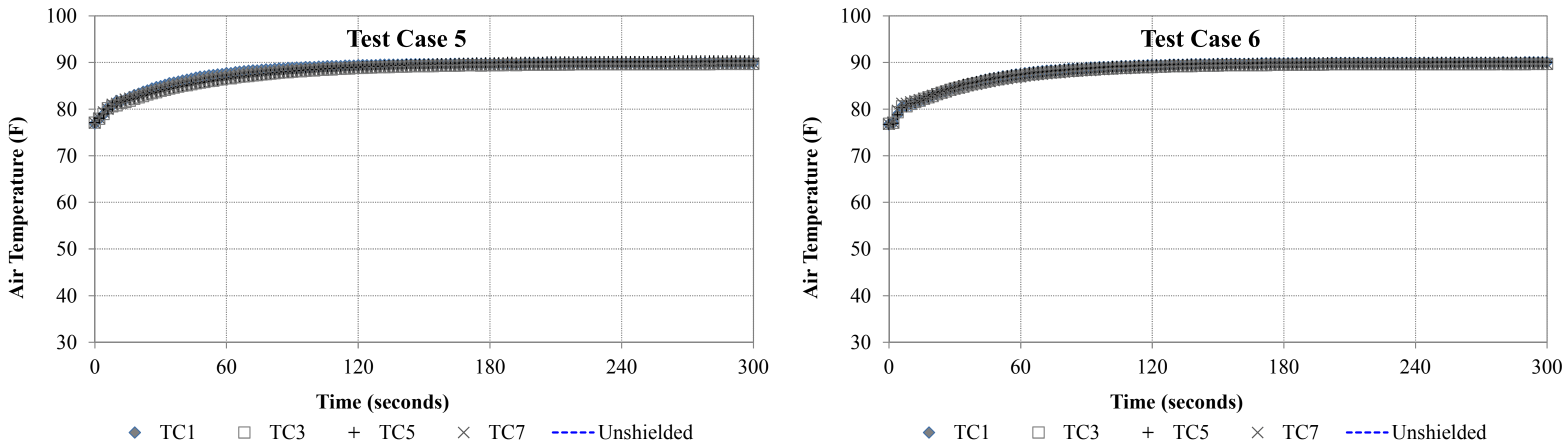


(a) Tested Thermocouples (TC1, TC3, TC5, TC7) without Shields

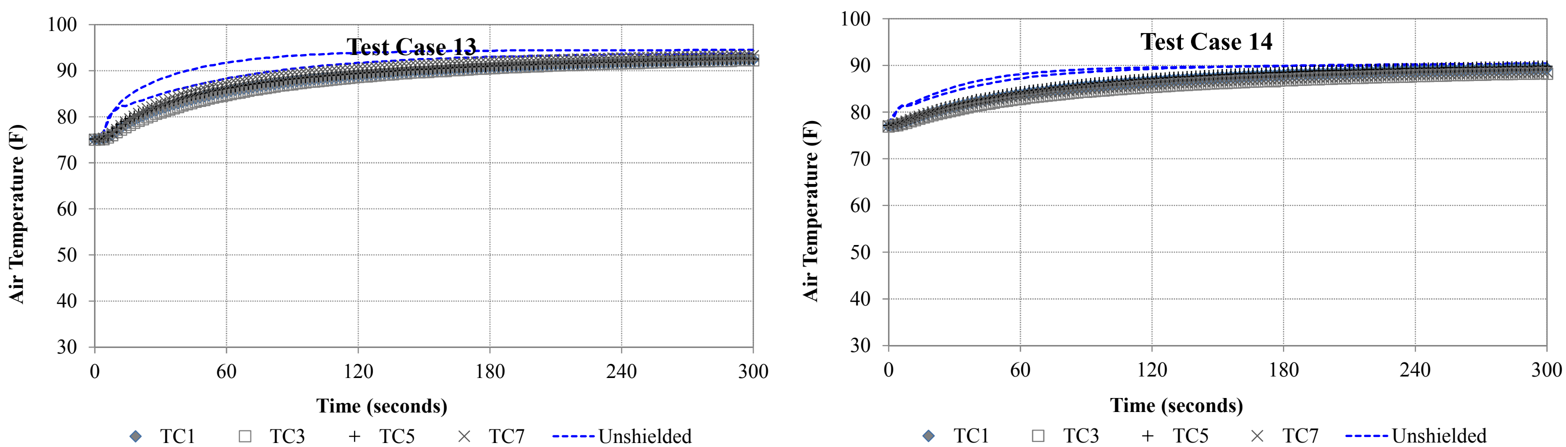


(b) Tested Thermocouples with Shields

Figure C-22: Response Time Testing Results of the Four Thermocouples (i.e., TC1, TC3, TC5, and TC7) against the Two Unshielded Reference Thermocouples: Cold Temperature to Room Temperature

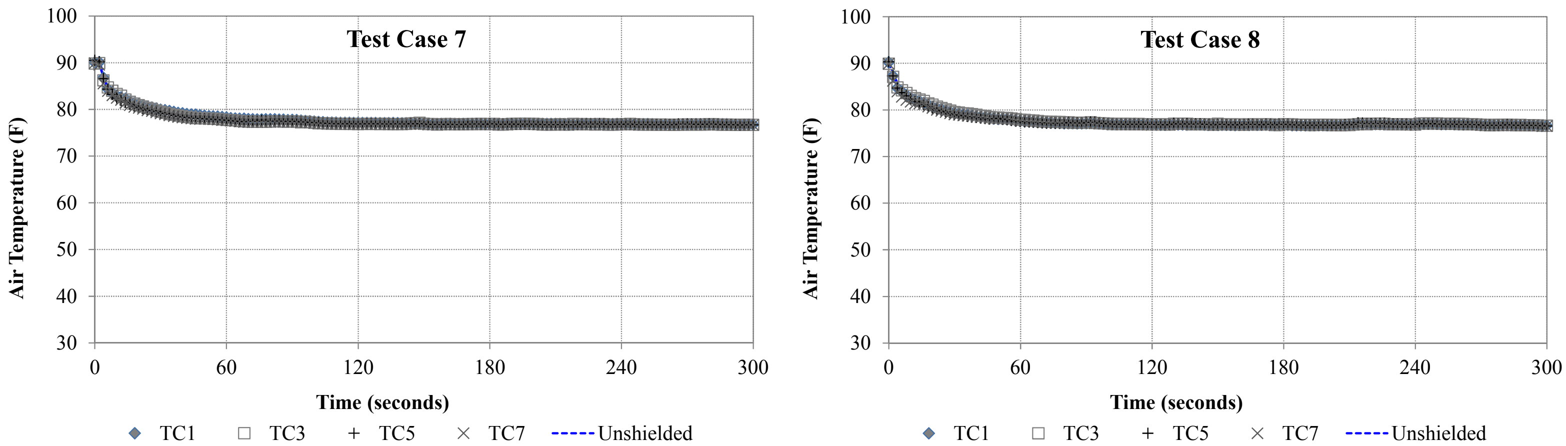


(a) Tested Thermocouples (TC1, TC3, TC5, TC7) without Shields

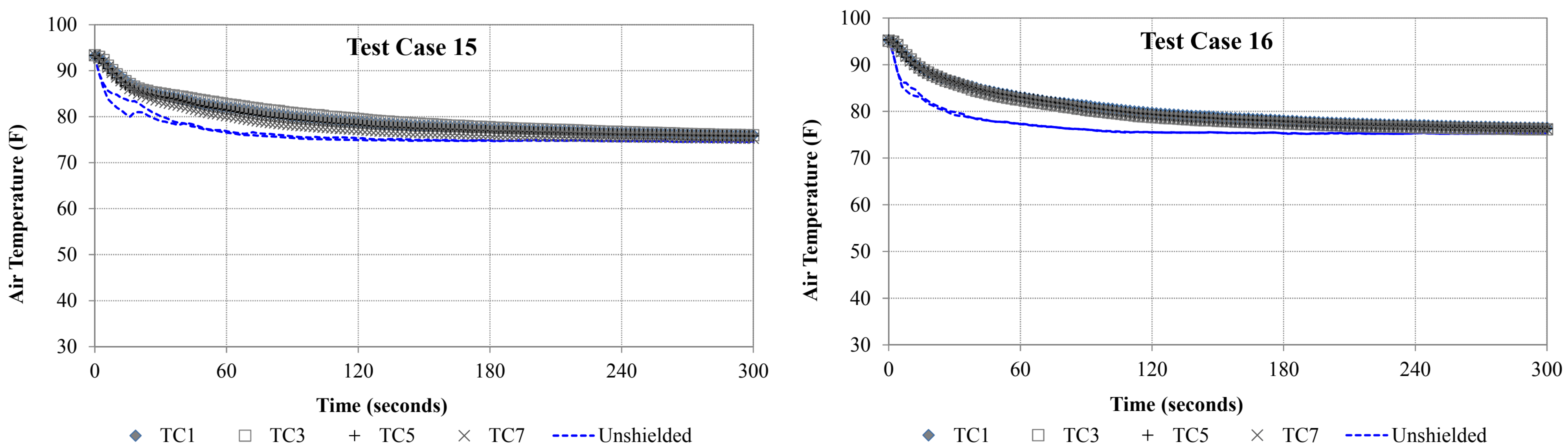


(b) Tested Thermocouples with Shields

Figure C-23: Response Time Testing Results of the Four Thermocouples (i.e., TC1, TC3, TC5, and TC7) against the Two Unshielded Reference Thermocouples: Room Temperature to Hot Temperature



(a) Tested Thermocouples (TC1, TC3, TC5, TC7) without Shields



(b) Tested Thermocouples with Shields

Figure C-24: Response Time Testing Results of the Four Thermocouples (i.e., TC1, TC3, TC5, and TC7) against the Two Unshielded Reference Thermocouples: Hot Temperature to Room Temperature

Table C-2: Calculated Response Time of the Thermocouples with and without Shields

Test Set No.	Test Conditions				Average Temperature of TCs, T(sec) (F)						Calculated Response Time, τ (seconds)					
	Radiation Shields		Temperature Exposure		Tested TC (TC1, 3, 5, 7)			Reference TC			Tested TC				Reference TC	
	Tested TC (TC1, 3, 5, 7)	Reference TC	From	To	T(0)	T(300)	T(600)	T(0)	T(300)	T(600)	TC1	TC3	TC5	TC7	RTC1	RTC2
Set 1	No shields	No shields	Room Temp.	Cold Temp.	75.6	42.7	42.2	75.6	42.8	42.2	31	34	35	35	42	45
Set 2	No shields	No shields	Room Temp.	Cold Temp.	76.0	43.3	43.5	75.9	43.4	43.5	32	37	34	29	36	35
Set 3	No shields	No shields	Cold Temp.	Room Temp.	42.4	75.8	75.7	42.5	75.8	75.7	21	31	28	22	21	25
Set 4	No shields	No shields	Cold Temp.	Room Temp.	42.6	75.9	76.0	42.5	75.9	76.0	18	24	27	18	20	21
Set 5	No shields	No shields	Room Temp.	Hot Temp.	77.0	89.9	90.1	76.9	90.1	90.3	36	47	47	45	42	40
Set 6	No shields	No shields	Room Temp.	Hot Temp.	76.8	89.9	90.0	76.8	90.0	90.1	38	41	38	43	36	42
Set 7	No shields	No shields	Hot Temp.	Room Temp.	90.1	76.7	76.8	90.3	76.8	76.8	27	22	21	22	27	24
Set 8	No shields	No shields	Hot Temp.	Room Temp.	90.1	76.6	76.8	90.2	76.6	76.8	17	20	15	19	14	19
Set 9	Shields	No shields	Room Temp.	Cold Temp.	76.5	47.7	44.2	76.2	44.5	43.6	130	112	121	107	47	41
Set 10	Shields	No shields	Room Temp.	Cold Temp.	76.0	48.3	44.4	75.9	44.4	43.4	142	140	90	110	35	45
Set 11	Shields	No shields	Cold Temp.	Room Temp.	42.9	73.9	75.3	42.8	74.9	75.3	72	68	56	57	24	29
Set 12	Shields	No shields	Cold Temp.	Room Temp.	43.3	73.8	76.1	42.9	75.7	76.1	70	59	53	52	22	25
Set 13	Shields	No shields	Room Temp.	Hot Temp.	75.1	92.6	94.0	74.9	94.0	94.5	87	95	78	70	37	59
Set 14	Shields	No shields	Room Temp.	Hot Temp.	77.0	89.0	90.2	77.6	89.8	90.5	86	107	79	92	45	36
Set 15	Shields	No shields	Hot Temp.	Room Temp.	93.3	75.8	75.1	93.2	74.7	74.8	64	71	58	49	27	26
Set 16	Shields	No shields	Hot Temp.	Room Temp.	95.2	76.3	75.3	95.4	75.3	75.0	62	58	61	58	24	25

C.3 T-Type Thermocouples inside 38 mm-Diameter Table Tennis Balls Painted Gray for Globe Temperatures

There are no standardized procedures for globe thermometer calibration, but the same mechanism applied in the thermocouple calibration can be used: a comparison of the readings of the proposed globe temperature sensor against the reference globe thermometers (150 mm-diameter black globe) that conforms to the ISO 7243:1989 (ISO 1989). Another method is a comparison of the mean radiant temperature calculated using the measured globe temperature in a black enclosure against the average of the measured surface temperatures of the enclosure (Ugursal 2010). This study used the method proposed by Ugursal (2010).

The procedure used a sealed wooden box, of which interior surfaces were painted black, as shown in Figure C-25. For reference temperatures (i.e., average of the measured surface temperatures of the enclosure), six calibrated thermocouples were installed in the middle of each interior surface. The globe temperature sensor was hung to be located in the center of the enclosure along with one thermocouple for air temperature as well as an air speed sensor. The measured globe temperature, air temperature and air speed were used to calculate the mean radiant temperature. Finally, the calculated mean radiant temperature was compared against the reference temperature, which is an average of the measured surface temperatures of the enclosure.

Four test sets were designed for each of the four tested globe temperature sensors (Table C-3). Each test set consists of the combinations of two test conditions: existence of external heat source; and type of convection (i.e., natural or forced). An electric blanket was used to heat the floor of the enclosure, and a small fan was used to create forced convection.

Figure C-26 presents a residual plot showing the results of all sixteen test sets (i.e., four test sets per each globe temperature sensor). The residuals were calculated by subtracting the reference mean radiant temperature (i.e., average of the six measured surface temperatures) from the mean radiant temperature calculated using the measured globe temperature. Figures C-27 through C-30 present the results for each test condition, including no external heat source with natural convection (Figure C-27); no external heat source with forced convection (Figure C-28); heated floor with natural convection (Figure C-29); and heated floor with forced convection (Figure C-30).

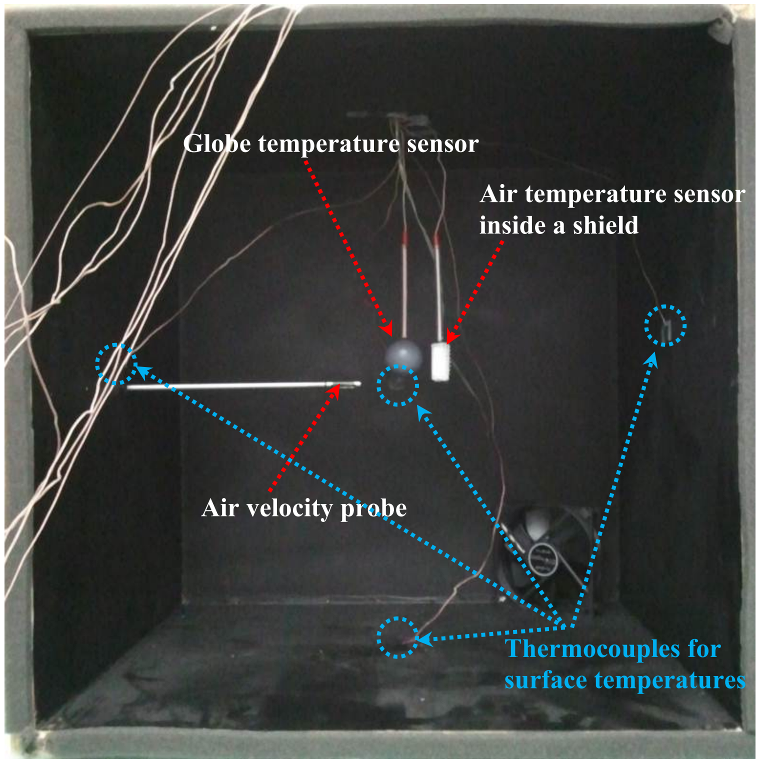


Figure C-25: Experimental Setting for the Calibration of the Four Globe Temperature Sensors by Comparing the Mean Radiant Temperature Calculated Using the Measured Globe Temperature against the Reference Temperature (i.e., Average of the Six Surface Temperatures)

Table C-3: Test Sets Designed to Calibrate the Four Globe Temperature Sensors

Test Set No.	Tested GT	Test Conditions			
	Globe No.	Mode		Electric Blanket	Fan
1	Globe 1	No External Heat Source	Natural Convection	OFF	OFF
2	Globe 1	No External Heat Source	Forced Convection	OFF	ON
3	Globe 1	Heated Floor	Natural Convection	ON	OFF
4	Globe 1	Heated Floor	Forced Convection	ON	ON
5	Globe 2	No External Heat Source	Natural Convection	OFF	OFF
6	Globe 2	No External Heat Source	Forced Convection	OFF	ON
7	Globe 2	Heated Floor	Natural Convection	ON	OFF
8	Globe 2	Heated Floor	Forced Convection	ON	ON
9	Globe 3	No External Heat Source	Natural Convection	OFF	OFF
10	Globe 3	No External Heat Source	Forced Convection	OFF	ON
11	Globe 3	Heated Floor	Natural Convection	ON	OFF
12	Globe 3	Heated Floor	Forced Convection	ON	ON
13	Globe 4	No External Heat Source	Natural Convection	OFF	OFF
14	Globe 4	No External Heat Source	Forced Convection	OFF	ON
15	Globe 4	Heated Floor	Natural Convection	ON	OFF
16	Globe 4	Heated Floor	Forced Convection	ON	ON

