A STUDY OF OCCUPANCY-BASED SMART BUILDING CONTROLS IN COMMERCIAL BUILDINGS

A Dissertation

by

CHUL KIM

Submitted to the Office of Graduate and Professional Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

Chair of Committee,	Jeff S. Haberl
Committee Members,	Juan-Carlos Baltazar
	Wei Yan
	Michael Pate
Head of Department,	Gregory A. Luhan

December 2020

Major Subject: Architecture

ABSTRACT

Occupant behavior has a significant influence on energy consumption in buildings because HVAC, lighting, equipment, and ventilation operations are often tied to occupancy-based controls. However, currently, the traditional methods for the prediction of occupant behavior using a building energy modeling approach has begun to face difficulties due to the complex nature of occupant behavior and the introduction of the new technologies (i.e., occupancy sensors) in new and renovated construction. Research in the previous studies revealed that actual occupancy rates in office buildings were quite different compared to typical simulation schedules used in the analysis of building codes and standards. Therefore, large potential energy use reductions are expected when occupancy-based controls are used in building operations. In addition, many workers are recently encouraged to work more at home, which may cause larger unoccupied periods for a significant portion of time at a commercial office building. This fact further increases the need to better understand various occupancy schedules and usage trends in building energy simulations.

However, currently, the U.S. commercial building energy codes and standards (i.e., ASHRAE Standard 90.1) do not fully support building energy modeling for occupancy-based controls for code-compliance. Performance paths (i.e., Appendix G method) in Standard 90.1-2016 offer only partial credits for occupancy-based lighting controls, which tend to underestimate the potential reduction from the use of occupancy-based controls. Also, the requirements of the ASHRAE Standard 90.1 performance path require the mandatory use of identical schedules for the baseline and the proposed design models, which do not present the calculation of reduction from occupancy-based controls.

Therefore, this study seeks to analyze occupancy-based controls to determine how varying factors may impact energy use reduction predictions in commercial office buildings. These factors include: different building types (i.e., lightweight versus heavyweight), with different system types (e.g., variable air volume versus packaged single-zone systems) by orientation (i.e., N,S,E,W) in different climates (e.g., cold and hot climates).

To achieve the goal of this study, a reference office building was analyzed based on the prototype office building model that was developed by the U.S. DOE and PNNL for small office building for Standard 90.1-2016. Using this model, different thermal zoning models were developed for single-zone and five-zone models to evaluate the impact of occupancy-based controls in the prototype office building. The impact of occupancy-based controls was then evaluated using simulation to study the influence of occupant behavior on HVAC, lighting, equipment, and ventilation system energy use. A sensitivity analysis of each occupancy control schedule (i.e., occupancy, lighting, equipment) was performed in 100%-0% variations to determine interactions between occupancy variables. In addition, simulations for a set of specific occupancy control schedules (i.e., occupancy, lighting, equipment) were conducted in hot-humid and cold-humid climate zones with different building designs (i.e., a raised floor lightweight building and a heavyweight building with varying window-to-wall ratios) and different HVAC system types (i.e., packaged variable air volume versus packaged single-zone systems) to identify potential energy use reduction of occupancy-based building controls on annual energy consumption. The results showed substantial energy reduction potential from varying factors related to occupancy-based controls in commercial office buildings. The evaluation in two climate zones showed a range of energy reduction in Houston and Chicago due to the weather-dependent loads (i.e., heating, cooling, ventilation). Heavyweight material models showed higher percent energy use reduction potential ratios and less energy use compared to the reference building and lightweight models. Also, smaller window-to-wall models represented less total energy use than higher window-to-wall models, which led to higher energy use reduction ratios for smaller window-to-wall ratios. The PVAV systems had higher total load reduction ratios and less total energy use than PSZ systems in Houston and Chicago, especially for heating loads. Whole-building occupancy-based controls revealed more energy use reduction potential ratios in Houston compared to Chicago.

The impact of orientation was different depending on thermal zone locations. However, the impact was not fully analyzed because this study did not evaluate combined occupancy sensor controls, daylight controls, and daylighting-based schedules. The largest energy use reduction contributors to occupancy modeling were the internal load factors (e.g., lighting, equipment). The outcome of this study should help guide the development of a guideline for evaluating how occupancy-based building controls can be better incorporated in different building types for different climate zones to reach compliance with ASHRAE Standard 90.1-2016.

DEDICATION

To

My Loving God and Family

ACKNOWLEDGEMENTS

I would like to thank God and my family for their consistent faith and contribution throughout my life. I have yearned for this moment many a long day with a sometimes excited heart and sometimes an exhausted mind from the long journey in the Ph.D. study.

Six years ago, I started my long journey into the Ph.D. program. At that time, I was convinced that this challenge would broaden my perspective in architecture and give me more opportunities to achieve my dream to make a more efficient and greener societies in this world. However, the process of this study was not always smooth. It was often blocked and detoured, which frustrated me in the middle of the journey to find solutions in order to solve my problems step-by-step. However, I believed that my study could be achieved with the help of many people.

Therefore, I would like to express my special thanks to the people who have helped me. First, I would like to express my special thanks to my Chair and advisor, Prof. Jeff S. Haberl, for his incredible support and guidance throughout the whole period of my study. He has been a good listener and has given me warm advice with the unchanging belief that encouraged me to withstand my hardships that I have encountered during my study. I am also grateful to Prof. Juan-Carlos Baltazar. He has also dedicated his valuable time to guide me with his plentiful knowledge and has inspired me to investigate my research down the right path. Also, I would like to gratefully thank Professor Wei Yan. He was kind to listen to my study and to give much-needed guidance even though he was very busy with his own teaching and academic work. Last but not least, I want to sincerely thank Prof. Michael Pate at the Department of Mechanical Engineering. He was willing to be my committee member and gave me incredible insights and suggestions to develop a more holistic research plan.

I would like to also thank my valued friends and colleagues at the Energy Systems Laboratory, particularly in the Texas Emissions Reduction Plan (TERP) group: Sungkyun Jung, Farshad Kheiri, Qinbo Li and Jounghwan Ahn. We have encouraged one another, which made me overcome my challenges during the Ph.D. program.

Lastly, I would like to express my deep gratitude to my loving father, Ilhwan Kim, my loving mother, Mija Kim, and my loving older sister, Hyejin Kim, for their endless love and devotion during this period. They have gladly participated in my long journey and patiently waited for my study for a long time with faith. I believe that they deserve this pleasure and honor together.

CONTRIBUTORS AND FUNDING SOURCES

Contributors to the study

This dissertation was supervised by a committee. The committee members include Prof. Jeff S. Haberl, Prof. Juan-Carlos Baltazar, and Prof. Wei Yan in the Department of Architecture and Prof. Michael Pate in the Department of Mechanical Engineering at Texas A&M University. The study was independently conducted and completed by the student.

Funding Sources

This study for the dissertation was partly supported by an ASHRAE Graduate Student Grant-in-Aid for the period of the 2018-2019 academic year. This support has been genuinely appreciated.

TABLE OF CONTENTS

Page

LIST OF FIGURES

LIST OF TABLES

Page

1. INTRODUCTION

1.1. Background

In our lives, people spend most of their time in the built environment for their residence and business. Representatively, buildings provide many places for physical safety from an external environment and a healthy indoor environment for thermal comfort and well-being. According to the U.S. statistics (U.S.BLS 2017) in 2017, employees typically consumed most of their daily schedules in the buildings. They used an average of 8.39 hours for their business and related activities and spent an average of 10.25 hours for household activities, including caring and helping household members or personal care like sleeping. These survey results underline why architects and engineers should carefully design building environments and effectively control building systems for occupants. However, most activities in buildings require energy consumption to operate building systems (i.e., HVAC, lighting, appliance, and ventilation).

As a result, the residential and commercial end-use energy in the United States accounted for about 40% of the 2016 total source energy use (97.4 Quadrillion Btu). Commercial buildings alone consumed 18.2 Quadrillion Btu, which was equivalent to 18.7% of the total source energy consumption (U.S.EIA 2017). Moreover, building systems (i.e., HVAC, lighting, equipment) are dominant contributors to energy consumption. For example, HVAC (Heating, Ventilation, and Air Conditioning) systems are in charge of 40% of the total commercial end-use energy consumption (Azar and Menassa 2012) to maintain healthy and comfortable indoor environments, which would be equivalent to 7.28 Quadrillion Btu per year. Also, the 2012 CBECS data showed energy consumption by building components in U.S. commercial buildings. 44% of the total energy consumption was reported from HVAC systems to operate heating, cooling, and ventilation systems and 18% of total energy consumption was used for lighting and equipment systems in commercial buildings (U.S.EIA 2016).

On the other hand, in building system operations, occupant behavior is a primary driver to determine building usage schedules and control types. However, the nature of occupant activities and usage habits in buildings is quite uncertain and unpredictable, which makes challenges in building energy simulations to estimate building energy performance accurately. Moreover, the effect of occupant behavior is heterogeneous because it is motivated by many interactions between occupant behavior-related factors, including indoor factors (i.e., biological, psychological, and social factors) and outdoor factors (i.e., place/location, time) (IEA-EBC, Annex 66 2013). It could significantly affect the operations of building systems (i.e., lighting, equipment, and HVAC systems) and load profiles (Yang et al. 2016, Hong 2014). Thus, the simulation assumptions of occupant behavior (i.e., schedule, setpoint-temperature) sometimes produced overestimated energy consumption depending on the modeler's expertise to control the indoor environment. However, the current tendency of building simulation approaches substantially underrated occupancy modeling and its influence in the building energy use (O'Brien and Gunay 2016). Therefore, the energy use reduction of occupant behavior has not been thoroughly examined in building energy performance calculations by practitioners in design, new construction, and retrofit processes.