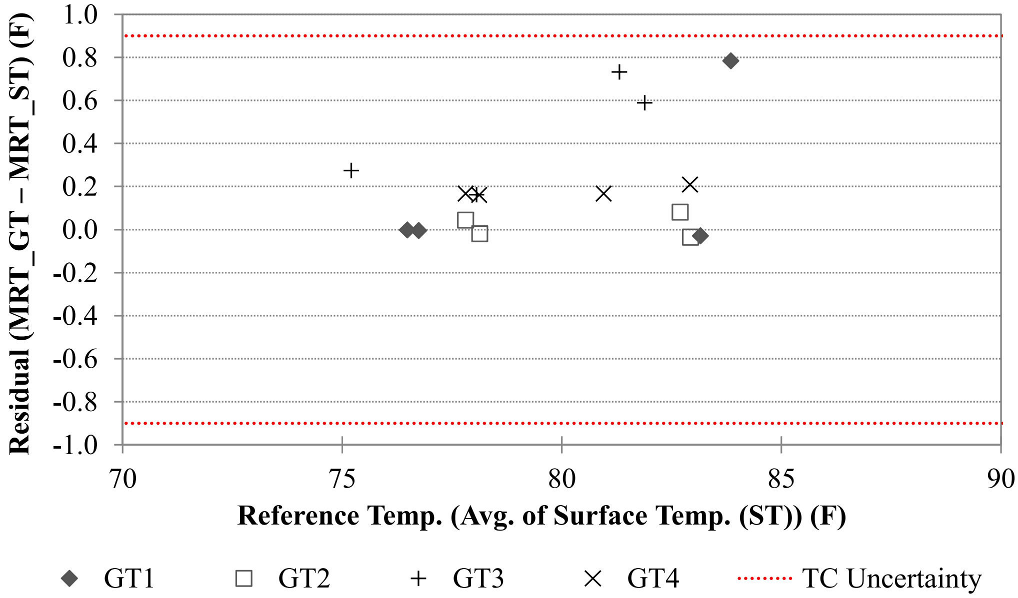


Figure C-26: Residual Plot against the Reference Temperature

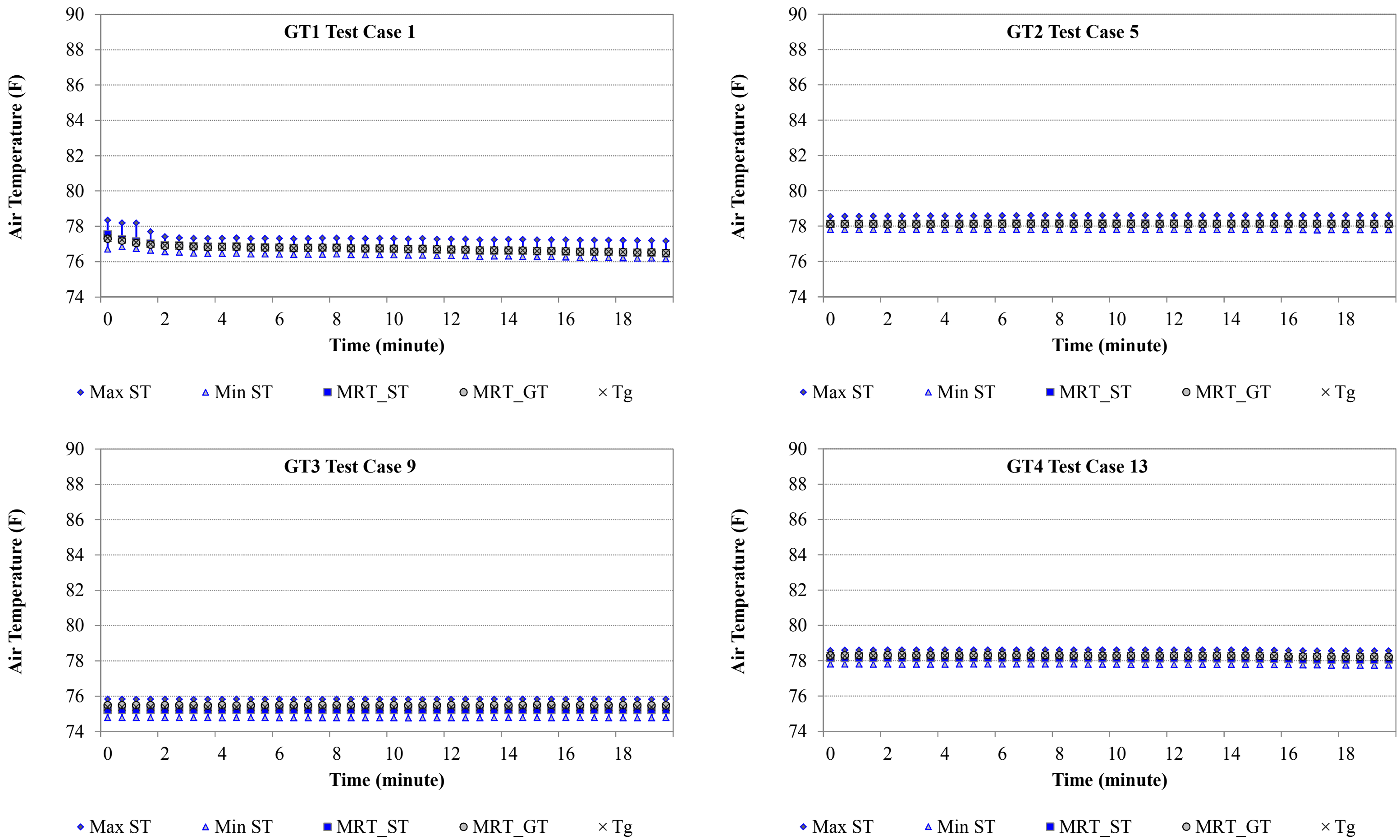


Figure C-27: Comparison of the Mean Radiant Temperatures (MRT) Calculated Using the Measured Globe Temperatures (i.e., GT1, GT2, GT3, and GT4) against the Reference Temperature (i.e., Average of the Six Surface Temperatures): No External Heat Source with Natural Convection

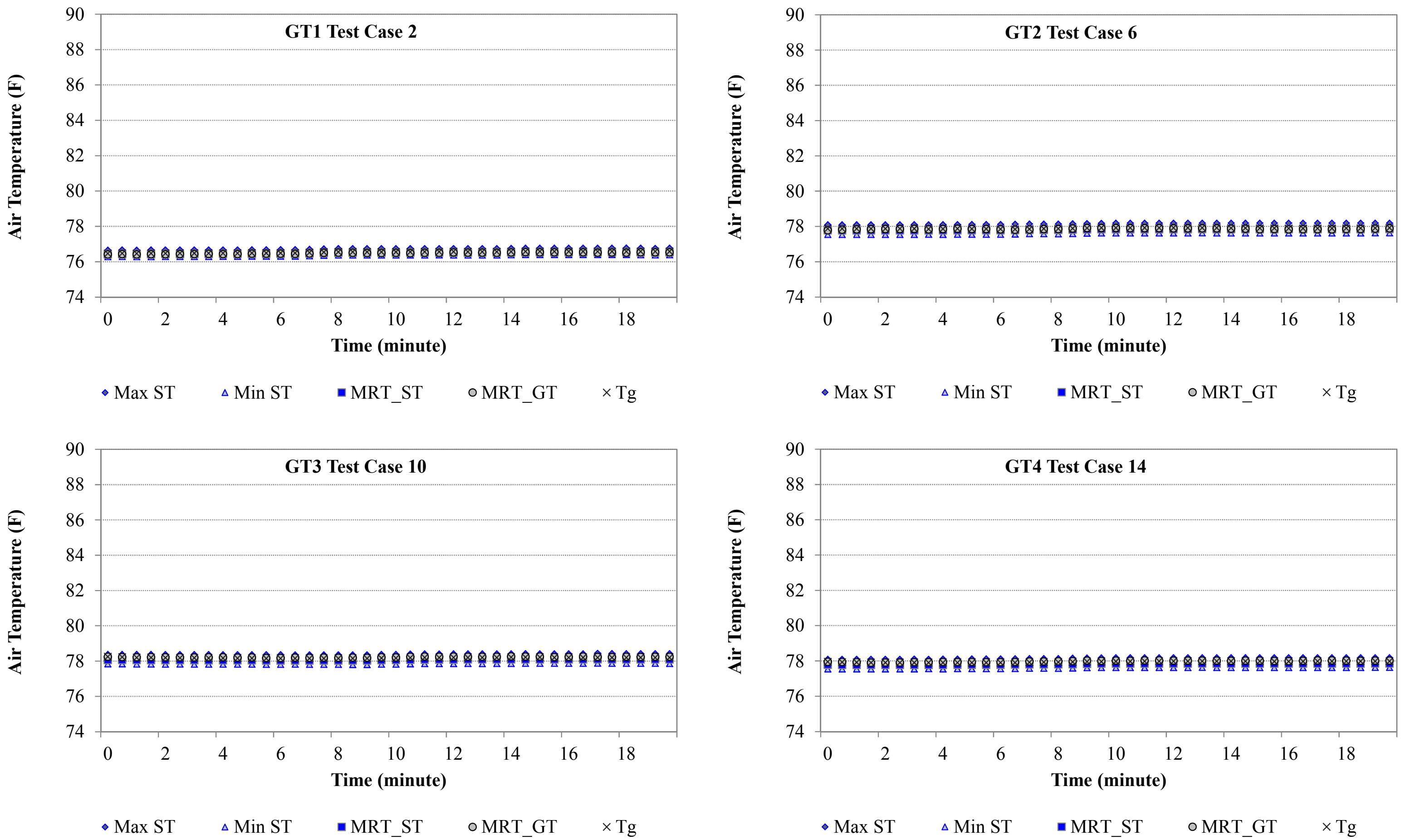


Figure C-28: Comparison of the Mean Radiant Temperatures (MRT) Calculated Using the Measured Globe Temperatures (i.e., GT1, GT2, GT3, and GT4) against the Reference Temperature (i.e., Average of the Six Surface Temperatures): No External Heat Source with Forced Convection

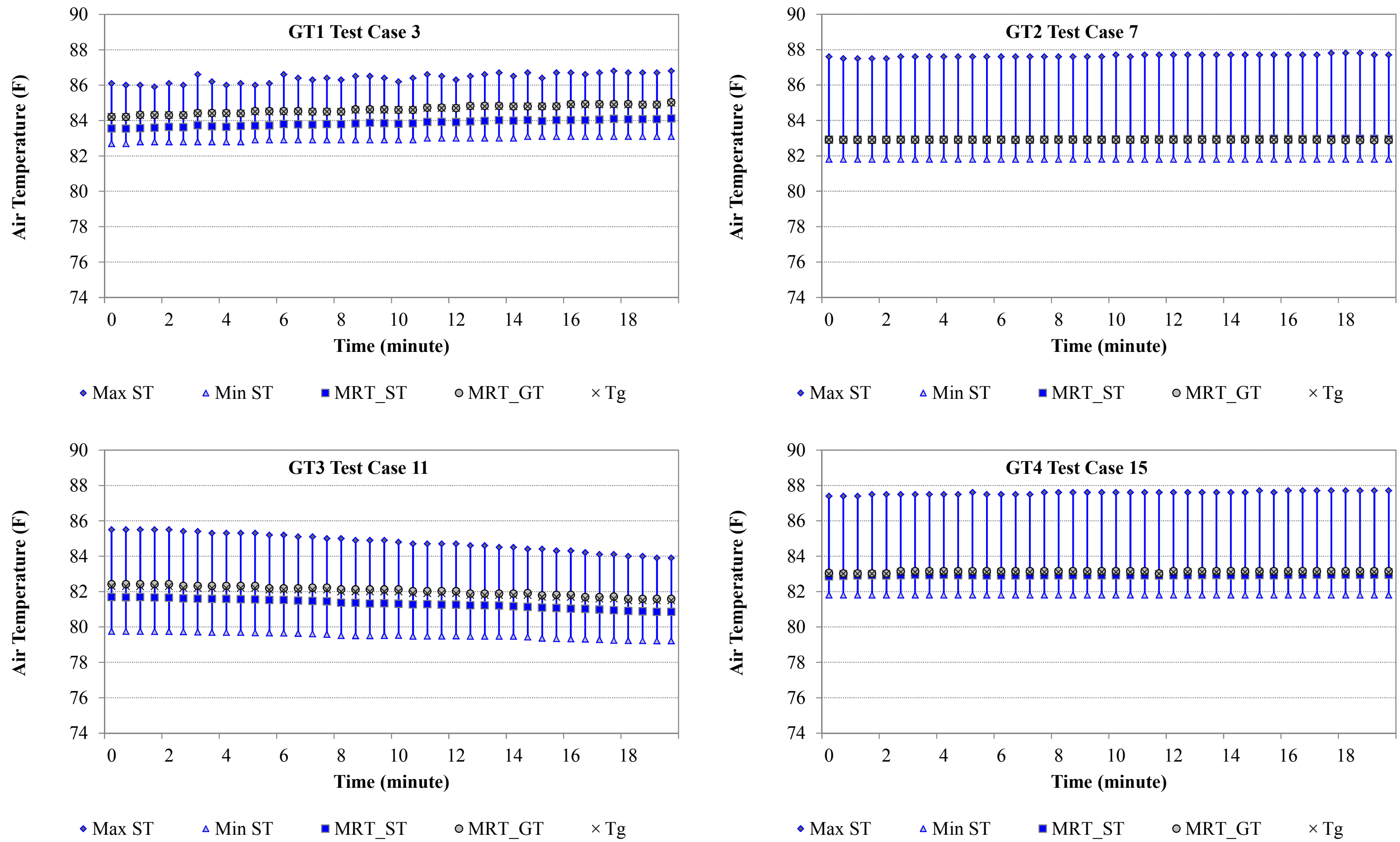


Figure C-29: Comparison of the Mean Radiant Temperatures (MRT) Calculated Using the Measured Globe Temperatures (i.e., GT1, GT2, GT3, and GT4) against the Reference Temperature (i.e., Average of the Six Surface Temperatures): Heated Floor with Natural Convection

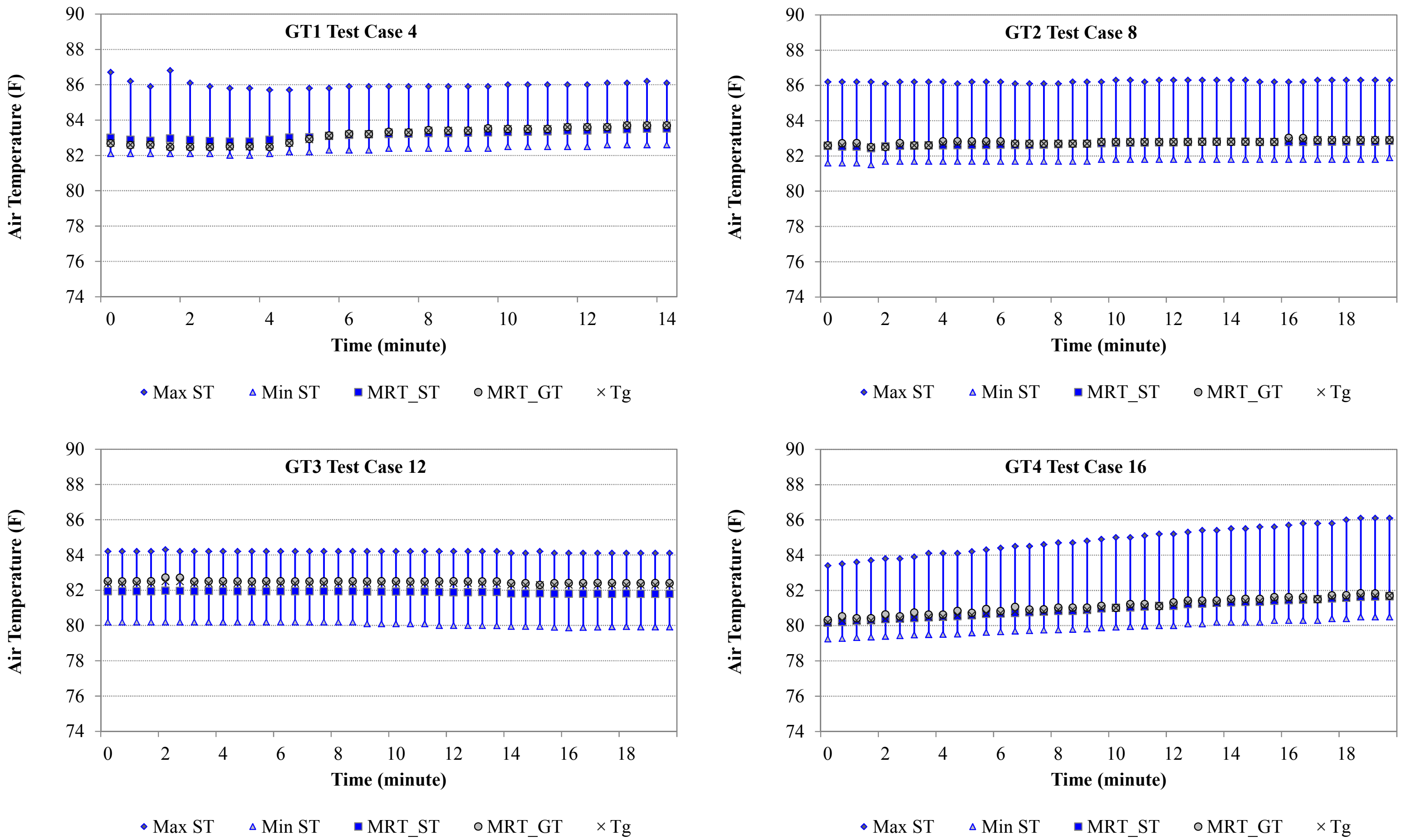


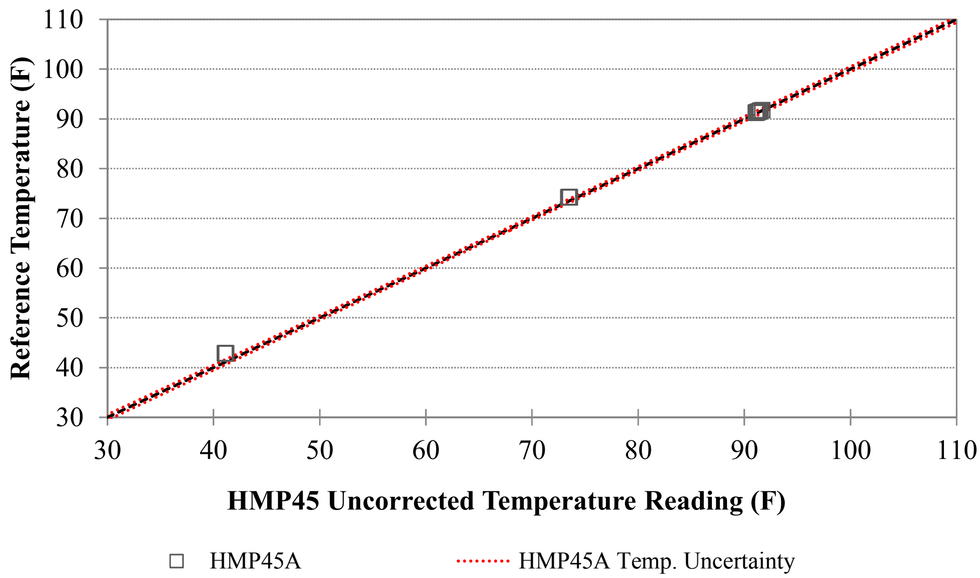
Figure C-30: Comparison of the Mean Radiant Temperatures (MRT) Calculated Using the Measured Globe Temperatures (i.e., GT1, GT2, GT3, and GT4) against the Reference Temperature (i.e., Average of the Six Surface Temperatures): Heated Floor with Forced Convection

C.4 Vaisala HMP45A Humidity and Temperature Probe

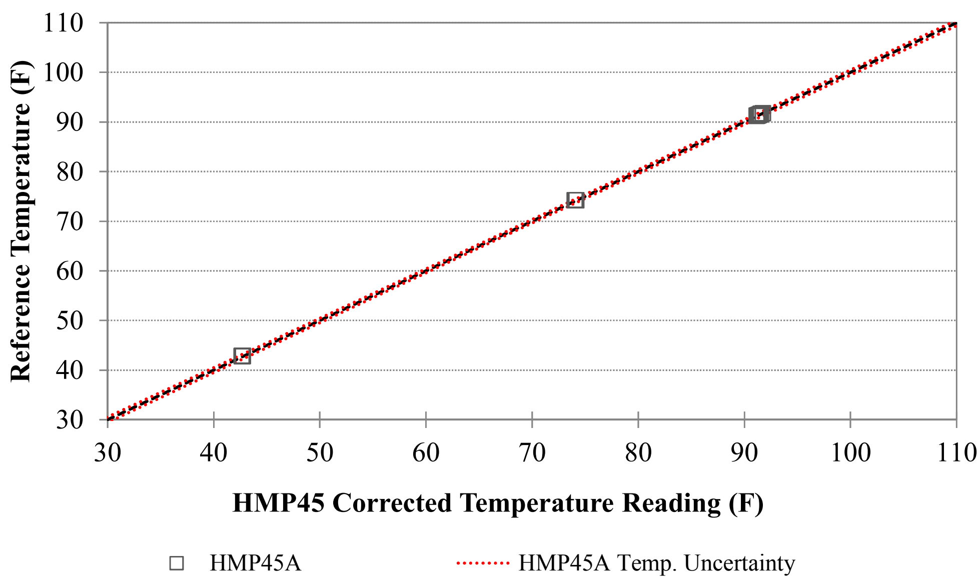
To accomplish a calibration of Vaisala HMP45A humidity and temperature probe for relative humidity (RH) measurement, the ASTM Standards E104-02 (2007c) was referenced for RH calibrations. Using the selected saturated salt solutions, a known RH was calculated. Three types of salts were used: Lithium Chloride for 11.3 ± 0.27% RH at 77 F; Magnesium Chloride for 32.8 ± 0.16 % RH at 77 F; and Sodium Chloride for 75.3 ± 0.12 % RH at 77 F (Greenspan 1977). The temperature sensor was calibrated against the calibrated RTD sensors[240] using the method described in the Appendix C.1.

Figures C-31 and C-32 show the calibration results of the Vaisala HMP45A temperature sensor, including a comparison of the Vaisala HMP45A temperature readings against the reference RTD temperatures before and after calibration as well as the residual plots before and after calibration. Figures C-33 and C-34 show the calibration results of the Vaisala HMP45A RH sensor, including a comparison of the Vaisala HMP45A RH readings against the reference RH before and after calibration as well as the residual plots before and after calibration.

[240] The RTD sensors were calibrated first against the ASTM certified liquid-in-glass thermometers under controlled temperature environments, including an ice point. The calibration data are presented in Figures C-3 and C-4.

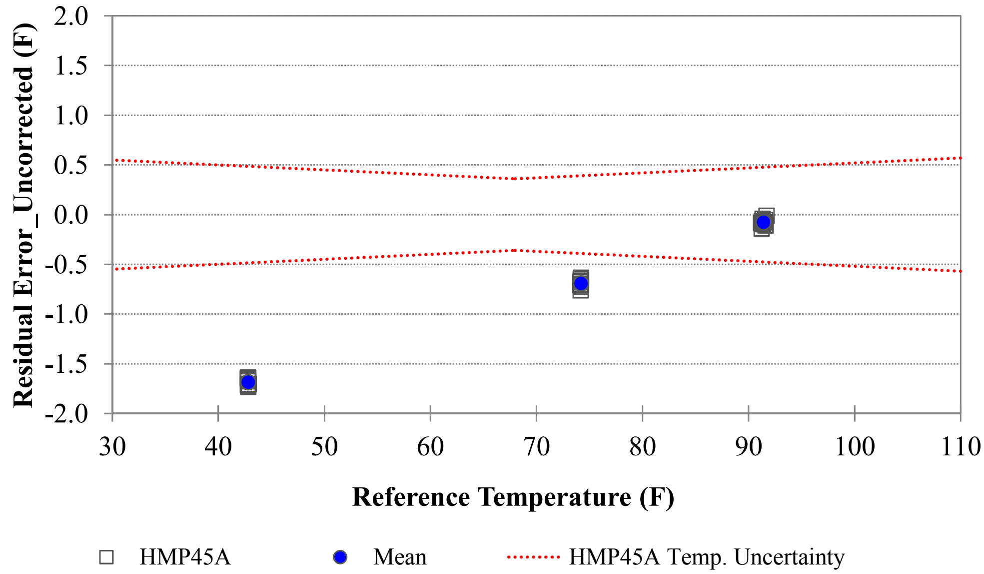


(a) Uncorrected Comparison (Before Calibration)

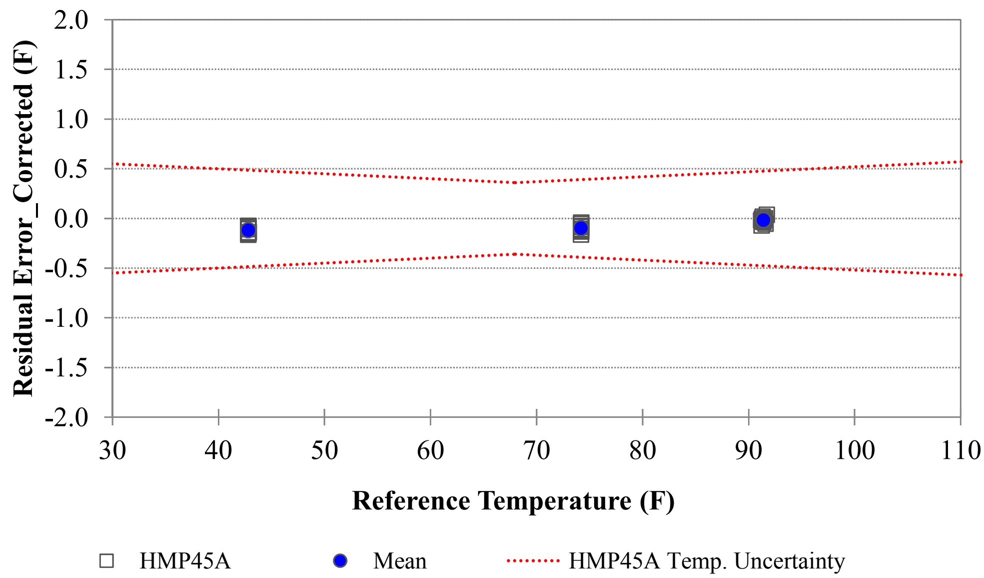


(b) Corrected Comparison (After Calibration)

Figure C-31: Comparison of the Vaisala HMP45A Temperature Readings against the Reference Temperatures from 43 F to 91 F

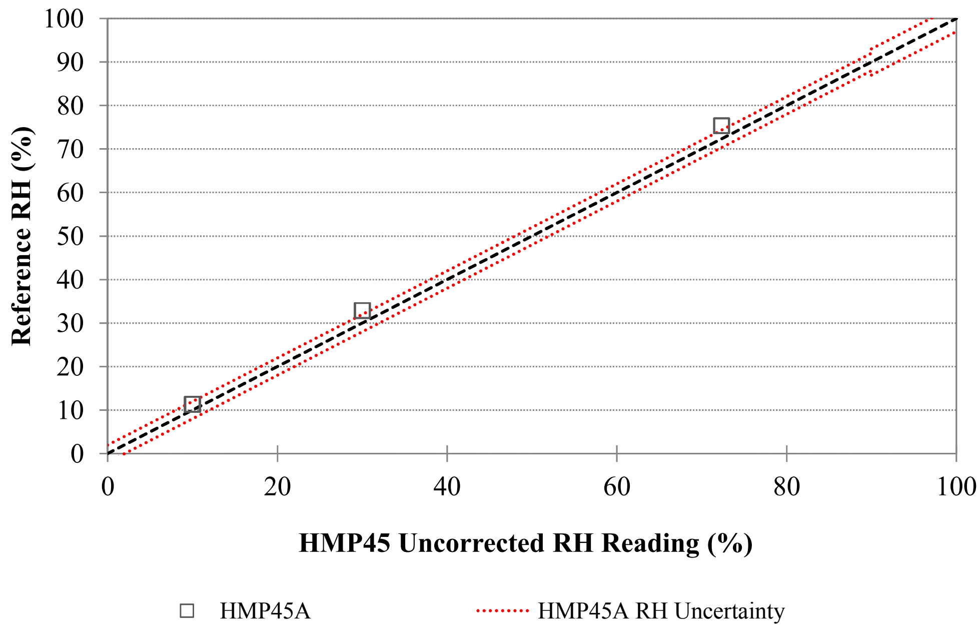


(a) Uncorrected Residuals (Before Calibration)

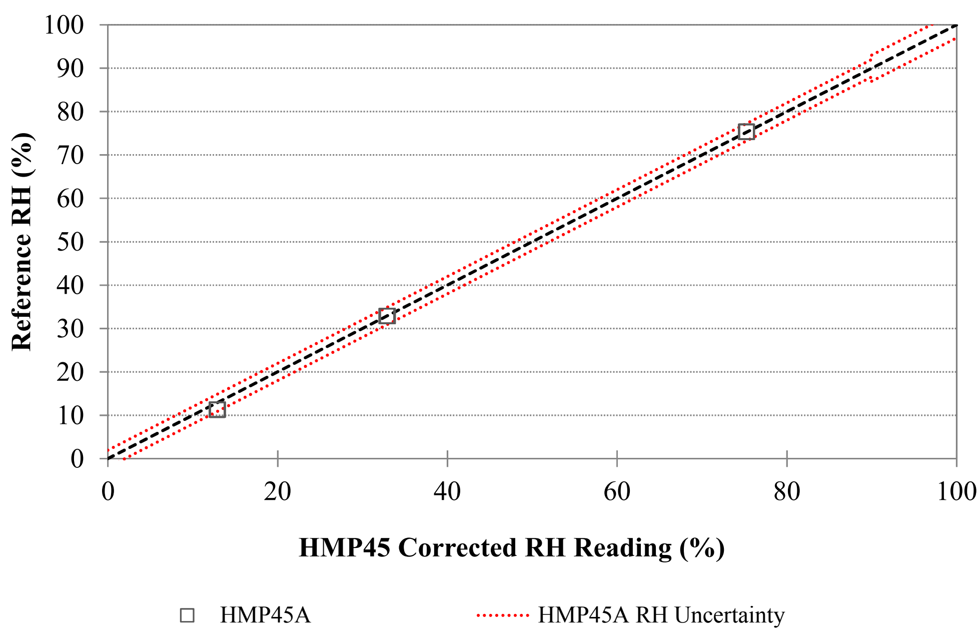


(b) Corrected Residuals (After Calibration)

Figure C-32: Vaisala HMP45A Temperature Residual Plot with the Manufacturer Specified Sensor Accuracy

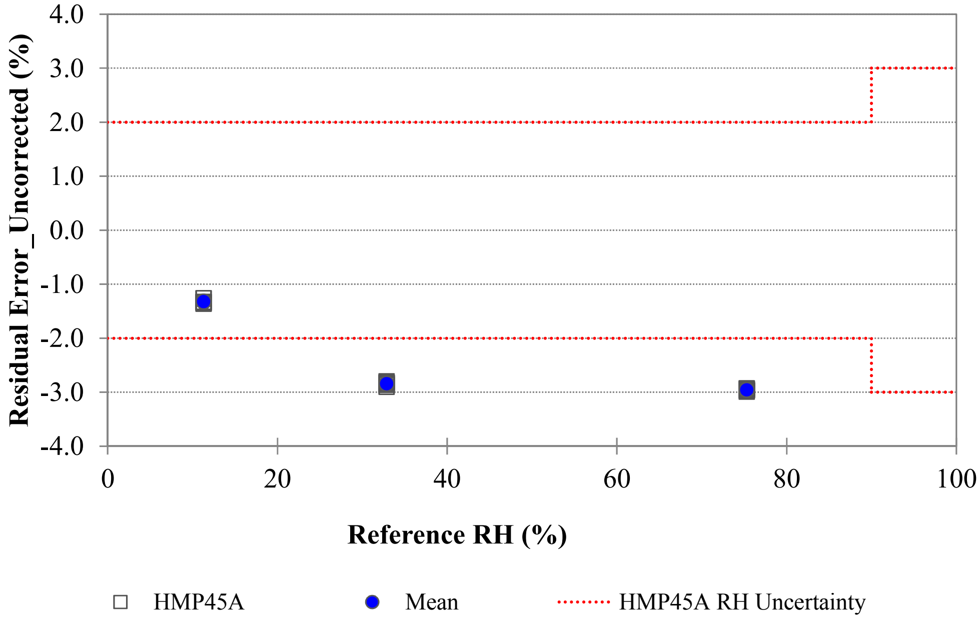


(a) Uncorrected Comparison (Before Calibration)

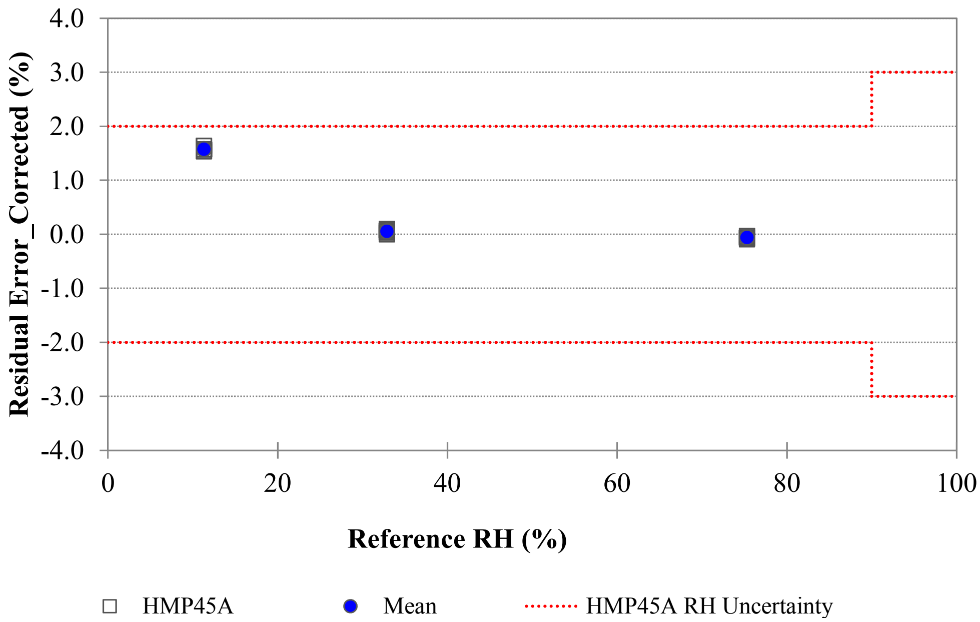


(b) Corrected Comparison (After Calibration)

Figure C-33: Comparison of the Vaisala HMP45A Relative Humidity Readings against the Reference Relative Humidity from 11.3% RH to 75.3% RH



(a) Uncorrected Residuals (Before Calibration)



(b) Corrected Residuals (After Calibration)

Figure C-34: Vaisala HMP45A Relative humidity Residual Plot with the Manufacturer Specified Sensor Accuracy

C.5 Telaire 7001 CO_2 Sensor

To accomplish a calibration of CO_2 sensors, a two-point calibration using bottled gases of pure nitrogen (0 ppm CO_2) and a known concentration of CO_2 (i.e., 1,000 or 5,000 ppm) is typically recommended. The calibration can be performed by flowing gases to the calibration port of the meter using a flow regulator. Another method is a comparison of the sensor of interest against the sensors that are recently calibrated by exposing them to various CO_2 concentrations. This study used a sensor-by-sensor comparison method for a verification purpose since the Telaire 7001 CO_2 sensor used in this study was a new sensor, which was calibrated by the manufacturer.