However, in reality, on the practitioner-side, an accurate estimate of a building's occupant behavior is a big challenge because there are no governing rules to understand occupant behavior in building energy consumption. Therefore, there is a need to accurately measure occupant behavior in buildings is to use occupancy sensors in new and renovated buildings. This is now a popular trend across the U.S. to cut down building energy consumption without the loss of indoor comfort. For example, occupancy sensors can be used by building system controls by signaling to the building systems when the room is not occupied so the building systems (e.g., HVAC) can switch to an energy use reduction in the unoccupied mode. (Yang et al. 2016). Therefore, new buildings that installed thermostats with occupancy sensors now have an excellent ability to capture additional energy use reduction compared to existing thermostats with fixed schedules because of the large amount of time that buildings are unoccupied during regular business hours.

Also, in building designs, building energy simulation plays an essential role in the analysis procedure to correctly predict annual energy use and peak building loads to achieve the design performance goals and to meet building energy code-compliance for new and existing buildings. To perform analytic simulations, schedules are significant elements to represent building occupancy and system operation status by day, week, and month for energy performance predictions. However, the conventional use of deterministic simulation schedules is limited to represent actual building schedules, which use typical weekday and weekend/holiday schedules offered from ASHRAE Standards. This is because energy modelers do not often have the time or budget to obtain customized schedules for each zone of the proposed building that reflects the anticipated occupancy in the respective thermal zones in the building. Therefore, it is common practice in the building energy modeling of new commercial buildings to use simplified or fixed schedules with little or no regard for the potential energy use reduction such as occupancy-based thermostats to design more realistic schedules (Labeodan et al. 2015). As a result, it is accustomed to seeing significant discrepancies between the simulated occupancy schedule (i.e., fixed schedule) and the measured occupancy schedule in the building (Yang et al. 2016) as an example in Figure 1.

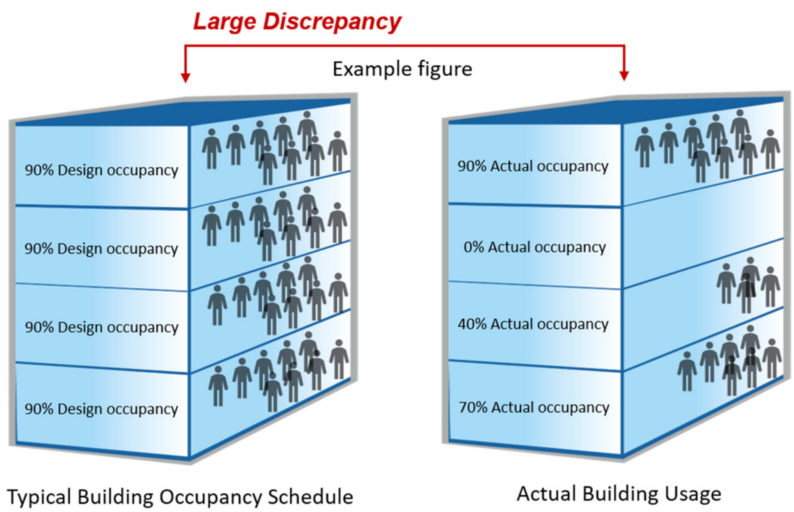


Figure 1. Significant Discrepancies Between Typical and Actual Occupancy Schedules

Therefore, recently, research by (O'Brien et al. 2018a,b,2020; Abdeen et al. 2020) pointed out the problems of the current single-type simulation schedules and suggested updates to occupancy schedules and modeling methods based on the occupancy-related studies and field measurement for new constructions and retrofits in codes and standards.

In the United States, ANSI/ASHRAE/IES Standard 90.1 is the most commonly used commercial building energy standard that provides the minimum efficiency requirements except low-rise residential buildings. The latest revision, Standard 90.1-2019 (ASHRAE 2019) offers a prescriptive path and two compliance paths for users to meet the code requirements: The prescriptive path includes mandatory provisions of selected energy efficiency features of building components (i.e., R-values and U-values of insulation, lighting power density, occupancy sensor requirements for lighting control, the use of daylighting and the efficiency requirements for HVAC systems). The performance path contains two different paths: the Energy Cost Budget (ECB) and the Appendix G, Performance Rating Method (PRM).

However, in code-compliance for performance paths of Standard 90.1-2019, varying occupancy schedules for the proposed model analysis do not receive full credit in Standard 90.1-2019 because the provisions for building energy modeling require the use of the identical occupancy schedules as the standard building. Thus, if someone wants to design occupancy-based building system controls for better building energy efficiency and energy use reduction, it could not be acceptable in the present Standard 90.1-2019 for full credits.

Therefore, this study seeks to evaluate the impact of occupancy-based building controls for different building types (i.e., lightweight, heavyweight), different system types (i.e., PSZ, PVAV) with varying window-to-wall ratios in different weather conditions. This will contribute to identifying the more potential energy use reductions from occupancy-based controls, which currently is not fully supported in Standard 90.1-2019 because of fixed schedules in both the proposed and reference buildings.

1.2. Purpose and Objectives

The purpose of this study is to evaluate the impact of Occupancy-Based Controls (OBC) for different building systems (i.e., PSZ, PVAV), different building envelope materials (i.e., lightweight, heavyweight), varying designs (i.e., window-to-wall ratio), and different climates (i.e., hot and cold climate zones) to develop occupancy modeling credits to improve performance paths in building energy codes and standards. To accomplish this goal, this study used U.S.DOE and PNNL's prototype models to develop a reference model and other office model variations with different building design and weather conditions. The potential energy use reduction was calculated to support the development of occupancy modeling credits for occupancy-based controls. The outcome of this study will contribute to the improvement of building performance estimation methods for performance compliance paths in Standard 90.1-2019. The objectives of this study are as follows:

1) Review the previous literature to secure reliable and objective data, facts, information and knowledge, such as the influence of schedules in building energy use, occupancy modeling methods (i.e., deterministic, stochastic models), commercial prototype building models, code-compliance in Standard 90.1-2016 (ASHRAE 2016a) and Standard 90.1-2019;
2) Develop reference models of small office buildings using different architectural design (i.e., envelope material, window-to-wall ratio) and HVAC systems (i.e., PSZ, PVAV) in hot-humid and cold-humid climate zones to demonstrate the impact of occupancy-based controls in the proposed designs compared to conventional building simulations without occupancy-based controls;
3) Determine the impact on energy use using different occupancy usage intensity (100%-0%) for the proposed occupancy modeling credits;
4) Summarize the proposed occupancy-based control credits, using occupancy schedules (i.e., occupancy, lighting, equipment), as a reference to develop the occupancy modeling credits for the performance paths in ASHRAE Standard 90.1-2019.

1.3. Organization of the Dissertation

The organization of this study consists of seven chapters, including 1) Introduction, 2) Literature review, 3) Significance and limitations of the study, 4) Research methodology, 5) Simulation results and analysis, 6) Development of occupancy credits, and 7) Conclusions and future works.

Chapter 1 presents the background of the study, purpose, and objectives of this study. In chapter 2, this chapter provides the review of U.S. building energy codes and standards, occupant-related influencing factors in building energy use and their definitions, and what are challenges in occupancy-related studies, including occupancy-based building control schedules, building evaluation, and energy modeling methods. Chapter 3 shows the significance and limitations of this study. Chapter 4 describes the research methodology step-by-step with procedure descriptions for this study. DOE-2, as a whole-building energy simulation program, was used to develop reference building analysis models based on the PNNL commercial building prototype models for Standard 90.1-2016 that were the latest prototype model version for Standard 90.1 posted in 2019. Also, this chapter discusses the analytical approaches and development approaches to quantify the impact of occupancy-based building controls (i.e., HVAC, lighting, and equipment) and develop occupancy-based building control credits. Chapter 5 calculated the energy performance of occupancy-based building control in DOE-2.1e models that were derived from the PNNL models in EnergyPlus. This chapter computed the influence of building occupancy in building energy use in different building design and system conditions using reference building models. Based on the analysis results, Chapter 6 developed occupancy-based control credits to provide a reference for the future improvement of the modeling methods for code-compliance in Standard 90.1-2019. Chapter 7 summarizes this research and provides conclusions of this study in terms of the impact of occupancy-based building control and proposed credits. Future work is also described for further study to improve this research.

2. LITERATURE REVIEW

2.1. Building Energy Codes and Standards

In need of energy savings, building energy codes and standards are regarded as effective approaches in many countries to regulate minimum building energy performance. For example, in the U.S, building energy codes and standards have led to an overall energy efficiency improvement in buildings across the states. The improvement of Standard 90.1-2016 slashed 34.2% of energy cost and consumption in commercial buildings on a national scale against requirements in Standard 90.1-2004 (Liu et al. 2018). Besides, the recent tendency of these codes and standards is becoming more stringent and enforcing high-performance building designs using design approaches and improved technologies to meet intensified code requirements. Therefore, this chapter reviewed the previous literature of building codes and standards in the U.S, including the history; the description of performance paths in ASHRAE Standard 90.1-2019 (i.e., Energy Cost Budget (ECB) Method, Appendix G Performance Rating Method (PRM)); the features of ASHRAE Standard 90.1-2019 and details of code-compliant modeling.

2.1.1. The History of Building Energy Codes and Standards

In history, the U.S. has developed and adopted numerous building energy codes and standards since the 1970s. For example, the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) and the International Code Council (ICC) are representative entities that are in charge of developing building energy codes and standards (i.e., ASHRAE Standards, IECC codes) for the code enforcement community (Bartlett et al. 2003).