The procedure used an ice box and dry ice to produce various CO_2 concentrations (i.e., low CO_2 concentration, medium CO_2 concentration, and high CO_2 concentration). For low CO_2 concentration (i.e., 400 ppm), the two new Telaire 7001 CO_2 sensors were located outdoors, while for medium CO_2 (i.e., between 1,200 and 1,300 ppm) and high CO_2 (i.e., between 2,250 and 2,300 ppm) concentrations, the two sensors were placed inside an ice box with an adequate amount of dry ice. In addition, the sensors were exposed to normal indoor setting, which varied between 800 to 1,000 ppm. Figure C-35 shows a time-series plot of the two CO_2 sensors that were exposed to various CO_2 concentrations. Figures C-36 shows a comparison result of the two CO_2 sensors, and Figure C-37 presents the residuals that were calculated by subtracting the reference CO_2 concentration (i.e., average CO_2 concentration of two sensors) from the measured CO_2 concentration of each sensor.

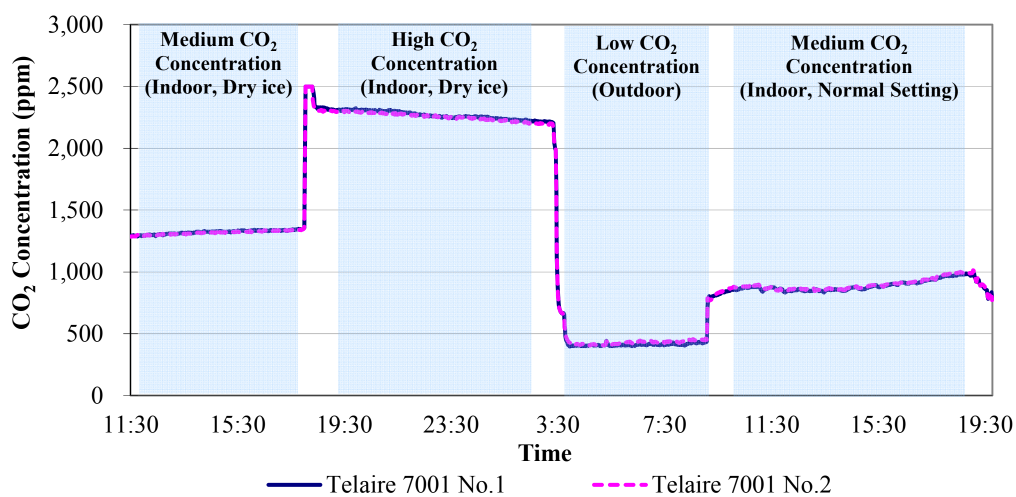


Figure C-35: Time-Series Plot of the Two Telaire 7001 CO_2 Sensors Exposed to Various CO_2 Concentrations

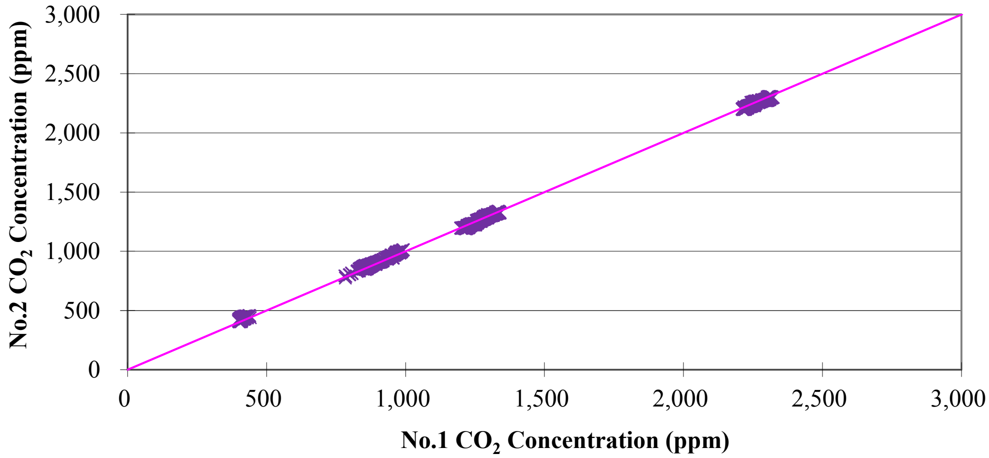


Figure C-36: Comparison of the CO_2 Readings of the Two Telaire 7001 CO_2 Sensors

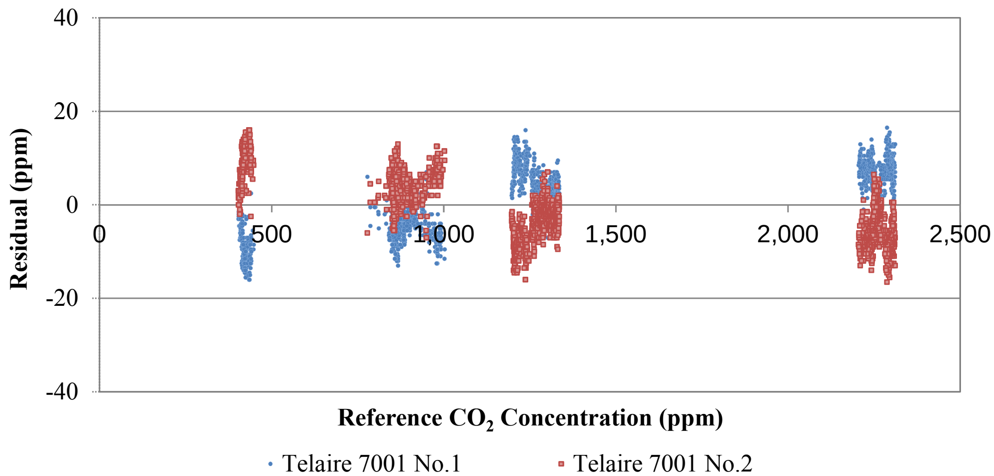


Figure C-37: Residual Plot of the Two Telaire 7001 CO_2 Sensors against the Reference CO_2 Concentration (i.e., Average CO_2 Concentration of the Two Telaire 7001 CO_2 Sensors)

C.6 Licor LI-210 Photometric Sensors

There are two illuminance calibration methods typically used in industry: a source-based and a detector-based method (Ohno 1997). The source-based method uses a standard lamp (i.e., 683 lumens per watt for spectral luminous efficacy at a wavelength of 555 nm). The accurate distance between the lamp and the sensor needs to be measured, and using the inverse square law, the reference illuminance can be calculated. The detector-based method relies on a direct substitution of the photometers with the NIST standard meter on the same illuminated plane.

Since the Licor LI-210 photometric sensors used in this study are new sensors, which were calibrated by the manufacturer, in this study, the readings of the two Licor LI-210 photometric sensors were compared against the readings of the four Extech 401025 sensors for a simple verification purpose. Both the two Licor sensors and the four Extech sensors are new sensors that were calibrated by the manufacturer. The procedure used a horizontal metal plate mounted to a mobile cart, and all six sensors were placed on the plate and exposed to various illuminance levels by moving the cart around from indoors to outdoors.

Figure C-38 shows a comparison of the Licor LI-210 photometric sensors' illuminance readings against the reference Extech illuminance readings. Figure C-39 presents the residuals that were calculated by subtracting the reference illuminance (i.e., average of the four Extech illuminance readings) from the measured illuminance of each Licor LI-210 photometric sensor.

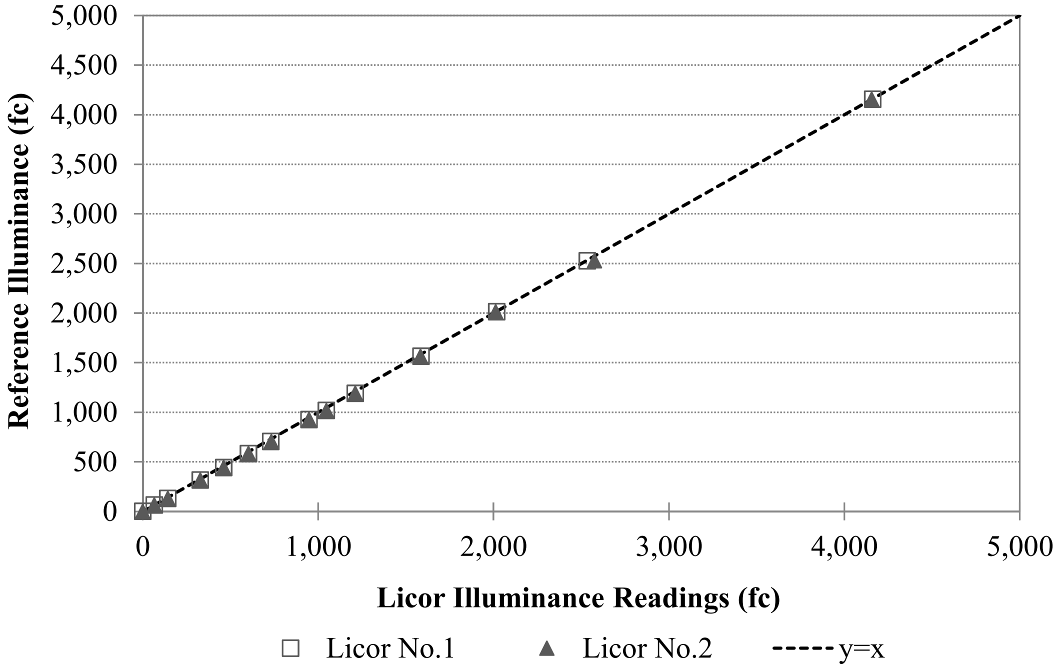


Figure C-38: Comparison of the Licor LI-210 Illuminance Readings against the Reference Illuminance from 0 to 4,150 fc

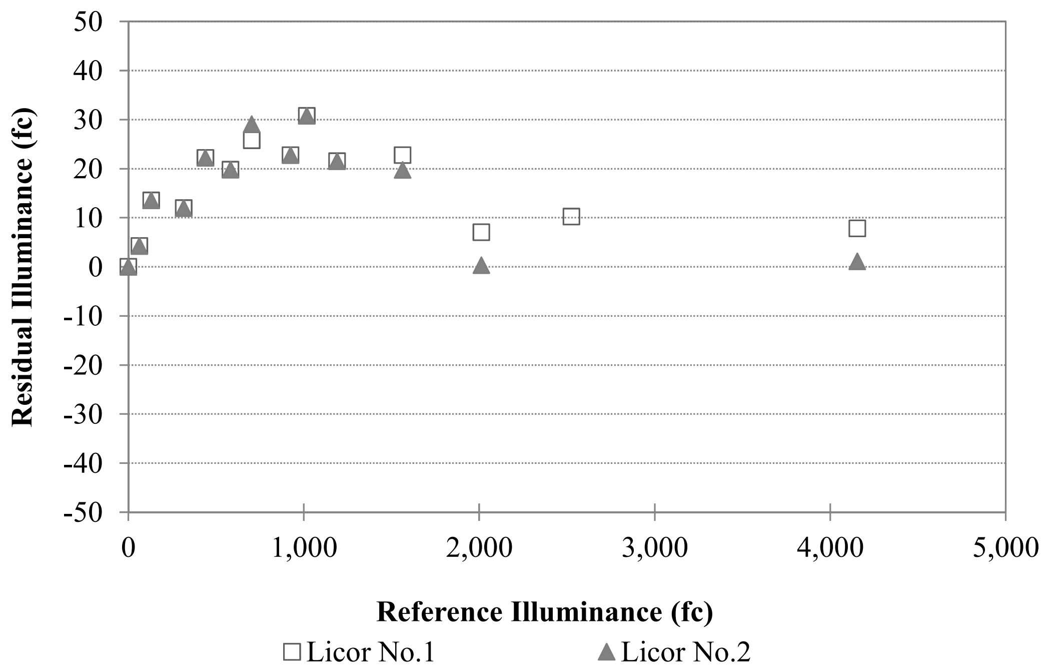


Figure C-39: Residual Plot of Illuminance Readings of the Two Licor LI-210 Photometric Sensors

C.7 Extech 407780 and TES 1350 Sound Level Meters

To accomplish a calibration of the Extech 407780 and TES 1350 sound level meters, a one-point calibrator (Bruel & Kjaer Type 4230)[241] that produces a calibration tone of 1 kHz at a level of 93.8 dB for 0.5" microphone was used. The calibration was performed by placing the calibrator on to the microphone (Figure C-40).

The calibrated two sound level meters were then compared against each other in a semi-reverberant sound room at the Texas A&M Riverside Energy Efficiency Laboratory (Figure C-41). The tested meters were mounted to a pole in the testing room (Figure C-42). To produce various sound pressure levels, a RSS (Reference Sound Sources) installed in the facility was used along with two kitchen hood fans. Table C-4 shows the five test sets performed in this study. Figure C-43 shows a comparison of the Extech 407780 readings of A-weighted and C-weighted sound pressure levels against the TES 1350 readings. Figure C-44 presents the residuals that were calculated by subtracting the Extech 407780 readings from the sound pressure levels of the TES 1350.

Table C-4: Test Sets Designed to Calibrate the Four Globe Temperature Sensors

Test Set No.	TES/Extech Response Mode	Test Conditions			Data Collectin Time
		Blower 1	Blower 2	RSS	
A-weighted dB					
Set 1	Slow	OFF	OFF	OFF	15 sec
Set 2		ON	ON	OFF	15 sec
Set 3		OFF	OFF	ON	15 sec
C-weighted dB					
Set 4	Slow	ON	ON	OFF	15 sec
Set 5		OFF	OFF	ON	15 sec

[241] Bruel & Kjaer Type 4230 calibrator conforms to the ANSI S1.4-1983 (ANSI 1983).

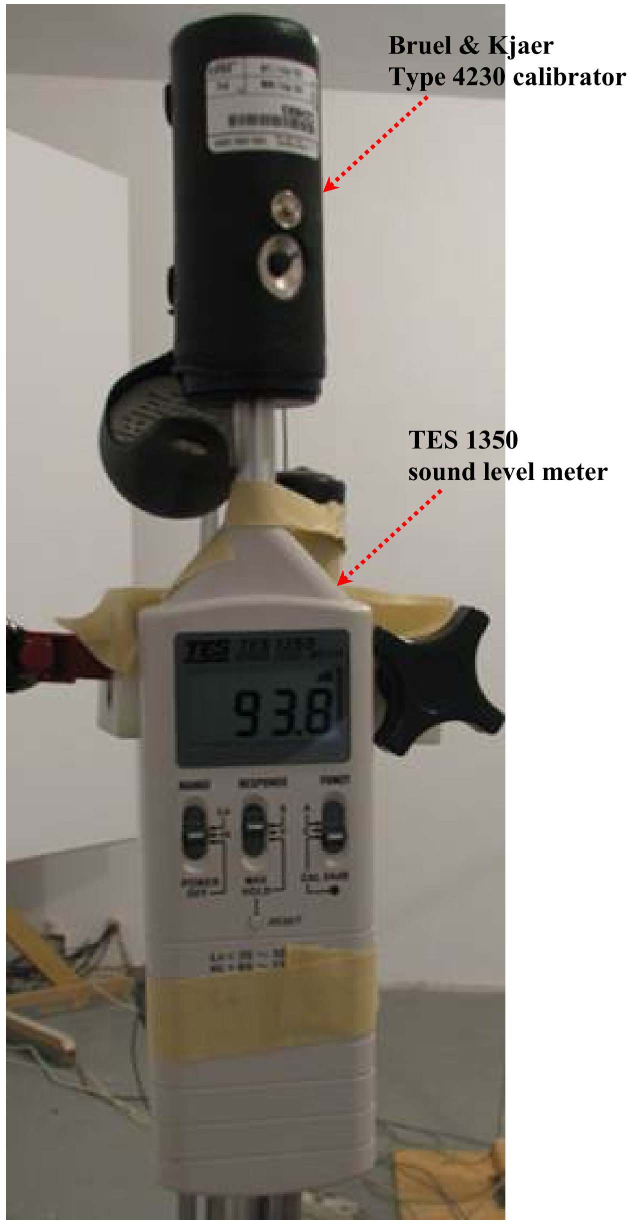


Figure C-40: Experimental Setting for the Calibration of the TES 1350 Sound Level Meter Using a Bruel & Kjaer Type 4230 Calibrator