The first building energy codes in the U.S. appeared in the 1970s to respond to energy security problems caused by oil embargos. During the period, significantly limited oil supplies and increasing energy prices pressed governments for the development of building energy codes to improve energy efficiency in buildings. As a result, in February 1974, the National Bureau of Standards (NBS, now the National Institute for Standards and Technology, NIST) published a first energy-conserving guideline, the NBSIR 74-452, *Design, and Evaluation Criteria for Energy Conservation in New Buildings*. The NBSIR 74-452 offered a component performance approach and prescriptive provisions to design HVAC and lighting systems with three compliance paths: 1) A prescriptive path, 2) A performance path with equal or higher performance than the basic prescriptive design, 3) An alternative path including a credit for renewable energy. Soon after this, ASHRAE took charge of the development of national building energy standards and firstly published Standard 90-75, *Energy Conservation in New Building Design* in 1975 for residential and commercial buildings with technical support from the Illuminating Engineering Society (IES). In 1980 a revised edition of Standard 90-75 was published as ANSI/ASHRAE/IES 90A-1980 that provided revised Sections 1 through 9 of Standard 90-75 (Hunn et al. 2010). The new revision of Standard 90-75 was accomplished by splitting the standard into three parts: 1) 90A-1980 for the prescriptive path (Sections 1 to 9 of 90-75), 2) 90B-1975 for the alternative performance path (Sections 10 and 11 of 90-75), and 3) 90C-1977 (Section 12) for “annul fuel and energy resource determination” (ASHRAE 1980). In 1982, ASHRAE further divided the original Standard 90 A,B,C Standards into a commercial and a residential standard, which were called Standard 90.1 and 90.2 Standards (Halverson et al. 2009, Hunn et al. 2010).

In 1992, the U.S. Energy Policy Act of 1992 (EPACT) became effective. This Act required all state governments to institute building energy codes. Besides, the EPACT indicated that state governments should upgrade their energy codes to meet or exceed Standard 90.1. After the 1992 EPACT, ASHRAE developed Standard 90.1-1999, the next revision to Standard 90.1-1989 (Hunn et al. 2010).

In 1999, the ASHRAE Board of Directors approved continuous maintenance on the standard to correspond to the publication update periods of the International Energy Conservation Code (IECC). Accordingly, in 2001, Standards 90.1-2001 commercial and 90.2-2001 residential were published as the first revised standards under continuous maintenance. Following this, five revisions were published every third year, beginning in 2004 through 2019 (2004, 2007, 2010, 2013, 2016, 2019). Standard 90.1-2016 firstly allowed Appendix G to be used as a performance path for compliance with the standard. Finally, of importance to this study, the performance path Appendix G in 90.1-2016 introduced a credit for occupancy sensors by lighting power allowance changes that more efficiently control lighting fixtures when spaces were not occupied or partially occupied. In Standard 90.1-2019, there was no more update further for occupancy-based controls in performance paths.

Figure 2 depicts the status of code adoption by U.S. state governments (U.S.DOE 2020). Most states typically adopted Standard 90.1 for commercial buildings. However, there are still many states that have not adopted the latest building energy codes, which could lead to inefficient building performance and energy waste for system operations due to no considerations about the recent code changes. More information for the history of building energy codes and standards is detailed in Appendix C.

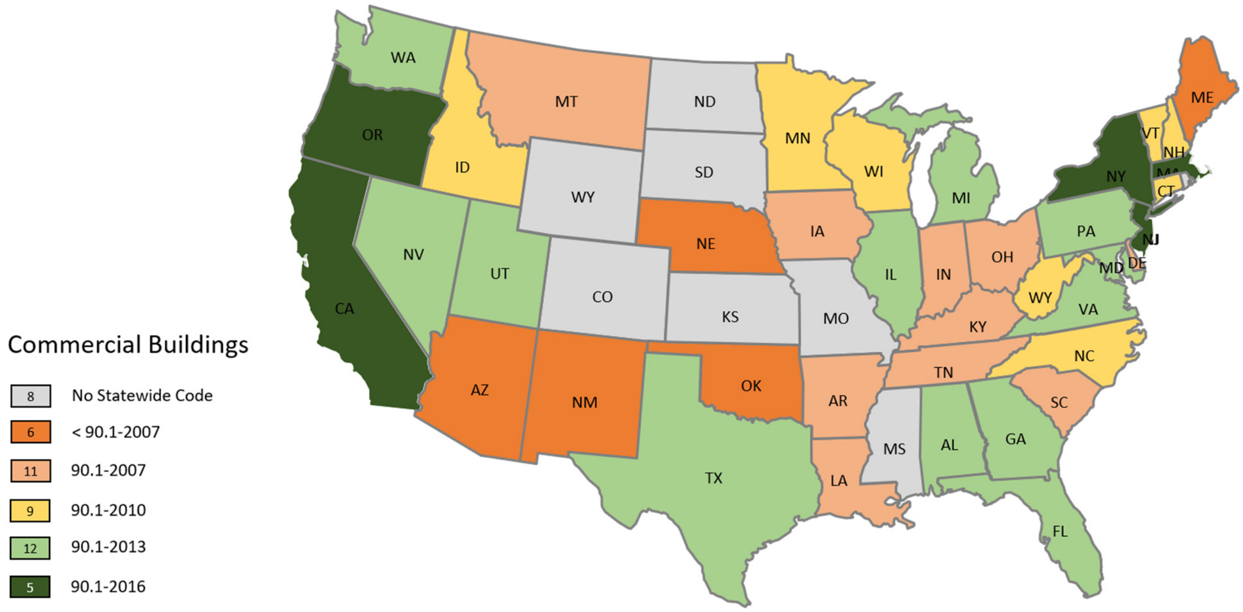


Figure 2. Status of State ASHRAE 90.1 Adoption (as of June 2020)

2.1.2. The Features of ASHRAE Standard 90.1-2016 and 90.1-2019

Standard 90.1-2016 included significant changes compared to the previous Standard 90.1 published in 2013 (ASHRAE 2013,2016a). The main changes to the application of the performance paths are organized into three parts: (1) a new metric for the Appendix G; (2) a new fixed performance of the baseline design beyond versions of the standards; and (3) a new credit for occupancy sensors for lighting system controls. In the first change, the new Appendix G performance path introduced a new metric, the Performance Cost Index (PCI) that can be used to rate the designed building performance through whole-building energy simulation. In the second change, the new Standard 90.1-2016 set Standard 90.1-2004 as the baseline building energy performance level. Therefore, this indicates that the baseline design from the 2016 edition can be analyzed as a particular level of energy performance in Standard 90.1-2004, which allows the user to perform a more objective evaluation of a building rating when using updated standards.

Last but not least, in Standard 90.1-2016, the new modification from addenda dx to Standard 90.1-2013 gives occupancy sensors credits to reduce lighting power allowances using the Space-by-Space Method (ASHRAE 2016a, Table G3.7). For example, Table G3.7 (See Appendix B) presents the range of the reduction to the lighting power density for space with occupancy sensors, depending on common space type (i.e., Auditorium, atrium, hotel, and office). Such a lighting power allowance reduction can be calculated by multiplying the occupancy sensor reduction factor times the lighting power density. This flexible rating method enables designers to create more opportunities to save lighting energy in commercial buildings.

In 2019, ASHRAE published a new Standard 90.1-2019 (ASHRAE 2019). The latest version of Standard 90.1 included updates in the prescriptive provisions of building envelope, lighting, and mechanical sections. In summary, the minimum criteria of SHGC and U-factor for fenestrations were updated in all climate zones. Also, lighting power allowances for the Space-by-Space Method and the Building Area Method were upgraded to represent real-world conditions, including IES recommendations. In occupancy sensor reduction of the Space-by-Space Method, there were no significant changes in occupancy credits for lighting systems in performance paths.

2.1.3. Code-Compliant Performance Paths of Standard 90.1-2019

In Standard 90.1-2019, there are two performance paths for code-compliance: (1) the Energy Cost Budget (ECB) Method; and (2) the Appendix G: Performance Rating Method (PRM). The ECB method is an existing performance path to provide an alternative to the prescriptive path in Standard 90.1. The Appendix G Method was a newly approved performance path in the 2016 version of 90.1. The previous Appendix G Method in ASHRAE 90.1-2013 was to be used solely for building performance in beyond-code programs. In the next two chapters of this study, the code-compliance requirement of the two performance paths in Standard 90.1-2016 and Standard 90.1-2019 is reviewed.

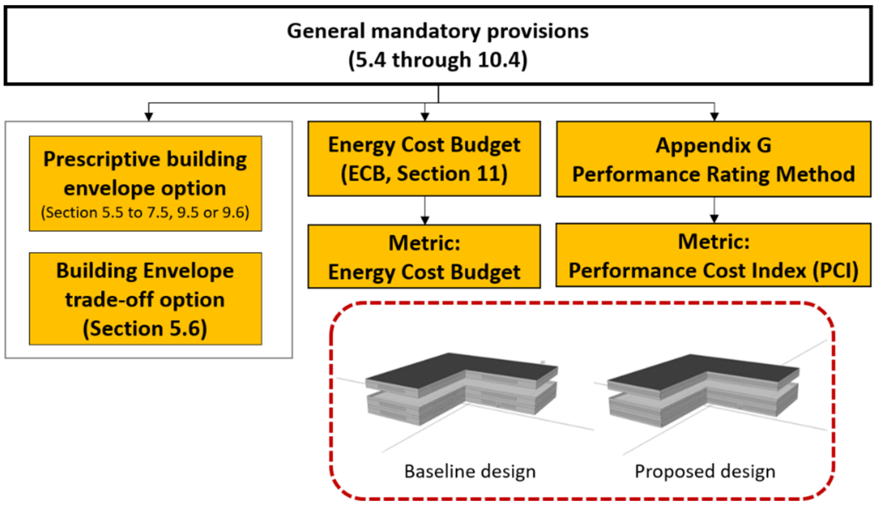


Figure 3. ASHRAE 90.1-2019 Code-Compliance Paths

2.1.3.1. Energy Cost Budget (ECB) Method

The Energy Cost Budget (ECB) method is an alternative performance path to comply with Standard 90.1-2019. For compliance of the ECB method, the proposed design must first satisfy all provisions of Section 5.4 through Section 10.4 and show that the design energy cost (i.e., the proposed design) is at least equal to or less than the energy cost budget (i.e., baseline design), as calculated by an approved hourly, whole-building energy simulation program. The energy simulation programs that are used to calculate the ECB method must be computer-based programs, such as DOE-2, TRNSYS, and EnergyPlus, which must be tested with ASHRAE Standard 140-2014 (ASHRAE 2014a). Such programs directly compare the annual hourly-simulated design energy cost and the annual hourly-simulated baseline energy cost to determine if a building complies with the codes.