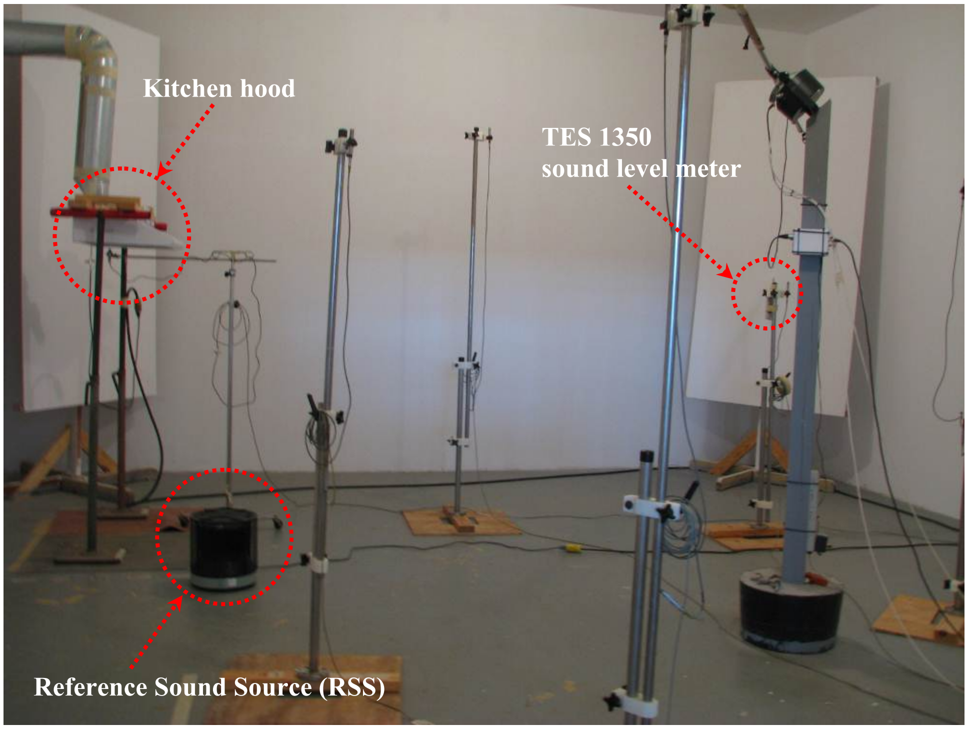


Figure C-41: Semi-Reverberant Sound Room at the Texas A&M Riverside Energy Efficiency Laboratory

Figure C-42: Experimental Setting for the Calibration of the TES 1350 Sound Level Meter In a**:** Semi-Reverberant Sound Room at the Texas A&M Riverside Energy Efficiency Laboratory

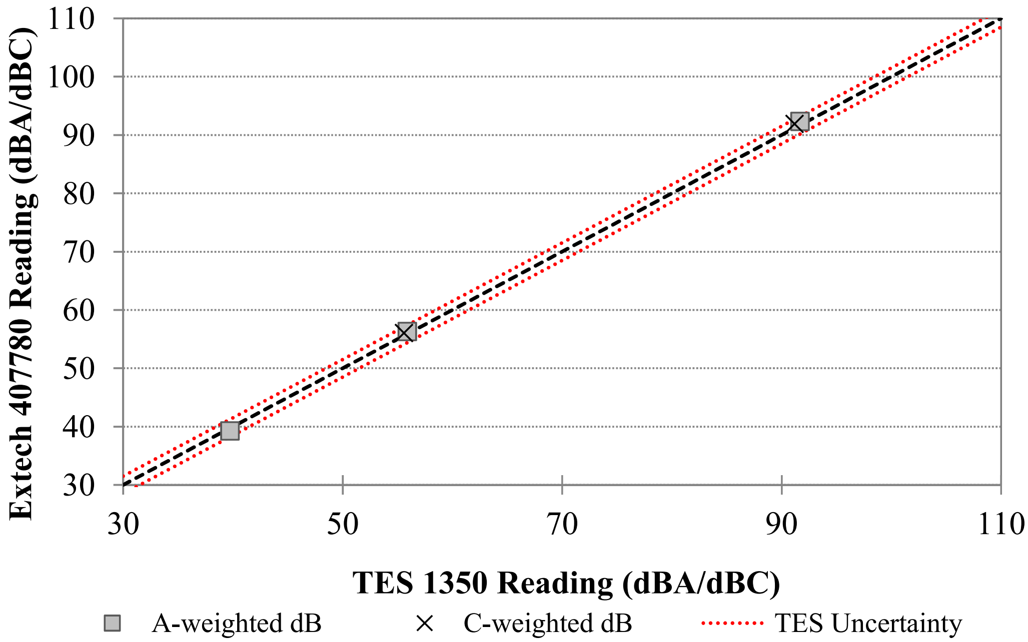


Figure C-43: Comparison of the Extech 407780 Readings of A-Weighted and C-Weighted Sound Pressure Levels against the TES 1350 Readings from 39 to 92 dBA and from 56 to 92 dBC

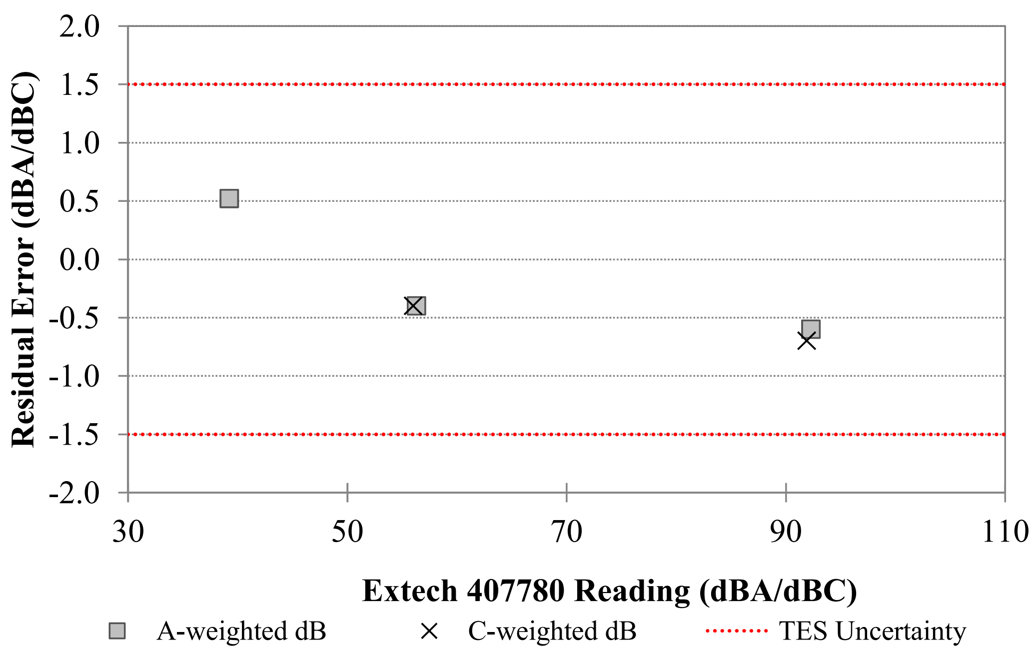


Figure C-44: Residual Plot of the A-Weighted and C-Weighted Sound Pressure Level Readings of the Two Sound Level Meters (Extech 407780 and TES 1350)

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APPENDIX D
DATA SYNTHESIS: CHILLER NO.2 ELECTRICITY USE

This appendix presents the method to synthesize the electricity use of the chiller No.2. It was found that hourly Other Electricity Consumption, which was determined by subtracting the sum of all end-uses from WBE consumption, consistently increased whenever the chiller No.2 was operated, as shown in Figure D-1 for two months from July to August 2009. Meanwhile, the electricity use of the chiller No.2 was consistently lower than the chiller No.1 at the same weather or chiller operating conditions, and the magnitude of the difference in the measured electricity use between the two chillers was similar to the increase in Other Electricity Use whenever the chiller No.2 was run (Figure D-2). Other Electricity Use is the calculated residuals that mainly consist of the exterior lighting electricity use for parking lots. The hourly profiles of Other Electricity Use that were calculated using the ASHRAE RP-1093 Diversity Factor Toolkit showed that the profile followed the expected trend (i.e., constant electricity consumption in nighttime and lower consumption in daytime) when the chiller No.1 was run (Figure D-3). On the other hand, when the chiller No.2 was run, the profile did not yield a regular repeating pattern by the hour of day.

Thus, this study calculated temperature dependent regression models of hourly Other Electricity Use when the chiller No.1 was run for nighttime and daytime, separately, as shown in Figure D-4 for 2009 models. Using the calculated models, the hourly Other Electricity Use when the chiller NO.2 was run was predicted and subtracted from the measured hourly Other Electricity Use when the chiller No.2 was run. These residuals were then added to the measured hourly chiller electricity use when the chiller No.2 was operated. As an example, Figure D-5 presents the measured hourly chiller electricity use of chiller No.1 and No.2 along with the modeled (i.e., synthesized) hourly chiller No.2 electricity use for two months from July to August 2009.

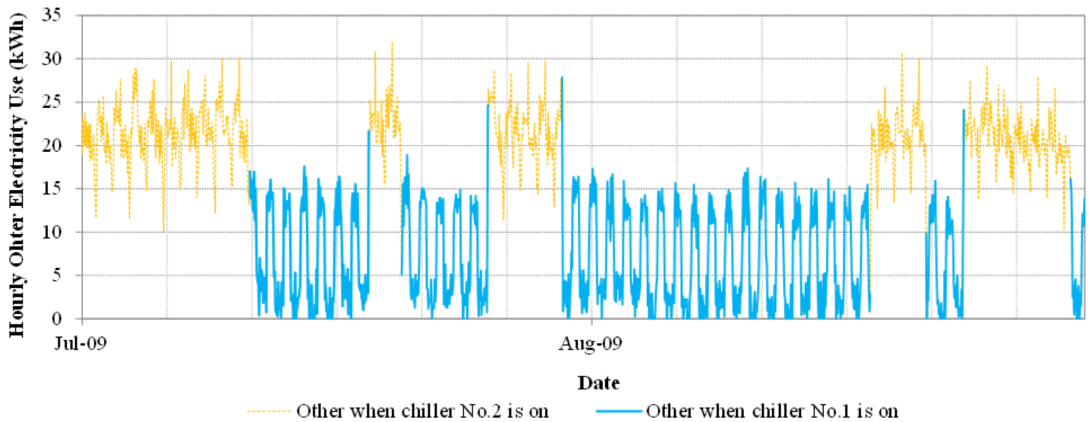


Figure D-1: Hourly Other Electricity Use of the Case-Study Building: July and August 2009

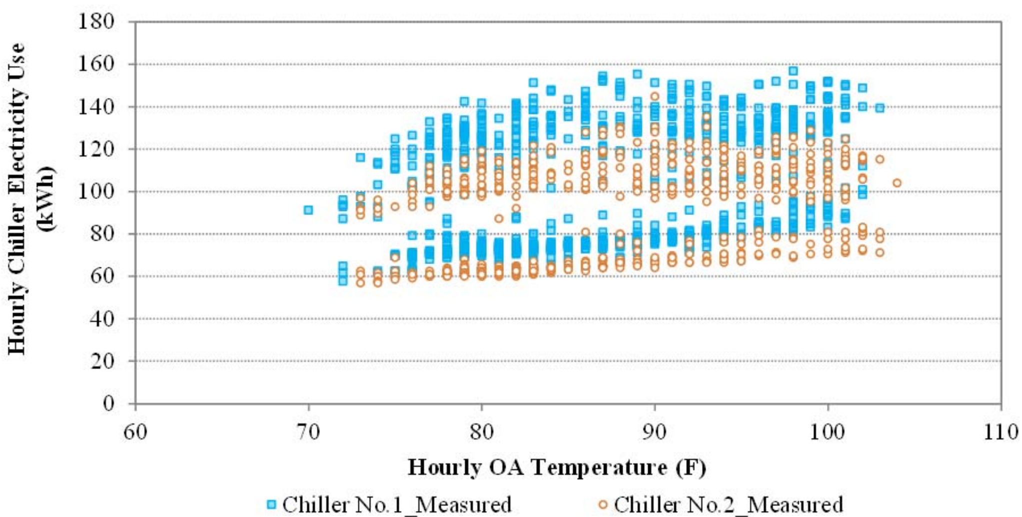
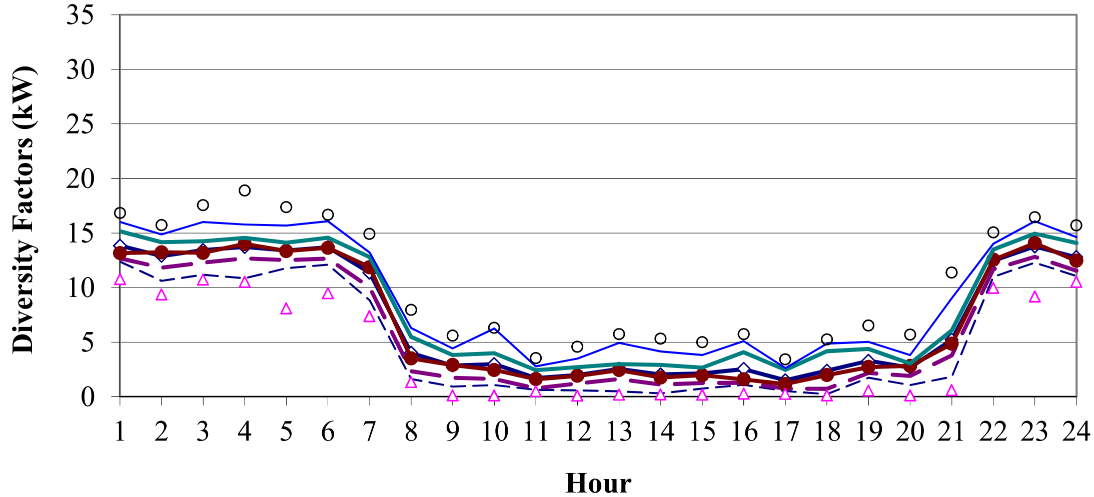
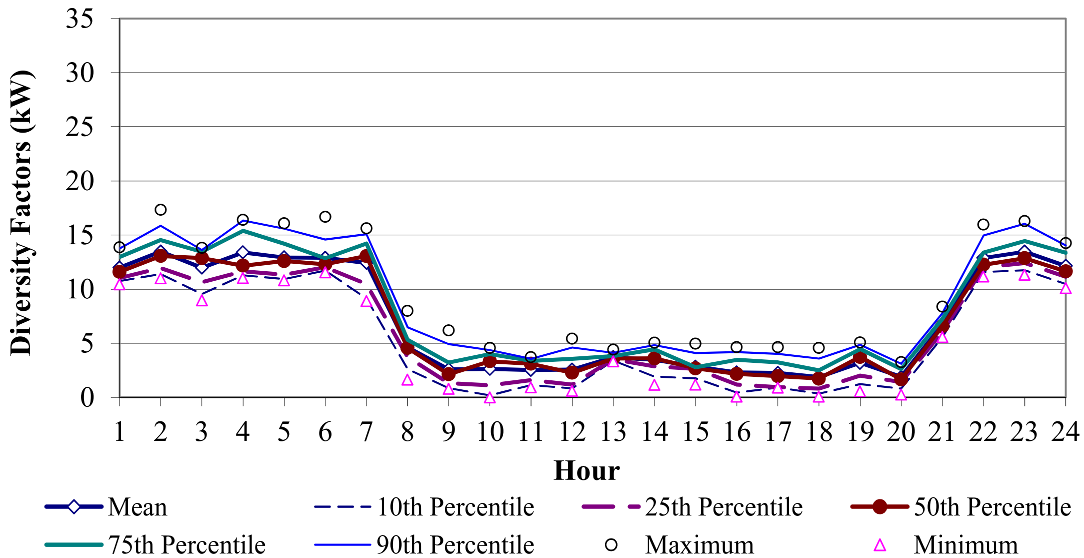


Figure D-2: Hourly Chiller Electricity Use of the Case-Study Building versus Outdoor Temperature: July and August 2009



(a) Weekday Profiles



(b) Weekend Profiles

Figure D-3: Other Electricity Use Hourly Profiles when the Chiller No.1 was Run for Weekdays and Weekends: July and August 2009

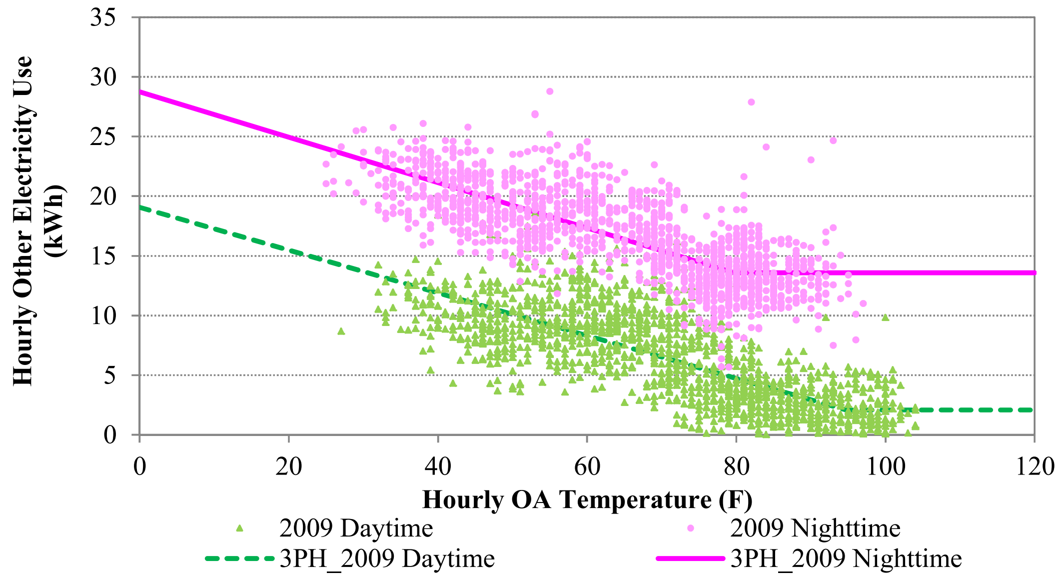


Figure D-4: Hourly Other Electricity Use of the Case-Study Building in 2009 when the Chiller No.1 was Run, Including 3-P Heating Change-Pont Models for Daytime and Nighttime

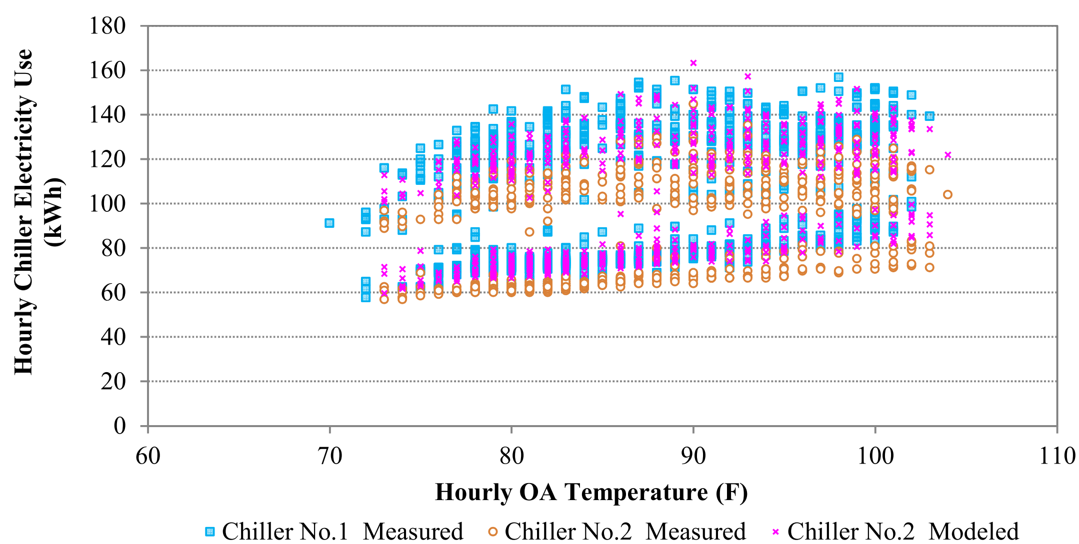


Figure D-5: Measured versus Modeled Hourly Chiller Electricity Use of the Case-Study Building: July and August 2009

APPENDIX E
IEQ DATA

This appendix presents the IEQ performance data measured in eleven office spaces of a case-study building from July to September 2011 using the portable instrumentation cart recording the occupancy using an occupancy sensor, including: four air temperatures (4 in., 24 in., 43 in., and 66 in.), four globe temperatures (4 in., 24 in., 43 in., and 66 in.), relative humidity, air speed, CO_2, total volatile organic compounds (TVOCs)[242], horizontal and vertical illuminance, as well as A-weighted and C-weighted sound pressure levels (SPL). The measurements were made over a one week period in each office with a scan interval of 10 second. The cart was placed as close to the occupant as possible while ensuring enough space for occupants to minimize disturbances. Figures E-1 through E-11 present the 5 minute interval time-series plots of the IEQ performance data collected in each of the elven offices (i.e., ID 1 through ID 11 in Table 30).

[242] The TVOCs were measured using an instrument that produces a voltage signal that increases as the TVOCs level increases. This instrument was selected to quantify the relative amount of TVOCs in the measurement space by detecting most solvent-based VOCs, including acetone, benzene, diacetone alcohol, formaldehyde, methylene chloride, methyl ethyl ketone, perchloroethylene, toluene, and trichloroethylene.

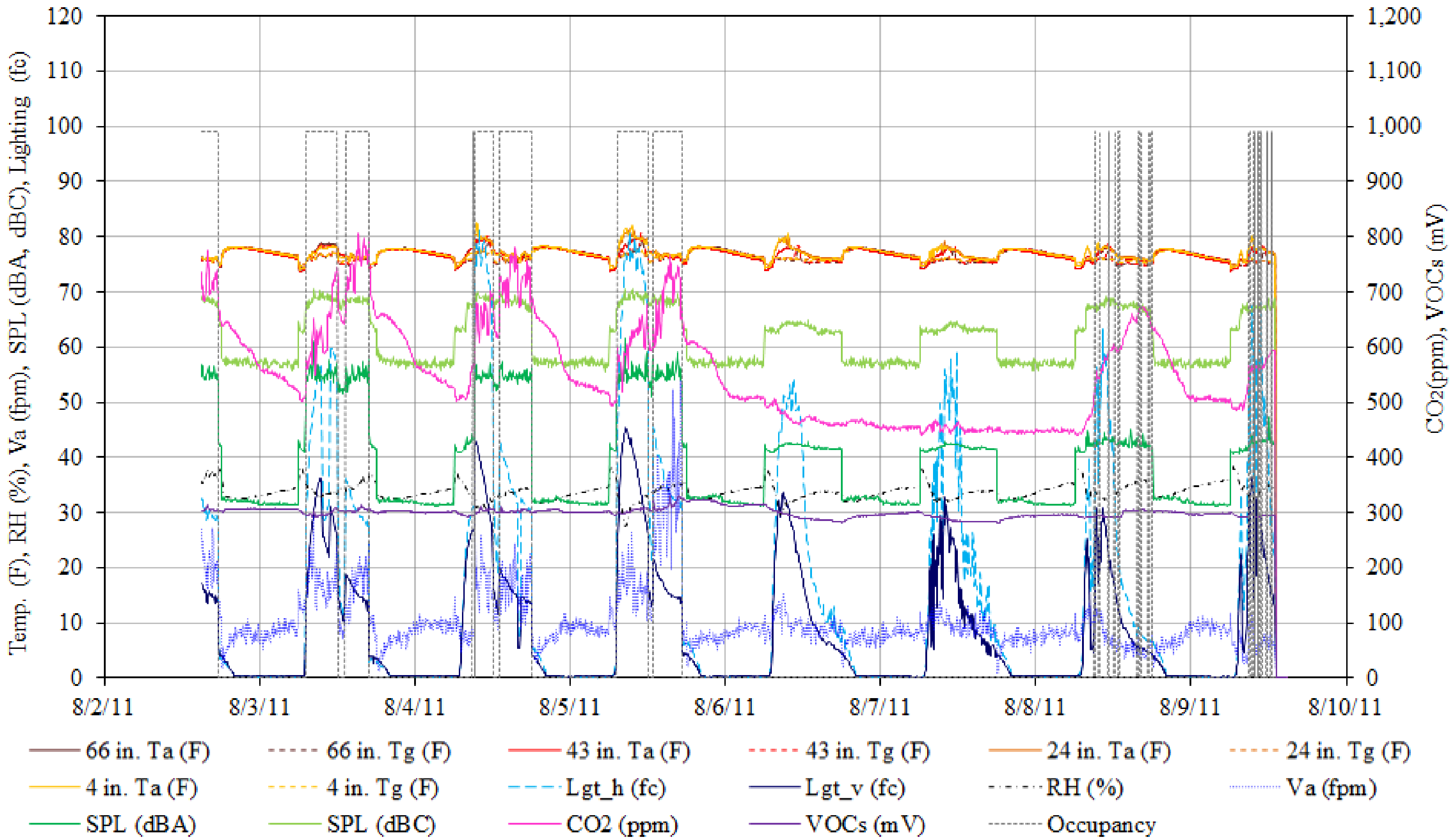


Figure E-1: 5 Minute IEQ Performance Data Measured in ID 1 East-Facing Office on the Second Floor of the Case-Study Building (August 2 to 9, 2011)

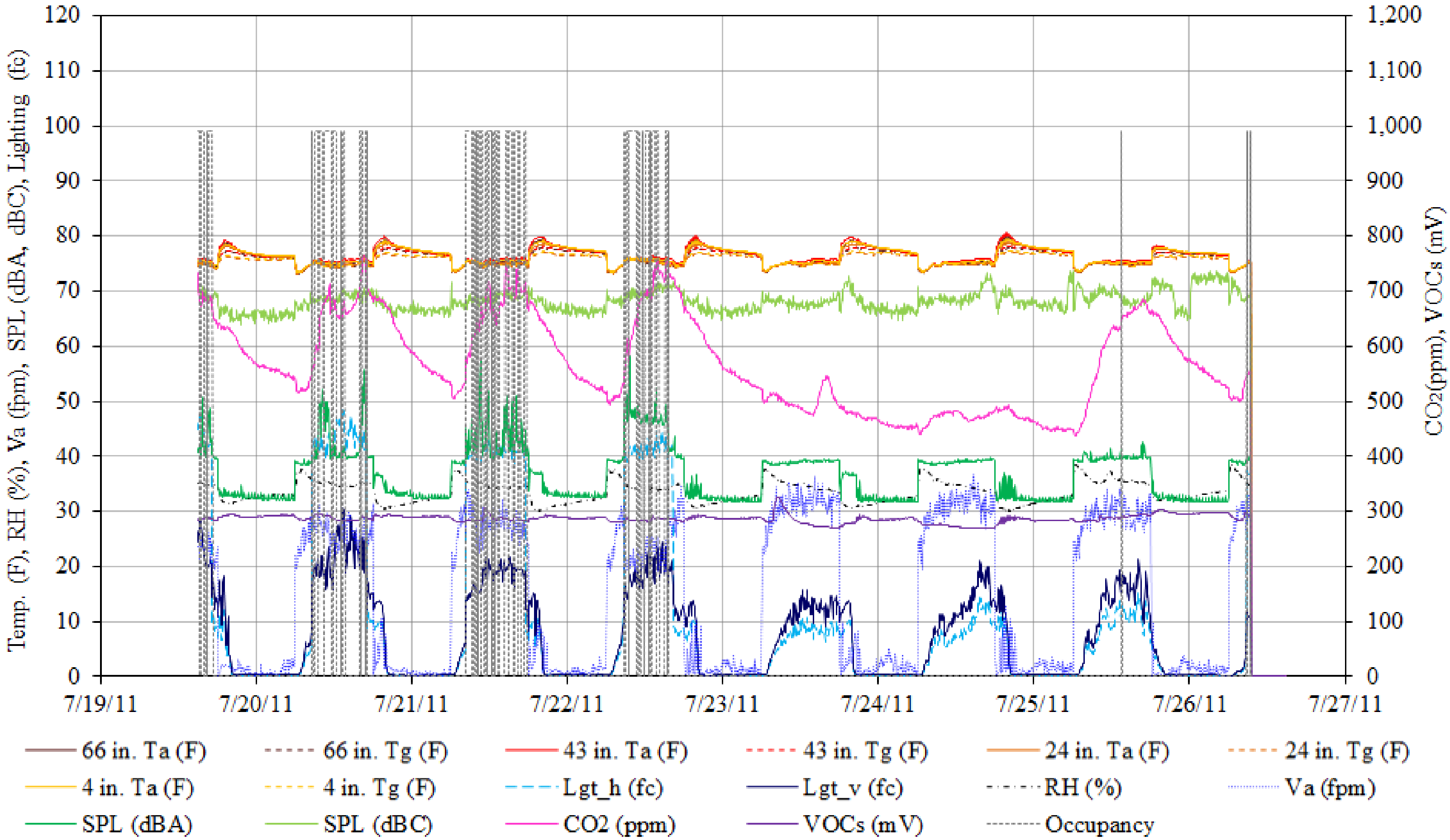


Figure E-2: 5 Minute IEQ Performance Data Measured in ID 2 North-Facing Office on the Third Floor of the Case-Study Building (July 19 to 26, 2011)

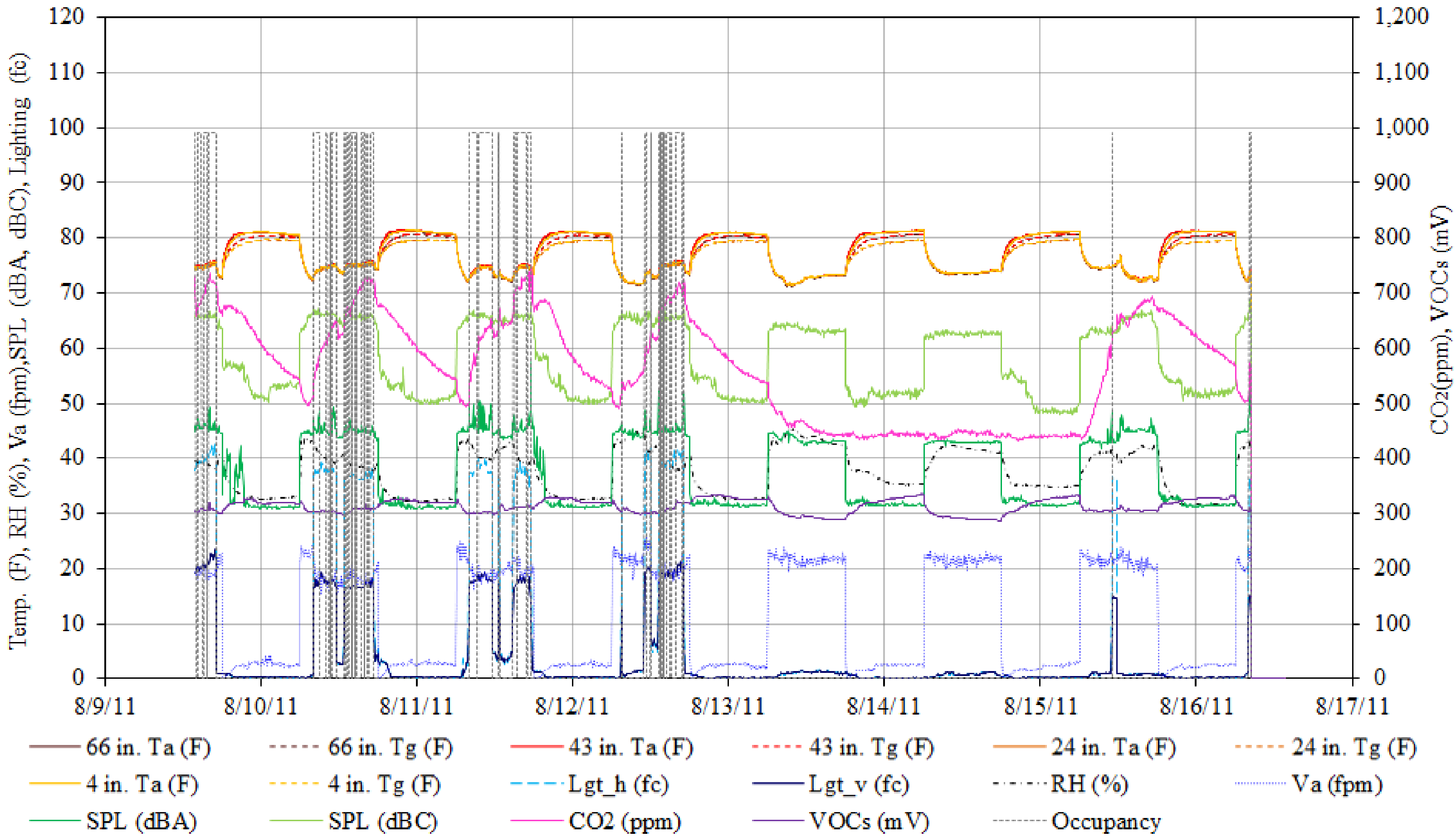


Figure E-3: 5 Minute IEQ Performance Data Measured in ID 3 North-Facing Office on the First Floor of the Case-Study Building (August 9 to 16, 2011)

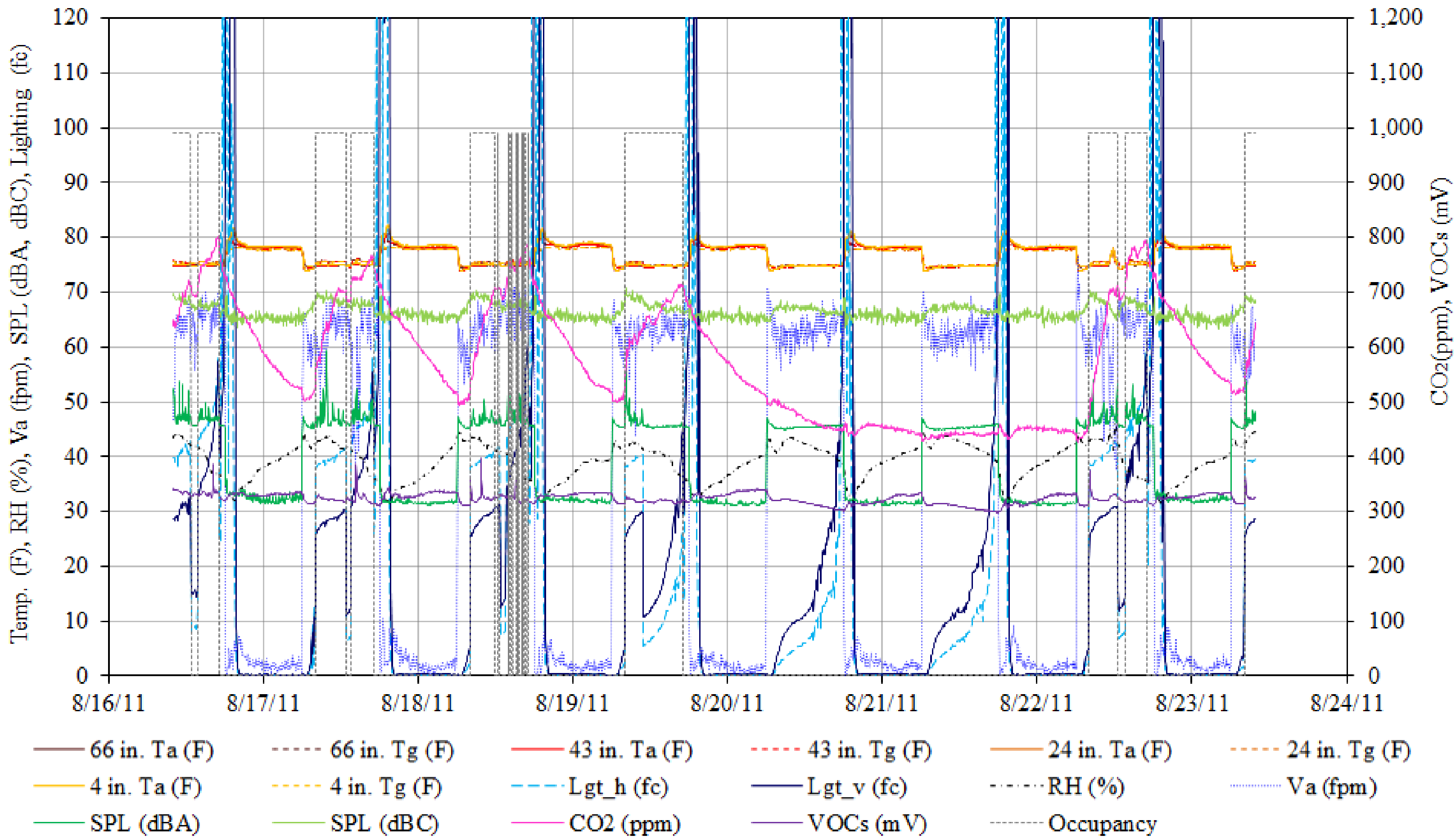


Figure E-4: 5 Minute IEQ Performance Data Measured in ID 4 West-Facing Office on the Second Floor of the Case-Study Building (August 16 to 23, 2011)