In the ECB method, the simulation design model shall be identical with the baseline model in input parameters (i.e., weather data, thermal blocks or zoning, and schedules) and all features except the new energy efficiency features of the building. Finally, the results of both the design energy cost and the baseline energy cost must be compared using purchased energy rates (ASHRAE 2013b, 2016a, 2019).

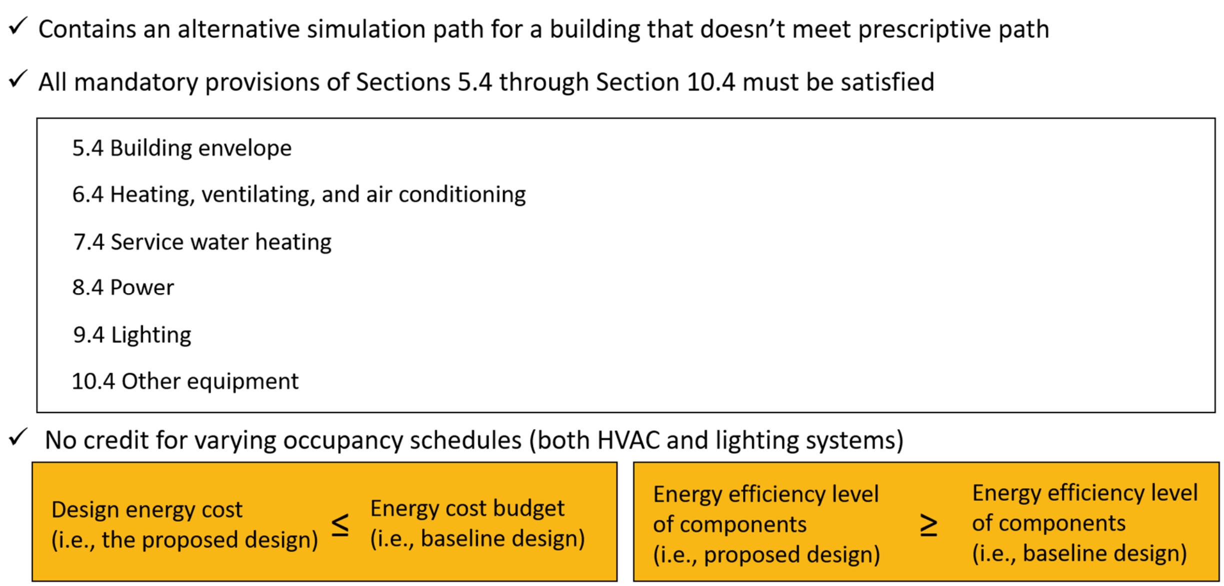


Figure 4. Code-compliance Requirement for the Energy Cost Budget (ECB) Method

2.1.3.2. Appendix G: Performance Rating Method

Appendix G: Performance Rating Method was approved as a new simulation-based performance path in Standard 90.1-2016. This is the result of a recent revision (Addendum bm) to Standard 90.1-2013 (Rosenberg and Eley 2013, ASHRAE 2015a). Before Standard 90.1-2016, the Appendix G was only allowed to be used to evaluate the energy performance of a proposed design for "beyond code" programs, such as the Leadership in Energy and Environmental Design (LEED) for green building rating (USGBC 2017), Standard 189.1-2014: *the Design of High-Performance Green Buildings Except Low-Rise Residential Buildings* (ASHRAE 2014b), and the International Green Construction Code (ICC 2015b). Currently, Standard 90.1-2019, the Appendix G is a more flexible performance path than the ECB method in the procedures used in the computer simulation modeling to design energy-efficient buildings that exceed the Standard requirement (ASHRAE 2016b, ASHRAE 2014c, Rosenberg and Hart 2016, ASHRAE 2019). For example, the Appendix G in Standard 90.1-2019 allows changes to lighting power allowances for the improved lighting controls using occupancy sensors, whereas HVAC controls using occupancy sensors are not allowed.

Also, in 2016, the Appendix G introduced the Performance Cost Index (PCI) metric for code-compliance that is referred to the provisions of Section 4.2.1.1 of ASHRAE Standard 90.1-2016 and 90.1-2019. In the PCI method, the Performance Cost Index Target (PCI_t) shall not exceed the Performance Cost Index (PCI) using the equation provided by the Appendix G for the proposed design. Also, the design building shall comply with all mandatory provisions of Section 5.4 through Section 10.4 and meet the requirements of the interior lighting power allowance. Of this study, even though the Appendix G Method also assumed equivalent conditions similar to the ECB method, such as the modeling requirements of thermostat schedules, equipment schedules, and space classification to compare the results of the proposed building performance to the baseline building performance, it allows different schedules between the proposed design and the baseline building only in limited cases such as designing non-standard buildings (ASHRAE 2016a, 2019).

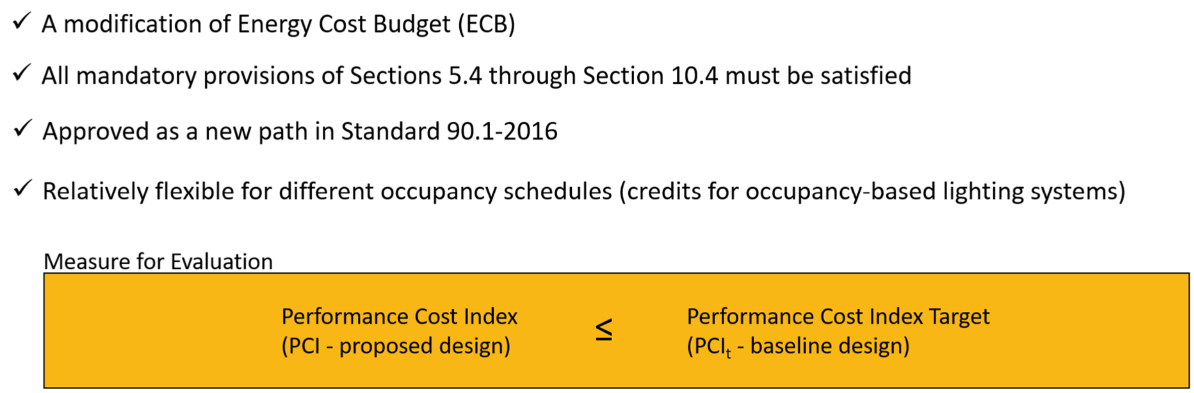


Figure 5. Code-compliance Requirement for the Appendix G Method

2.1.4. Details for Code-compliant Modeling

There are two performance paths in Standard 90.1-2019: the ECB method and the Appendix G: Performance Rating Method (PRM) that are used to evaluate a proposed building's energy efficiency using computer-based whole-building energy simulations. Both computer-based energy modeling methods contain the procedures to meet minimum requirements in Standard 90.1-2019, which could assist the process of developing code-compliant models and securing the total reliability of analysis results. Also, these two performance paths provide their own requirements from simulation program selections to energy modeling to yield acceptable results in simulations for code-compliance. This chapter reviewed the details of the energy modeling requirements for performance paths in Standard 90.1-2019, which should be utilized for a case study in this study.

2.1.4.1. The ECB Method: Modeling Requirements for Estimating Energy Cost Budget

The compliance calculation in the ECB method is based on a computer-based program to analyze building energy consumption. Simulation programs for compliance must be approved by the related authorities and meet minimum simulation program requirements (Section 11.4.1) in the ECB method for building energy modeling. In the ECB method, two designs are used to compare energy costs between the baseline and the proposed designs: energy cost budget (i.e., baseline design) and design energy cost (i.e., proposed design). Simulation users using this path must set up identical conditions in the simulations for code-compliance, including weather data and purchased energy rates.

The requirements for occupancy-based building modeling of Table 11.1.5 in Standard 90.1-2019 in the ECB method are listed below. Additional details for modeling specifications are continued in Table 11.5.1 in Standard 90.1-2019:

- The baseline design (budget building) is a modification of the proposed design that shall be identical with the design documents, including details about fenestration, opaque walls, lighting power and control, and HVAC system information.
- The same schedules shall be used for the proposed design and for budget building design.
- For the building envelope, the budget building design shall use the same conditioned floor area and the same building dimensions and orientations with the proposed design.
- The lighting schedules shall follow the automatic lighting control requirements in Standard 90.1-2019, which shall also be equally applied to the budget building design (baseline model).

- Thermal blocks (i.e., thermal zoning) for designing an HVAC system shall be the same for the budget building design. The HVAC system efficiency shall meet or exceed the minimum prescriptive requirement.

2.1.4.2. Appendix G. Method: Modeling Requirements for Rating Energy Performance

In Standard 90.1-2019, the performance calculation in the Appendix G method exploits different concepts than the ECB method to represent the baseline and the proposed designs, which includes the Performance Cost Index (PCI, proposed design) and the Performance Cost Index Target (PCI_t, baseline design). The PCI represents the ratio of the proposed building performance to the baseline building performance. The performance requirement for the proposed design shall not be more than the PCI_t value that would be calculated by using the equation and tabulated data in Section 4.2 in Standard 90.1-2019, which offers the energy cost and Building Performance Factor (BPF) as shown in Appendix A (ASHRAE 2016a).

The energy modeling requirements of Table G3.1 in Standard 90.1-2016 for the Appendix G method are shown below. Additional details for modeling specifications are included in Table G 3.1 in Standard 90.1-2019:

- The floor area of the baseline design model in the Appendix G method is identical to the floor area of the proposed design model. The proposed design can be adjusted and compared to the baseline design (i.e., envelope properties and areas, fenestration, walls, lighting, and HVAC system design, types, and controls).
- The schedules of the baseline design shall be configured using the same schedules in the proposed design. Unlike the ECB method, the Appendix G method allows two exceptions:

1) set-points and schedules may be altered when using the methodologies of ASHRAE Standard 55-2013, Section 5.3.3 “Elevated Air Speed” or Appendix B of ASHRAE Standard 55-2013, “Computer program for Calculation of PMV-PPD”. 2) The schedule may be varied when required to use non-standard efficiency measures, using the modified schedules approved by an associated authority.

- The building envelope shall use the identical conditioned floor area and the same building dimensions as the proposed design. The orientation of the baseline model shall simulate the actual orientation and rotated orientations of: 90, 180, and 270 degrees; with the performance being the average of the results of the four orientations.
- Lighting schedules for automatic lighting controlled by occupancy sensors shall be simulated by cutting down the lighting schedule each hour based on the occupancy sensor reduction factors and space types.
- Thermal blocks for HVAC zones in the proposed design are identical with the baseline design. The baseline HVAC systems shall be developed as complying with the description of Section G3.1.1-G3.1.3 in Standard 90.1-2019.

2.1.4.3. Occupancy Modeling for Codes and Standards

Currently, occupant modeling in building performance simulations is an emerging research area and has hardly started into practice or building codes and standards (O’Brien et al. 2018b, O’Brien et al. 2020a). However, most building energy codes and standards’ performance paths implicitly assume buildings under steady and near-capacity occupancy conditions, although these schedules are not actual operating conditions. As a result, buildings are not prone to be designed with optimal energy performance in the actual building usage of partial and fluctuating occupancy (O'Brien and Gunay 2019). Therefore, many academic discussions and research studies are recently in progress to improve occupancy modeling in codes and standards, including O'Brien et al. (2018a,b), O'Brien et al. (2020a), and Abdeen et al. (2020).

First, O'Brien et al. (2018a,b) provided a brief roadmap that is being developed for advancing detailed occupant modeling in building codes and standards. This paper and report developed the roadmap based on a survey of building energy simulation users, a stakeholder workshop, and the literature for better occupant modeling. The roadmap was based on a technology roadmap guide from the International Energy Agency, such as goals, milestones, gaps and barriers, action items, and priorities and timelines. In their research, six methods were suggested as below to incorporate improved occupant modeling into building codes and standards.

- Revision of prescriptive requirements based on occupant simulation research or the literature
- New prescriptive requirements based on occupant simulation research
- Update of simulation schedules and densities using the latest field measurements
- Update of simulation schedules or the introduction of new schedules developed from occupant simulation-related studies
- Update of mandatory procedural changes regarding occupant modeling
- Development of specified occupant modeling approach (i.e., instead of schedules)

For example, O'Brien et al. (2018a, 2018b) suggested multiple occupant scenarios for occupancy, receptacles, and lights instead of a single standard simulation (both for baseline and proposed building models). Multiple occupant scenarios can be applied by multiplying simulation schedules by 0.75, 1.0, and 1.25. Also, for updating schedules from simulations, these studies recommended a decision tree based on parametric simulations depending on design variables and climate to apply quasi-custom schedules (i.e., high-use, average-use, low-use).

In another study from IEA-EBC Annex 79, O'Brien et al. (2020a) investigated 23 regions' building energy codes and standards from the viewpoint of quantitative aspects (i.e., schedules, densities, and setpoints) and mandated requirements and approaches. This review found extensive occupant-related values, approaches, and attitudes. For instance, substantial variations were revealed across the codes concerning the occupancy, lighting, and equipment power density values. This fact highlights the need for developing occupant behavior modeling approaches for occupancy-based building performance codes and standards. In addition, occupants are often shown only implicitly, and expectations about energy use reduction from occupant behavior vary greatly. Only a few codes considered occupant feed-back and system usability. Based on the findings of the review, this study recommended three points as below for future building energy codes:

- More in-situ studies to gather long-term data in various contexts (i.e., countries, building types) to advance confidence of both simulation schedules (and densities) and more improved occupant models (i.e., agent-based and dynamic)
- More in-situ and simulation studies to update prescriptive requirements, such as control zone sizes, control algorithms, and building system usability
- International committee to review building energy codes and standards, including occupant-related aspects.

Lastly, Abdeen et al. (2020) conducted a comparative review of occupant-related energy aspects of the National Building Code (NBC) of Canada. This study explored the current occupant-related assumptions in the National Building Code (NBC) of Canada in comparison with other data sources. Six parameters were selected for the review (i.e., setpoint temperatures, domestic hot water (DHW) use, appliances lighting and plug loads, internal heat gains, mechanical ventilation, and the number of occupants). Each parameter was compared using available data sources against the NBC assumptions. Researchers found that a variety of code assumptions substantially differed from findings in recent measurement-based research, such as temperature setpoints, total daily volume and hourly schedule for DHW. Internal heat gains showed a similar profile in the available data as NBC, excepting the absence of morning peak hours. Based on the findings, this study recommended potential updates of NBC using one of four approaches: 1) update code values (e.g., setpoint temperatures), 2) update the code values depending on home-specific characteristics (e.g., the number of bedrooms for DHW consumption), 3) update code schedules (e.g., internal heat gains), or 4) supplement additional requirements and specifications (e.g., application and plug loads).

In the literature review, previous and ongoing studies pointed out the problems of the current standard schedules (i.e., single schedule, discrepancy between the actual and the proposed) and the need for updating simulation schedules based on the extensive field measurement. Also, multiple schedule scenarios were suggested as one of the examples to improve the codes and standard schedules. Therefore, based on the literature review, occupancy-based controls using different usage densities (i.e., OBC 100%-0%) can be an effective approach for improving the simulation schedules in codes and standards.

2.1.4.4. Code-compliant Building Performance Simulation (BPS) Tools

Building systems (i.e., lighting, equipment, HVAC) accounted for 64% of the total energy use of U.S. commercial buildings (Davis 2016, U.S.EIA 2016). Over the last 30 years, numerous energy simulation programs have been developed over the years to enable users to more accurately predict and advance building energy performance while saving energy cost and design time. Currently, there are many different simulation programs available for code-compliant whole-building energy analysis, including EnergyPlus (NREL 2017), DOE-2.1e (LBL 1991), eQUEST 3.65 (JJH 2018), and TRNSYS (TESS 2017).

For code-compliance in performance paths, general requirements are defined in Standard 90.1-2019 that describes the minimum abilities of whole-building energy simulation programs to be used in the performance evaluations. In accordance with the ECB Method in Standard 90.1-2019, energy simulation programs must be capable of load calculations for a minimum of 1,400 hr/yr for both the *design energy cost* and *energy cost budget* calculations and contain hourly variations of loads (i.e., occupancy, lighting power).