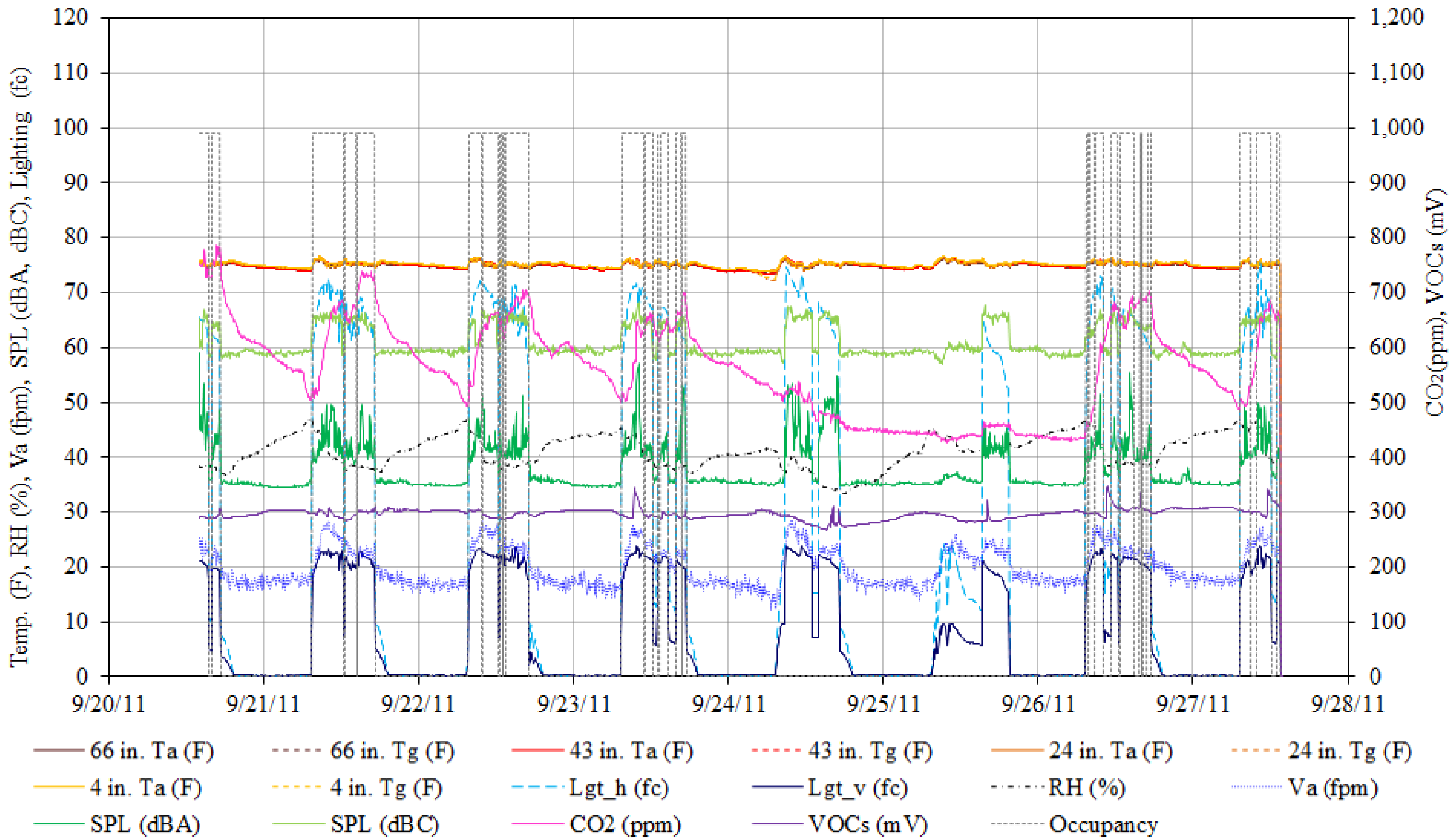


Figure E-5: 5 Minute IEQ Performance Data Measured in ID 5 Northeast-Facing Office on the Fourth Floor of the Case-Study Building (September 20 to 27, 2011)

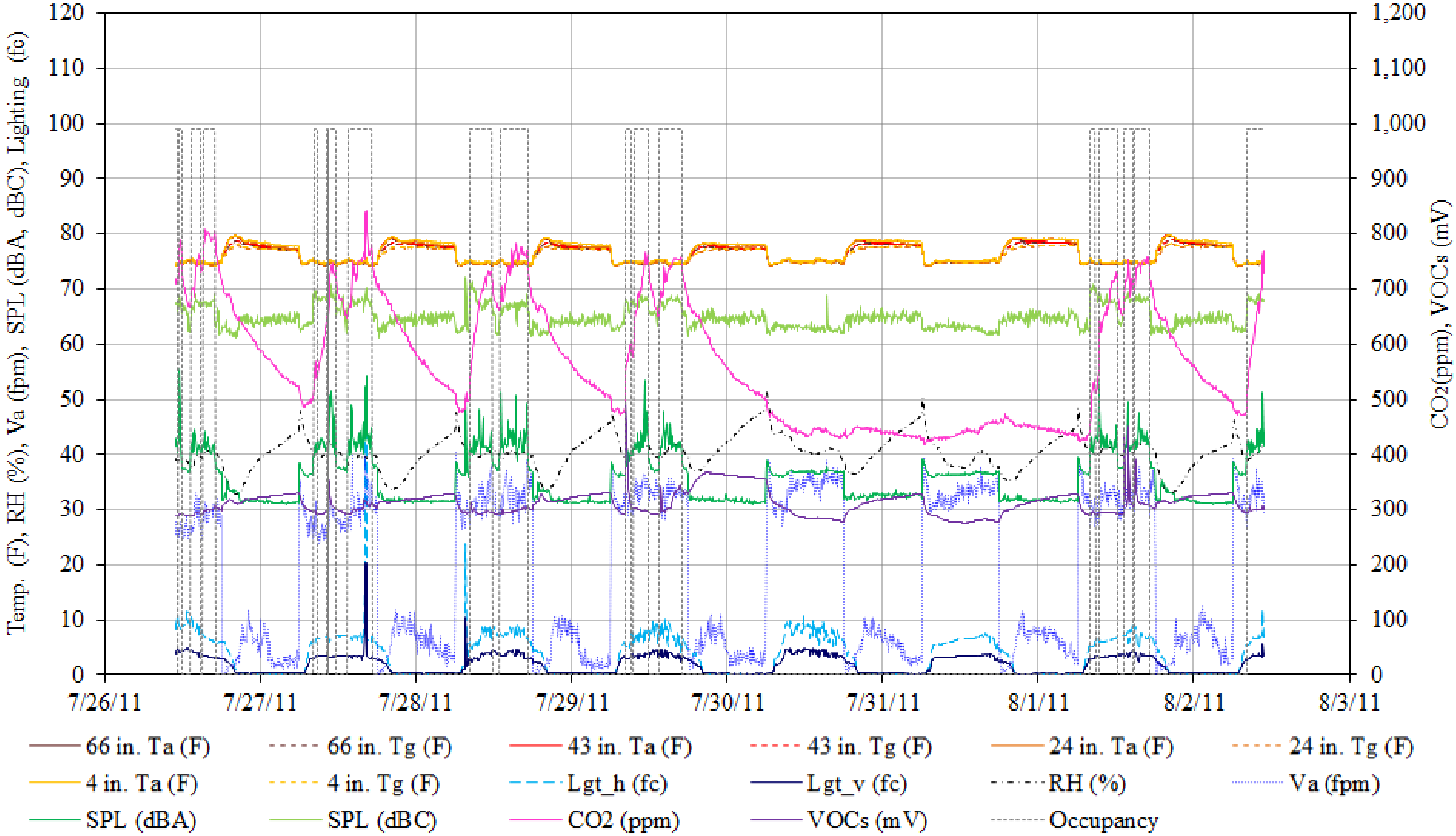


Figure E-6: 5 Minute IEQ Performance Data Measured in ID 6 North-Facing Office on the Fifth Floor of the Case-Study Building (July 26 to August 2, 2011)

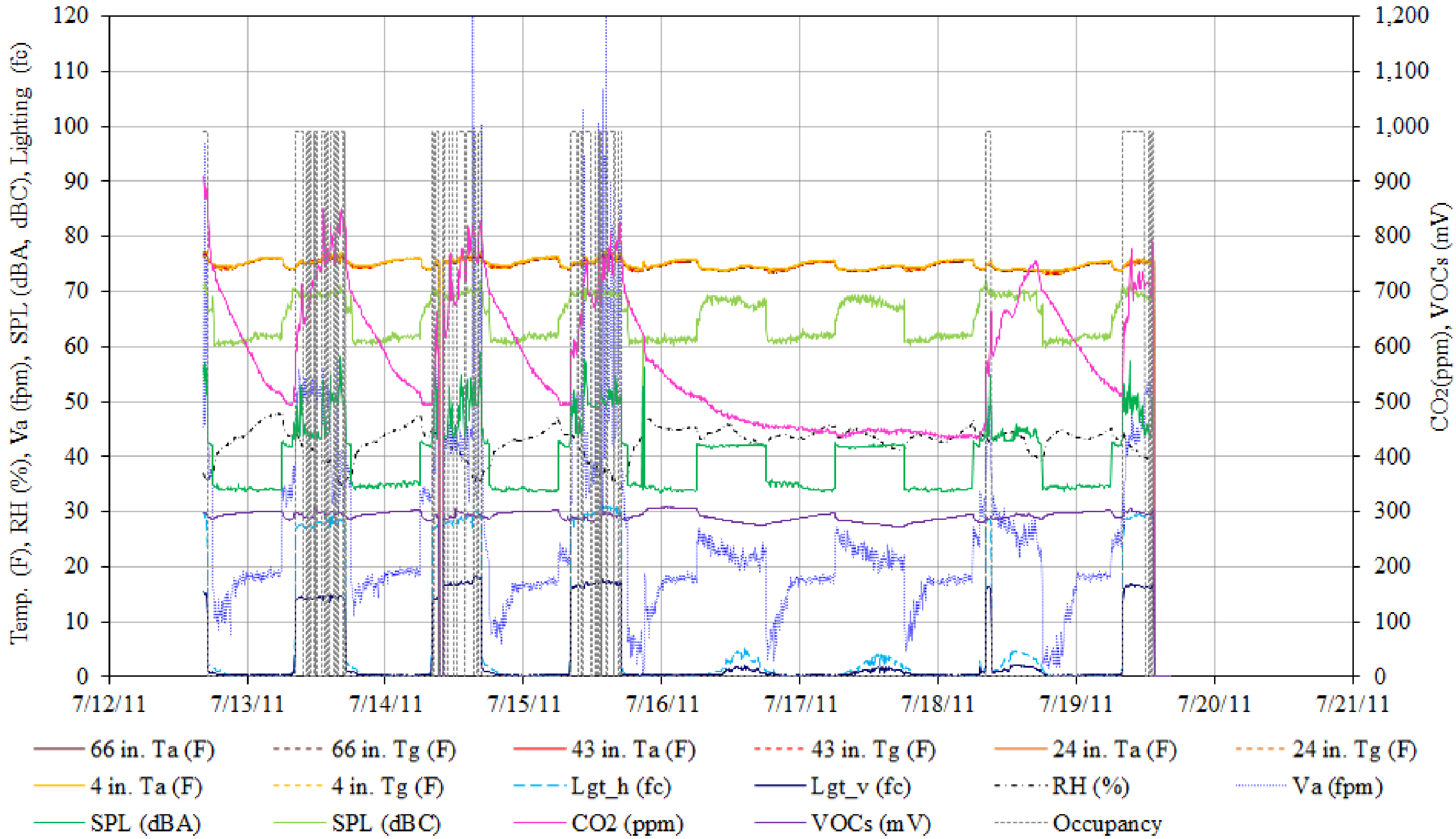


Figure E-7: 5 Minute IEQ Performance Data Measured in ID 7 South-Facing Office on the Second Floor of the Case-Study Building (July 12 to 19, 2011)

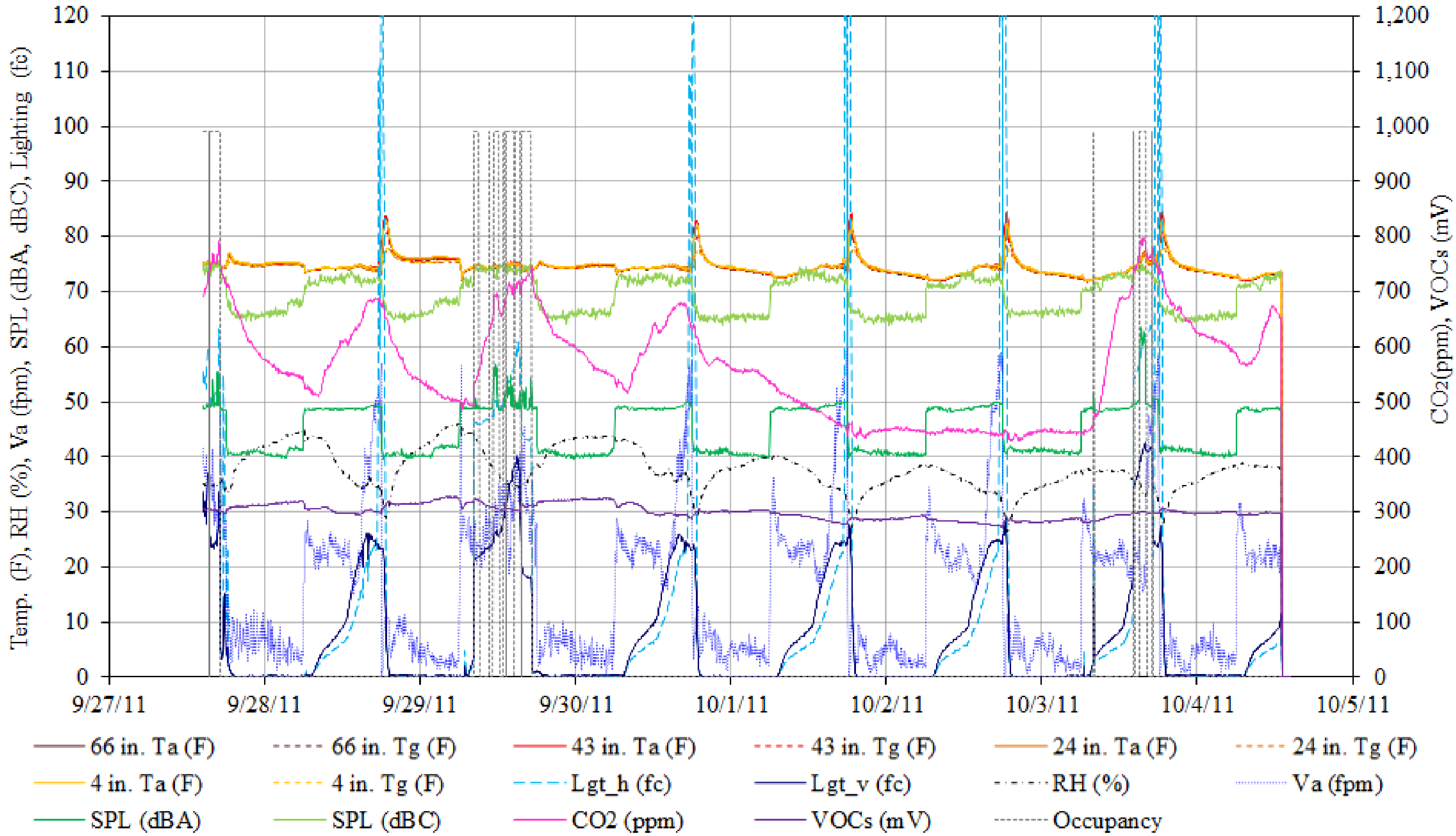


Figure E-8: 5 Minute IEQ Performance Data Measured in ID 8 East-Facing Office on the Seventh Floor of the Case-Study Building (September 27 to October 4, 2011)