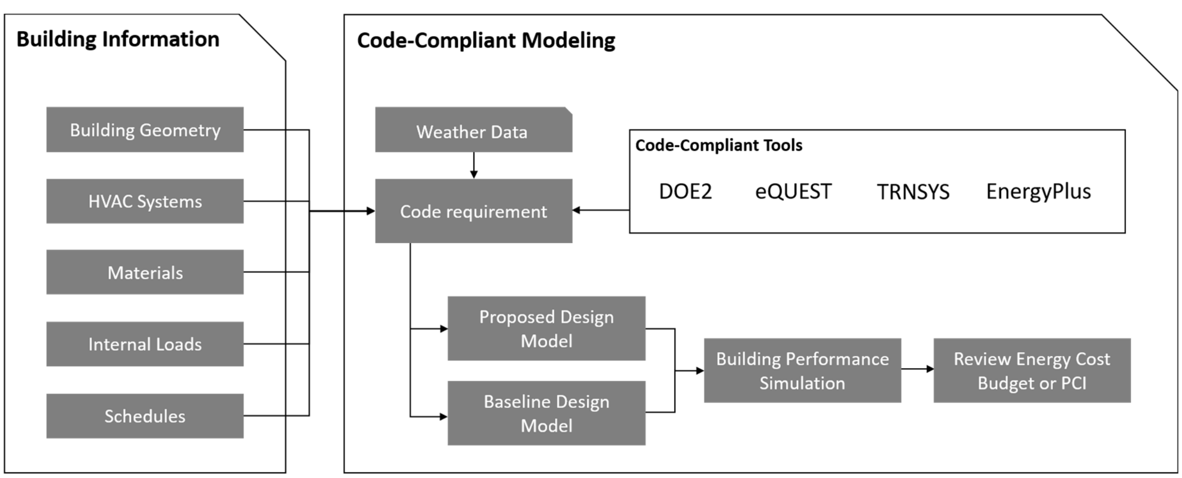


Figure 6. Whole-Building Energy Simulation Tools for Code-Compliance

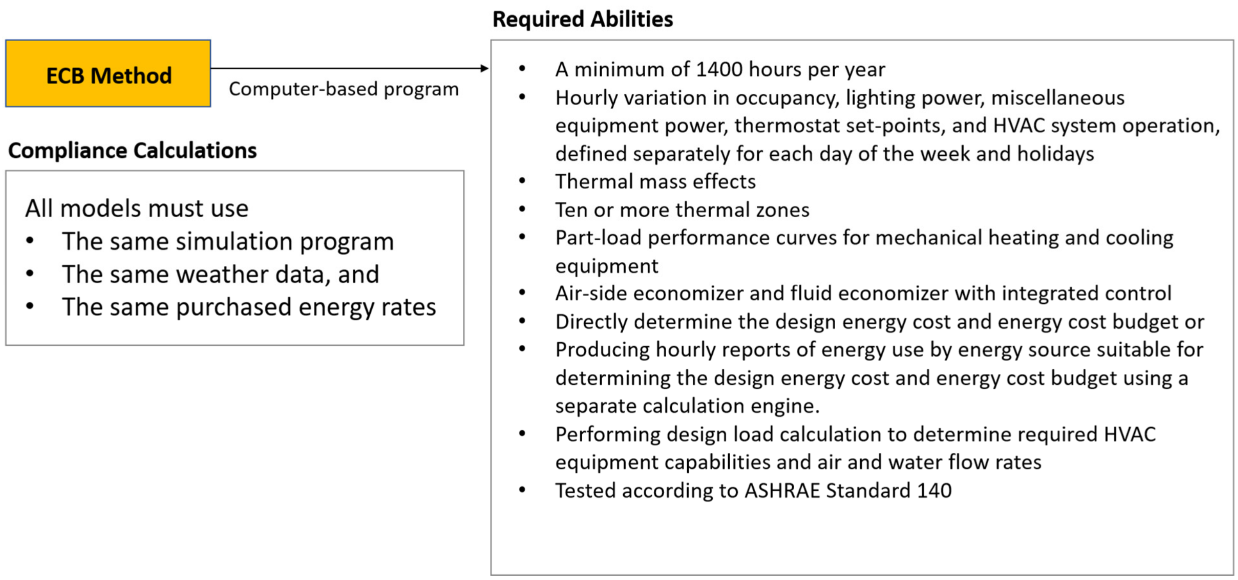


Figure 7. Simulation Program Requirements in the ECB Method

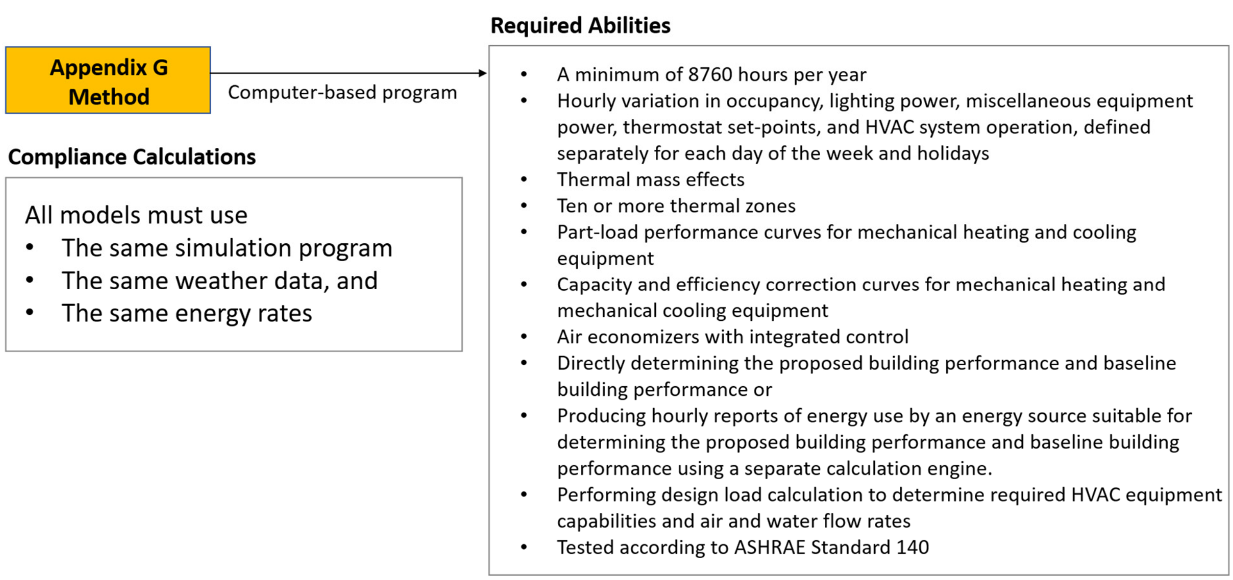


Figure 8. Simulation Program Requirements in the Appendix G Method

On the other hand, energy simulation programs in the Appendix G. Performance Rating Method must cover load calculations for a minimum of 8,760 hr/yr and the *baseline building performance* and *proposed building performance* with hourly variations. In both the ECB and the Appendix G methods, the simulation programs for both performance paths must be tested using Standard 140-2014, *Standard Method of Test for the Evaluation of Building Energy Analysis Computer Programs*, except Section 7 and 8. However, the current requirements for simulation programs do not incorporate the functions of actual usage schedules for occupancy, HVAC and lighting system (ASHRAE 2014a, 2016a, 2019), which might cause constraints and uncertainties in the results of building energy modeling and simulations that block to reduce discrepancies from actual energy consumption in buildings.

Therefore, it is essential to understand the functions and features in selections of whole-building energy simulation programs to develop proper code-compliant models for different performance paths in Standard 90.1-2019. Additional detailed description for building energy simulation tools is represented in Appendix F.

2.1.4.5. Summary

In summary, even though Standard 90.1 provides two performance paths for code-compliance using computer-based simulations, there are some limitations to obtain the occupancy-based building control credits in both performance paths. For example, the current ECB method offers no direct credit for occupancy-based building controls in the energy modeling method, and the Appendix G method uses a fixed credit from Standard 90.1-2019 only for occupancy sensor reductions in the space-by-space method to calculate the lighting power allowance and schedules. In this respect, it can be concluded as the ECB method has more difficulties in representing occupancy-based building controls for lighting, HVAC, and other building systems, which might leave out the energy use reduction potential for occupancy-based controls and deprive architects and engineers of the credits of emerging technologies for code-compliance in Standard 90.1-2019.

Therefore, these days, researchers began their discussion to improve occupancy modeling in building codes and standards. Despite the significant role of building energy codes and standards in occupancy modeling, the occupant-related aspects are typically studied simply and have been overlooked in the leading research. Only a few studies investigated occupancy-based controls of building energy codes and standards and made potential recommendations for future codes and standards. These studies commonly pointed out the needs to update the current standard schedules and introduce options to express multiple usage levels of simulation schedules for more realistic simulations.

In terms of code-compliant simulation programs, there are many whole-building energy simulation tools (i.e., DOE-2.1e, eQUEST, and EnergyPlus) available to meet the requirements of both performance paths in Standard 90.1-2019. However, these programs mostly model predetermined and static schedules as input parameters, which do not easily capture varying actual schedules or stochastic models for simulations.

2.2. Influence of Occupancy Schedules in Building Performance Simulations

In building energy consumption, occupant behavior is one of the influential factors. This affects building system operations and usage patterns. Therefore, there have been many previous efforts to identify occupant behavior in building energy consumption to economize on energy cost without the loss of occupant comfort. This chapter describes the previous and ongoing projects and research, including the topics of occupant behavior, schedule development, and the influence of the occupancy schedules in the building energy performance.

In the previous and ongoing occupant behavior research, there are two major entities that have dominated occupant behavior research: the International Energy Agency-Energy in Buildings and Communities Programme (IEA-EBC) and ASHRAE Multi-Disciplinary Task Group on Occupant Behavior in Buildings (MTG-OBB).

Firstly, the global collaborative research project group, IEA-EBC Annex 53: *Total Energy Use in Buildings: Analysis and Evaluation Methods,* identified that occupant behavior and related activities occupied a large portion of the discrepancy between the proposed and the actual energy use. They defined six reasons that could generate the discrepancy: 1) climate, 2) building envelope, 3) building equipment, 4) operation and maintenance, 5) occupant behavior and 6) indoor environmental conditions. Among these reasons, the last three are categorized as occupant influenced factors (IEA-EBC, Annex 53 2016). Such facts have motivated many researchers to acknowledge the importance of predicting and accurately modeling occupant behavior to optimize the operations of buildings, particularly in lighting and HVAC systems (i.e., IEA-EBC, Annex 66 2018, ASHRAE 2018).

In addition, in 2013, the IEA approved a continuing project group of the Annex 53, the Annex 66: *Definition and Simulation of Occupant Behavior in Buildings* for 2013-2018, which aimed at identifying a standard occupant behavior and developing a quantitative analysis approach for occupant behavior to predict the influence of occupant behavior associated with building energy use and indoor environment. The Annex 66 established five subtasks: a) occupant movement and presence models in buildings; b) occupant action models in residential buildings; c) occupant action models in commercial buildings; d) integration of occupant behavior models with building energy modeling programs; and e) applications in building design and operations. The Annex 66 also studied occupancy diversity in both energy modeling and analysis as an essential factor to estimate building energy performance as this affects the operation of the building HVAC systems (IEA-EBC, Annex 66 2013). In 2018, the Annex 66 published a final report with several deliverables (IEA-EBC, Annex 66 2018, 2017b, 2017c, 2017d). Their final report package has a significance as comprehensive research of occupant behavior in building energy use. It includes plentiful information and reviews based on their surveys, participants' studies, and previous literature. The reports described methods for collecting occupant data, modeling methods of occupant behavior, the development of occupant behavior modeling tools and integration into building energy performance programs (i.e., EnergyPlus), and an international survey in workspaces.