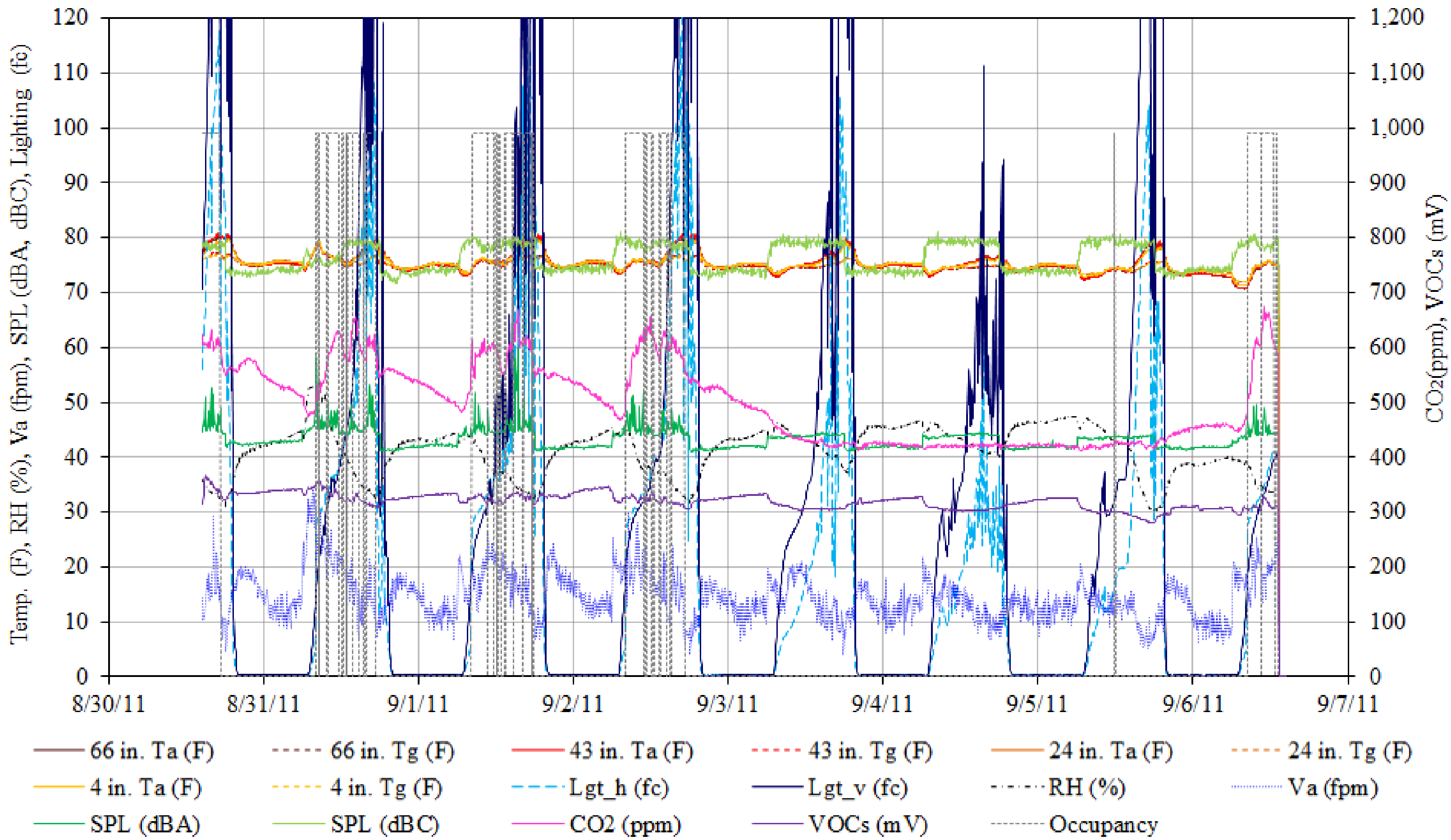


Figure E-9: 5 Minute IEQ Performance Data Measured in ID 9 West-Facing Office on the Sixth Floor of the Case-Study Building (August 30 to September 6, 2011)

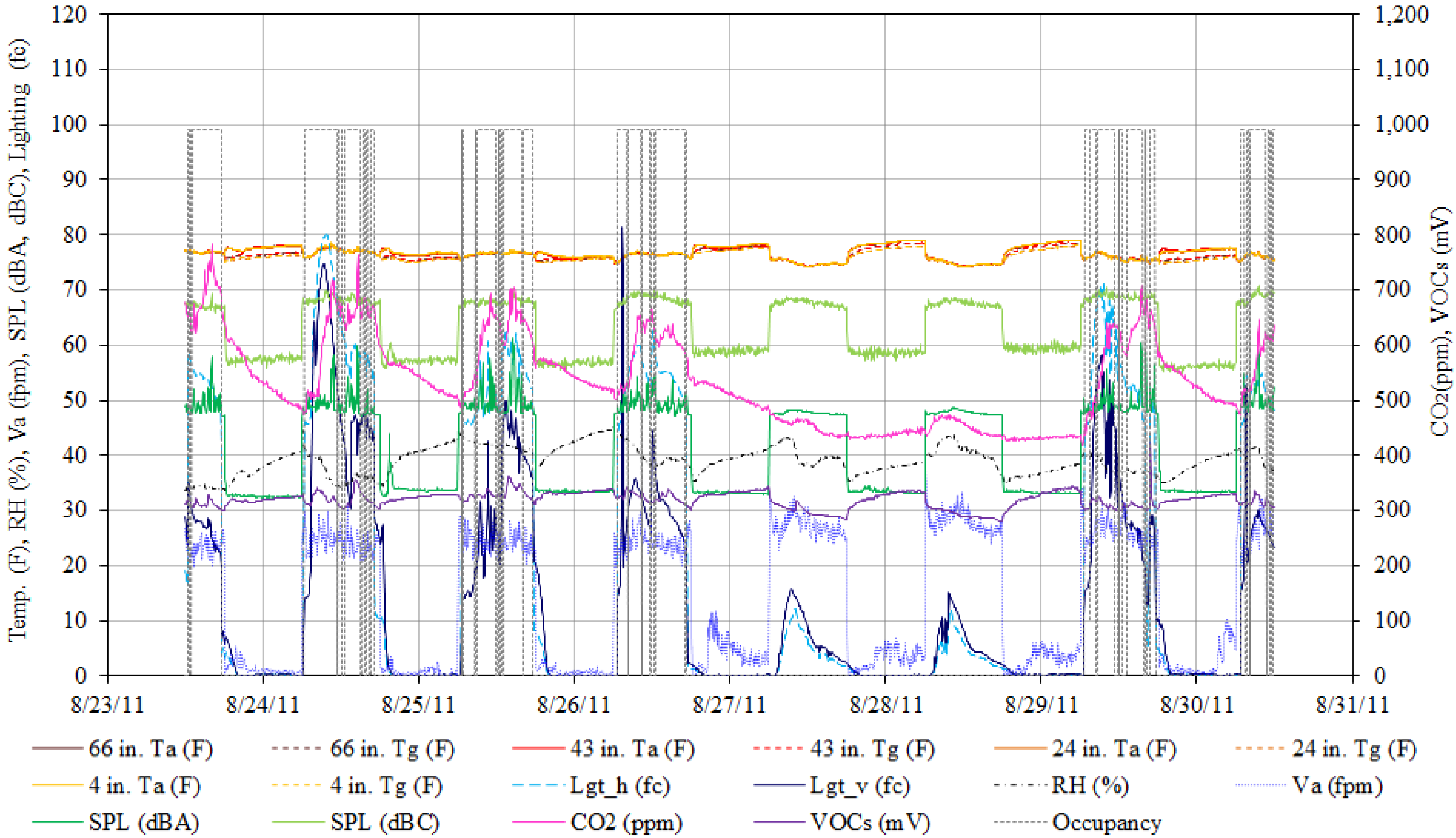


Figure E-10: 5 Minute IEQ Performance Data Measured in ID 10 East-Facing Office on the Sixth Floor of the Case-Study Building (August 23 to 30, 2011)

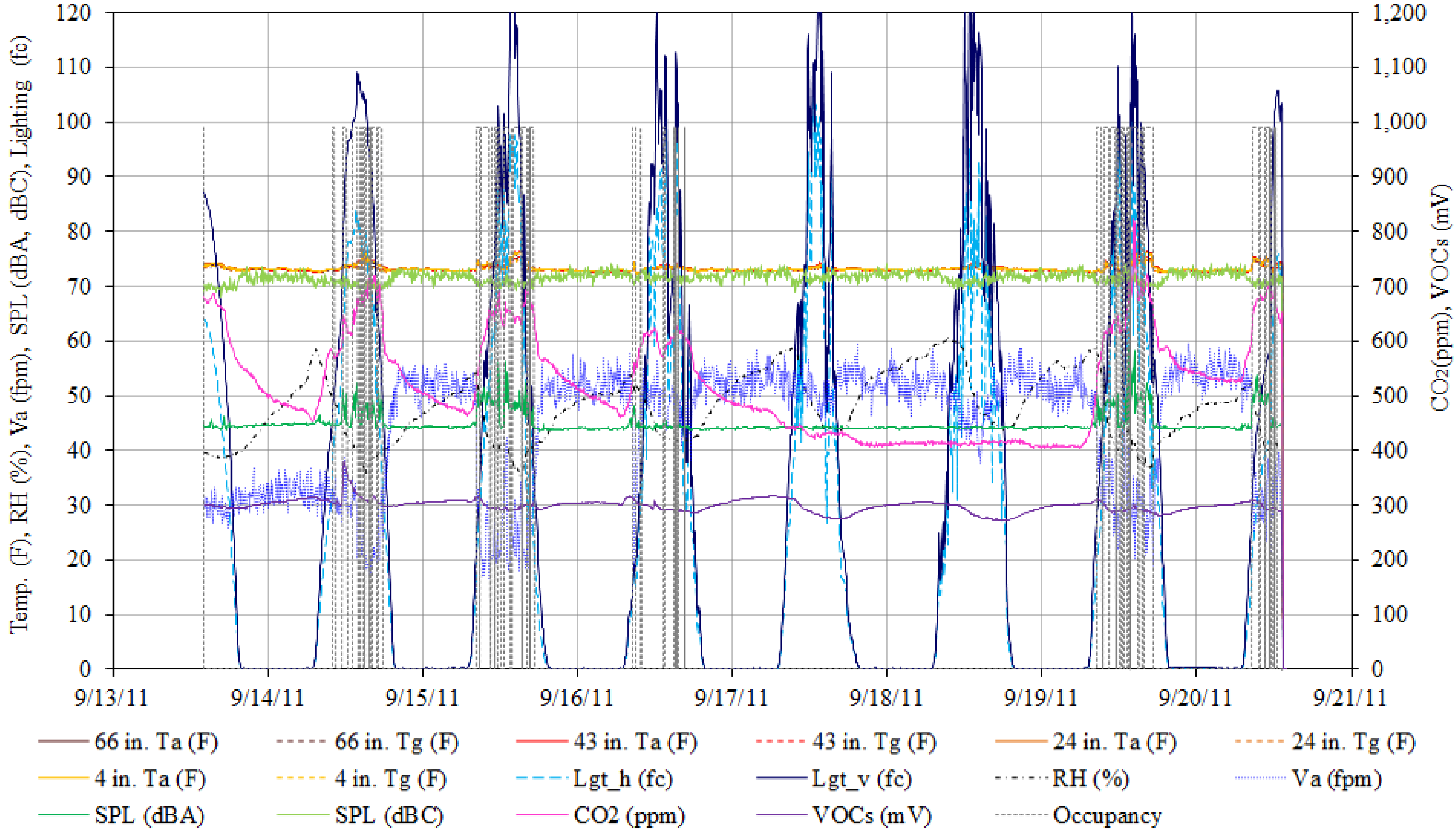


Figure E-11: 5 Minute IEQ Performance Data Measured in ID 11 South-Facing Office on the Sixth Floor of the Case-Study Building (September 13 to 20, 2011)

APPENDIX F
EXAMPLE IEQ DASHBOARD SNAPSHOTS

This appendix provides a description of the example time-series IEQ dashboard plots presented in Figures 142 through 145. The IEQ performance data used in this example are the 1 minute interval data collected during a pilot test of the developed IEQ monitoring system, which was conducted in another building located in the same city as the case-study building in June 2011. The building used in this example is a new one-story office building conditioned with ten packaged rooftop AHUs. The data was collected in an interior shared office space over one week from June 9 to 15, 2011 for thermal comfort (Figure 142), IAQ (Figure 143), lighting (Figure 144), and acoustics (Figure 145) with the corresponding benchmarks as applicable.

In Figure 142, the air temperatures (solid lines) and globe temperatures (dotted lines) at four different heights are presented using different colors in the upper plot, and in the lower plot, the calculated vertical air temperature difference between head (43 in.) and ankles (4 in.) is plotted with the corresponding benchmarks in the ASHRAE Standard 55-2004 and Standard 55-2010. Almost no variations were observed between air and globe temperatures, which are not unreasonable for interior offices without solar radiations. A vertical air temperature difference was found to be smaller than the 3 F criteria specified in the ASHRAE Standard 55-2004 and Standard 55-2010, although it approached the 3 F limit during the unoccupied hours when the system was not run. When compared the thermal environments during occupied versus unoccupied, it was observed that the space was conditioned differently for business hours (i.e., 8 a.m. to 5 p.m. weekdays[243]) versus non-business hours[244], which were controlled by a setup schedule of the building's thermostat. One exception was found in the afternoon of Sunday, June 12, 2011, when the system was manually turned on for one hour. It was also observed that the space was pre-conditioned about two and a half hour before the building was occupied. During business hours, the rooftop AHU of the space was turned on and off to meet the regular set point of the corresponding thermostat, which yielded a constant magnitude of temperature variations in the plot between 70 F and 73 F.

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[243] This measurement week includes five weekdays: from June 9 to 10 and June 13 to 15.
[244] This measurement week includes two weekend days: June 11 to 12.

Next, in Figure 143 for IAQ, the indoor CO_2 concentration measured in the example office is plotted with the concurrent outdoor CO_2 concentration measured at the nearby Solar Test Bench (STB) (ESL 2012) on the roof of the Texas A&M Langford Architecture Center in the upper plot. The lower plot presents the TVOCs[245] measured in the same office. Not surprisingly, once the space was occupied, the CO_2 level of the space dramatically increased to the maximum level near 800 ppm, and it decayed to the level of outdoor CO_2 once the space was unoccupied[246]. A higher level of CO_2 buildup was observed in the afternoon. The observed CO_2 generation and decay patterns were pretty consistent between days. Meanwhile, once the system was turned off, a TVOCs buildup was observed in this newly-built building[247], although the level stopped increasing once it reached a certain level below 350 mV. The observed maximum level is still below the cautionary level per the manufacturer's note (Eco Sensors, Inc. 2011) which specifies two benchmarking criteria: cautionary at 650 mV (i.e., 25 ppm for perchloroethylene) and hazardous at 1,040 mV (i.e., 50 ppm for perchloroethylene)[248].

Figure 144 presents horizontal and vertical illuminance measured for lighting performance evaluation with the corresponding benchmarks provided in the ASHRAE PMP. Since the measurements were made in an interior office, any time-varying distribution of indices was not observed, which may indicate the appropriateness of the use of lighting spot measurements for interior offices.

Finally, Figure 145 presents A-weighted equivalent sound pressure levels (LAeq) and C-weighted equivalent sound pressure levels (LCeq) using different colors with the corresponding benchmarks for LAeq in the upper plot. In the lower plot, the calculated LCeq – LAeq difference is plotted. As a result, when the system was not run, the space's background noise (i.e., LAeq) was found to meet the criteria in the ASHRAE PMP, between 30 and 40 dBA. However, once the system was run, both LAeq and LCeq increased by approximately 10 dBA (or dBC). In

[245] The TVOCs were measured using an instrument that produces a voltage signal that increases as the TVOCs level increases. This instrument was selected to quantify the relative amount of TVOCs in the measurement space by detecting most solvent-based VOCs, including acetone, benzene, diacetone alcohol, formaldehyde, methylene chloride, methyl ethyl ketone, perchloroethylene, toluene, and trichloroethylene.

[246] There were some occasions when the indoor CO2 concentration exceeded the concurrently measured outdoor CO_2 concentration, which may be because of the location of this example building. This example building is located in a relatively remote area compared to the location of STB at the main Texas A&M campus.

[247] The building construction was completed in early 2011, and interior buildup construction was completed near June 2011.

[248] Hazardous conditions are the conditions near the Occupational Safety and Health Administration (OSHA) threshold limit values (TLV) of individual VOCs.

addition, some variations were observed in both LAeq and LCeq when the system was run, which was partly affected by the system on and off. For the LCeq, another type of variation was observed even when the system of this example office was not operated (i.e., on weekends from June 11 to 12). This variation occurred when one of other rooftop AHUs was run, which indicates poor acoustics of the building. When examined the LCeq – LAeq difference, this office was found to have a relative high LCeq – LAeq difference. Using the method by the Swedish National Board of Health and Welfare and the Swedish Royal Board of Building[249], the measured noise in this office can be considered as low frequency noise, which indicates a possibility of annoyance related to low frequency in this office.

[249] Based on some Swedish recommendations (Swedish National Board of Health and Welfare, as cited in Kjellberg et al. 1997; Swedish Royal Board of Building, as cited in Kjellberg et al. 1997), the measured noise can be regarded as low frequency if the LCeq – LAeq difference exceeds 15-20 dB, and if the difference is greater than 25 dB, there is a chance of serious low frequency noise annoyance.