Shortly after the Annex 66 was formed, ASHRAE launched the Multi-Disciplinary Task Group on Occupant Behavior in Buildings (MTG-OBB) that was recognized at the Orlando conference in January 2016, and it has developed now developing the Research Topic Acceptance Requests (RTARs) associated with occupant behavior (ASHRAE 2016c, 2017c). As part of this effort, in the 2018 ASHRAE winter conference at Chicago, Technical Committee (TC) 7.5 reported a plan to develop a new RTAR for occupancy-based HVAC control (ASHRAE 2018). The MTG-OBB meeting at 2019 ASHRAE winter conference in Atlanta addressed that various the RTARs and the work statements had been discussed to develop occupant behavior-related research projects, including Work Statement 1811 - Determining Occupancy Patterns in Clusters of Buildings with Data Drawn from Web-Based Social Media, Work Statement 1815 - Integrating Occupant Behavior Data into Building Performance Simulation, RTAR 1870 - Investigating Occupant Energy Behavior and Building-Human Interaction in Office Buildings, RTAR new (TC 4.7) - Baseline modification when building behavior changes, RTAR 1859 (TC 2.8) - Residential Water Fixture Use Schedules based on Measured Occupant Behavior, and URP - Global occupancy database. Also, the MTG-OBB is trying to update ASHRAE publications to create new chapters of occupant behavior. For example, 2019 Handbook HVAC Applications introduced a new description of occupant-centric sensing and control, and 2021 Handbook Fundamentals will include a new chapter of occupant modeling and simulation. The efforts of occupant behavior in the MTG-OBB have been massively expanding in collaboration with other ASHRAE TCs and research entities since 2016.

In addition to the MTG-OBB activities, as a partner of the Annex 66, the Occupant Behavior Research at Lawrence Berkeley National Laboratory (LBNL), funded by the U.S. Department of Energy (DOE), developed a web application for generating more realistic occupant schedules for commercial buildings based on the Database for Energy Efficiency Resources (DEER) building prototypes to represent the occupants' diversity and stochastics (LBNL 2017). The primary research goals of the LBNL effort are 1) to collect occupant behavior-related data and develop tools; 2) to simulate and quantify the influence of occupant behavior; 3) to improve policymaking related to occupant behavior on building energy consumption; and 4) to contribute to codes and standards (i.e., Standards 55, 62, 90 and 189 through the ASHRAE MTG.OBB, and the ASHRAE Handbook-Fundamentals) (LBNL 2018).

Last but not least, a new IEA-EBC Annex 79: *Occupant-Centric Building Design and Operation* began their study in fall 2018 for the 2018-2023 period right after the Annex 66 was terminated in May 2018. The purpose of this project is to incorporate occupancy and occupant behavior into the architectural design procedure to advance building energy performance without the loss of occupant comfort and usability. Given this objective, this project group has four specific subtasks posted on their website as following (IEA-EBC, Annex 79 2018): Subtask 1 is aiming to investigate multi-aspect environmental occupant exposure and its influence on occupant behavior and comfort in buildings. It includes a study of building interfaces to research the usability, occupant comfort, and energy implications as well. The scope of Subtask 2 is to explore and develop approaches and programs for modeling data-driven Occupant Presence and Action (OPA) analysis. For this, machine learning techniques (i.e., supervised and unsupervised learning algorithms) will be focused on developing new models and information for multi-aspect environmental exposure, building interfaces, and human behavior. The purpose of Subtask 3 is to develop improved approaches for existing occupant models that could consider comfort, usability, and energy performance to accomplish high-performance designs. In addition, Subtask 3 will develop implications for both prescriptive and performance paths of building energy codes and standards in collaboration with the ASHRAE MTG-OBB. The goal of Subtask 4 is to investigate and validate occupant-centric building controls, which will expose practical difficulties concerning the implementation of occupant-centric building controls in existing buildings. The results from this Subtask will quantify the potential possibility for improved occupant comfort and more energy use reductions through occupant-centric building controls.

In brief, since 2013, many research studies and collaborative projects have verified the significance of building occupancy in building energy performance and simulation prediction.

Moreover, the new ongoing project Annex 79 established a plan for their research subtasks, including political suggestions for the current codes and standards to improve both prescriptive and performance paths of occupant-centric building controls in cooperation with ASHRAE MTG-OBB. However, even though the research goals have sought to get a better understanding of occupant behavior for tool development and proposing new approaches or political implications, they have not explicitly developed and published a method to include credits for occupancy-based building controls in commercial building energy codes and standards.

2.2.1. Influence of Occupancy-Based Lighting Control

Occupancy sensors have come into extensive use with the availability and usability of occupancy-based lighting controls to optimize building system operations and maximize electricity use reduction in commercial buildings. The increased use of the occupancy sensors has allowed researchers to verify the energy use reduction from occupancy-based building controls in office spaces, including Guo et al. (2010), Haq et al. (2014), Hoes et al. (2009), Thornton et al. (2011), and Yan et al. (2015).

In previous studies, researchers indicated the problems in the use of fixed and simplified schedules for energy calculations (Hoes et al. 2009, Yan et al. 2015). Hoes et al. (2009) reported that the simulation in building simulations frequently utilized static occupancy schedules that were expressed as a fraction of the total occupancy. Also, Yan et al. (2015) reported that simplified schedules in simulations did not represent the actual influence of occupancy in energy modeling and analysis. Guo et al. (2010) addressed occupancy-based lighting control that showed a 30% total energy savings using occupancy sensors that controlled lighting systems in buildings. Such a fact indicates that there is a large gap between the current simulation schedules and measured building schedules from occupancy sensors for lighting controls.

In other studies, the results of occupancy-based lighting controls demonstrated substantial energy use reduction potential, depending on the system types and controls (Haq et al. 2014, Thornton et al. 2011). Haq et al. (2014) stated that lighting savings depend on the type of occupancy controls when comparing the results to previous research. This study showed considerable energy savings potential when applying actual occupancy in lighting systems. Also, Thornton et al. (2011) presented a quantitative analysis of the 53 addenda discussed in ASHRAE Standard 90.1-2007 and 2010. Of the 53 addenda, addendum 90.1-07x only addressed with lighting controls and efficiency. In the simulation results of this addendum, the time delay within 30 minutes showed 22% savings for private offices. This study also pointed out that control types (i.e., manual-on/off, automatic shut-off) and the proportion of daylight perimeter space also affected the amount of savings under occupancy-based lighting controls.

In summary, previous studies were reviewed to inspect the problems of existing simulation schedules and the energy savings potential from occupancy-based lighting systems. The previous literature studies reported that 22% to 30% of energy savings were expected from occupancy-based lighting controls. This implies that occupancy-based building controls for lighting systems provides significant potential for improving building energy efficiency.

2.2.2. Influence of Occupancy-Based HVAC Control

Many studies have analyzed the impact of occupancy-based thermostat controls in diversified settings to acquire a comprehensive understanding of HVAC system operation. In these studies, researchers focused on several topics: for example, occupancy variables (i.e., presence, business type, gender), advanced sensing technologies (i.e., accuracy, layout), control (i.e., set-points, set-back) and modeling methods (i.e., schedules). This chapter reviewed the previous studies that analyzed the effectiveness of occupancy-based HVAC controls for office building energy modeling, including Azar and Menassa (2012), Brooks et al. (2014), Glazer (2015), Haberl et al. (2015, 2016) and Shin et al. (2017).

In 2012, Azar and Menassa (2012) studied the influence of occupancy in office buildings using building energy simulation by reviewing nine characteristics (i.e., after-hours equipment use, after-hours lighting use) of typical office buildings. This study selected 30 typical representative buildings in the U.S. to verify energy sensitivity using parametric combinations of building occupancy. The result of the study found a considerable influence in building energy use from the occupant behavior in office buildings. Combined parameter variations showed up to a 23.6% change in building energy performance compared to the base-case models.

In another study conducted by Brooks et al. (2014), researchers monitored occupant presences in office spaces using wireless systems. The experiment was performed in a commercial building at the University of Florida employing the Measured Occupancy-Based Set-back (MOBS) controller for the HVAC equipment that reduced the air flow rate when the spaces were unoccupied. The result found a potential for energy savings of 37 percent when the actual occupancy data were used as inputs in the HVAC simulation. The controllers improved energy performance without the damage to indoor comfort. Also, this study showed a significant deviation in energy savings between the thermal zones in the experiment.

The ASHRAE 1651-RP project modeled occupancy sensors using previously published schedules for air-handling systems by changing the operational modes for occupied and unoccupied hours, which relates to the reduced airflow volume, and/or switching-off or altering thermostat set-points. In the study, the simulation used different operation settings for the thermostat set-points during unoccupied times and on/off mode of the VAV dampers into the spaces. The result of the study reported a 2-7% energy reduction depending on the climate zones (Glazer 2015).

Finally, the Fort Hood Army Base in Texas (Haberl et al. 2015, 2016; Shin et al. 2017) measured the actual building energy use and environment conditions to analyze the savings of a side-by-side net-zero building test facility. In this building, one-half of the building had a high-efficiency Variable Refrigerant Flow (VRF) system controlled by thermostats with occupancy sensors while the other half of the building had a standard air-to-air heat pump controlled by a thermostat with a night set-back. In the result, the savings were determined by using several methods, including weather-normalized, side-by-side measurements, and calibrated simulation models with varying thermostat schedules that reflected actual occupancy conditions. The analysis reported that the renovated space consumed 35 to 50% less energy than the un-renovated space, depending on which saving calculation methods were applied and which occupancy schedules were used. This study revealed the significant potential of occupancy-based building controls to achieve higher energy efficiency while maintaining thermal comfort during the occupied period.

In summary, simulations and experiments in the literature review evaluated the influence of occupancy in office buildings. The existing studies showed that the occupancy parameters could vary according to climate, occupant behavior, office type, lighting, and HVAC control types. Also, the previous studies have determined a significant variety of energy savings potential (2%-50%) by occupancy-based HVAC controls. The results from the previous studies indicate that building occupancy is a crucial factor in increasing energy efficiency and optimize lighting and HVAC system operations.

2.2.3. Influence of Occupancy Diversity in Building Energy Consumption

In buildings, occupant behavior can be interpreted as a process for action and reaction of occupants with the built environment to obtain satisfactory indoor comfort, usability, and productivity. This can be affected by physical, psychological, environmental factors, and thus, it is very complicated and challenging to be understood the actual effect of occupant behavior in building energy use. Therefore, uncertainties might often occur in the predicted energy performance and efficiency of occupancy-based building models. To resolve the uncertainties of occupant behavior, previous studies have discussed occupancy diversity in buildings to improve occupancy schedules and increase the accuracy of energy performance estimations.

In practices, energy modelers prefer to use typical or normalized occupancy schedules from published sources, such as ASHRAE Standard 90.1 user's manual (ASHRAE 2017b), the Commercial Reference Buildings developed by the National Renewable Energy Laboratory (NREL) (Deru et al. 2011) or the Commercial Prototype Building Models developed by the PNNL (PNNL and U.S.DOE 2018). However, there are significant differences in the published occupancy schedules compared to actual building usage schedules (e.g., usage intensity, pattern). This is because the commonly used schedules presume maximum occupancy or simplified occupancy schedules (Erickson and Cerpa 2010, Yan et al. 2015). Therefore, many papers attempted to identify the influence of occupancy diversity in order to improve the occupancy prediction algorithms and methods of building energy modeling, including Ekwevugbe et al.

(2013), Dong and Andrews (2009), Degelman (2000), Abushakra and Claridge (2001) Duarte et al. (2013), and D'Oca and Hong (2015).

Ekwevugbe et al. (2013) studied the current technological issues of occupancy sensing technologies in buildings, including untrustworthy data, privacy issues, and sensor drift. However, despite drawbacks in occupancy sensing, the study concluded that occupancy-based smart controls are a more effective way to control HVAC systems for open-plan offices to increase energy efficiency and save costs. In another study, Dong and Andrews (2009) tested different wireless and wired sensors (i.e., lighting, acoustics, temperature, and relative humidity) in a conference room of a commercial building in Pittsburgh, PA and conducted experiments about occupancy detection. In the study, they compared four different thermostat set-point operations using EnergyPlus simulations: A fixed system schedule; a schedule based on pre-determined occupancy; an occupancy (Motion) sensor schedule; and a dynamic occupancy schedule (i.e., a time and state-dependent use of a Markov model). The study found that the most effective approach to reducing energy consumption was a thermostat with a motion-based operation. Degelman (2000) found a significant occupancy influence on energy reductions in an office building in a hot-humid climate. This study used a Monte Carlo model to predict actual occupancy in buildings using the measured on-off status from motion sensors. The research reported that substantial energy savings could be available in almost all categories of end-use. For example, lighting showed the most excellent energy savings (29%). The total building energy-saving was 19% estimated.

Also, Abushakra and Claridge (2001) showed occupancy variability that was frequently undervalued in inverse energy models (i.e., regression model). In their study, they used a Short-term Monitoring Long-term Prediction (SMLP) inverse method to estimate the uncertainty of the occupancy variables in office buildings using different alternatives derived from lighting and equipment loads. The SMLP inverse method predicts annual energy use based on a short period of hourly data through the use of a multiple linear regression model. The researchers found increased reliability in the energy models that applied the occupancy variable, besides they rated a strong interaction between occupancy and building performance.

Duarte et al. (2013) studied occupancy patterns in a large office building using monitored sensor data to identify occupancy diversity factors. The variation in diversity factors showed up to a 46% difference compared to occupancy schedules in Standard 90.1-2004. When comparing measured occupancy data with stochastic occupancy models (Page et al. 2008), the occupancy profiles showed similar characteristics. This study pointed out that the difference in occupancy schedules may create miscalculated simulation results or may cause problems in the building HVAC system design since the code schedules could be used as a reference for energy modelers in simulation analysis.

D'Oca and Hong (2015) used a three-step data mining framework to develop occupancy patterns in office spaces. This study collected measured occupancy data from 16 offices in Germany, which were mined using a decision tree model and a rule induction algorithm. Then, a cluster analysis was utilized to determine occupancy patterns by occupant behavior. The four typical working profiles were finally developed, which could be used to provide more realistic occupancy schedules for building energy simulation programs. D'Oca and Hong (2015) showed a characterization of the occupancy probability in an office would help develop more accurate building energy models.

In summary, the review of the previous literature pointed out that occupancy diversity is large in actual buildings, which could generate uncertainties in energy estimations and predictions when using normalized occupancy schedules due to large variations in actual occupancy usages. However, using improved sensing technologies can help predict actual occupant behavior and improve energy performance predictions in buildings. Also, such a fact attests to the need for occupancy-based building controls for building systems to achieve higher efficiency and operation optimization in buildings.

2.3. Occupant Behavior Modeling Methods

Interpretation of occupant behavior in buildings is one of the conundrums for architectural engineers in the last decades. The significant adversity of occupant behavior modeling in building energy simulations is that occupancy related-factors are complicated and knotty to be understandable. The problem could militate against identifying the causal relationship between occupants and buildings. It also sometimes gives rise to uncertainty in building performance analysis. Therefore, the improvement method of occupant behavior modeling is very significant to alleviate uncertainty from the randomness and unpredictability of occupant behavior, especially in building energy performance simulations and high-performance building designs, such as near-zero or net-zero energy buildings (O'Brien and Gunay 2014, O'Brien et al. 2018). For example, many studies have observed very different results from the simulations using different occupant-related input parameters in different building designs. They have shown varying results due to the impact of occupancy-based building controls and interactions between occupant-related factors (i.e., occupant schedules, operable windows, lighting controls, thermostats, and appliance usage models) (O'Brien and Gunay 2014, IEA-EBC 2018, Annex 66).

After that, there have been numerous attempts using mathematical methods to develop improved occupant behavior modeling methods to accurately analyze the influence and interaction of occupant-related factors in building energy consumption. The mathematical modeling methods have advantages and disadvantages of data analyses depending on their methods, and to attain the best results from the different methods, it is necessary to choose proper suitable modeling methods for the study.

Thus, on the basis of the previous and ongoing occupant modeling method studies, IEA-EBC Annex 66 researchers tried to understand occupant behavior in building energy simulations and to develop occupant behavior models into current building energy simulation tools (i.e., eQUEST, EnergyPlus). The researchers found that several statistical approaches that were useful and most frequently used for occupant modeling, such as classical statistical model (i.e., general linear models), Markov and Hidden Markov chains, Mixed-effect model, and decision tree model (IEA-EBC, Annex 66 2018).

Similarly, Gaetani et al. (2016) categorized the most common simulation methods for occupant behavior analysis based on size, resolution, and complexity. As simulation frameworks, conventional models and agent-based models were defined: The conventional model contains the deterministic model, non-probabilistic model, and stochastic model. The agent-based model refers to the agent-based stochastic model. Deterministic models represent commonly used simulations for code-compliance, and contrariwise, probabilistic (also called stochastic) models consider characteristics of randomness. Also, the static model performs a fixed model that does not respond to transient states during the simulation process (e.g., a schedule corresponding to the number of occupants in a room over a day). An example of this model in practice is a set of ASHRAE Standard 90.1 schedules for lighting, plug loads, and occupancy. Most suitable applications of the model are building codes and standards primarily at the whole-building level for early design stages. The dynamic model captures the two-way interaction between occupants and buildings. Most suitable applications of the model are codes and standards at the room and zone scales, particularly related to adaptive comfort systems.

2.3.1. Static and Dynamic Methods

To understand occupancy modeling methods, it is required to figure out the characteristics of model types. Static (or known as steady-state) and dynamic (or known as the transient state) models are quite different positions about time-dependent changes in the buildings.

Static models typically provide fixed schedules that assume no changes related to schedules during the projection period, which have the definite advantage of easy to use for practical projects and transparent process for code-compliance building energy modeling (i.e., Standard 90.1-2016 User's Manual). However, it fails to carefully notice occupant behavior in different climates, indoor activities, and space types for building energy calculations. This is because these models adopt entirely previously determined schedules based on assumed conditions, and thus, they cannot respond to continuously varying external and internal environmental states. Therefore, the static model shows the conservative tendency of occupancy rates for office buildings (O'Brien et al. 2018). For example, occupancy schedules for Standard 90.1-2016 assume 95% of peak occupancy rate for a medium office during weekdays (ASHRAE 2017b), whereas the previous case study such as IEA-EBC, Annex 66 (2017b) reported that actual office spaces were used around 80% of the designed peak occupancy (i.e., Case 23). Such a nature makes obstacles to understand the state of occupant behaviors and control uncertainty in building use simulations.

On the other hand, dynamic models provide relatively flexible schedules that can consider the state changes of buildings by the interactions between buildings and states or events of occupant-related factors (i.e., occupancy rate, lighting system usage, and thermostat controls) during the estimated period. Such a characteristic of flexibility offers more reliable results using time-variant values in simulation predictions. For example, dynamic stochastic models as the emerging occupant modeling methods in the literature reviews (IEA-EBC, Annex 66 2018, O'Brien et al. 2018a) can surmise more realistic results to predict the actual building energy use than the conventional static models. However, this model may yield inconsistent results for every simulation because it uses different time-variant values for every calculation and only shows probability as a result of occupancy behaviors. Such a reason makes it difficult to secure reliability for code-compliance and to determine building energy performance for preliminary designs.

2.3.2. Deterministic and Stochastic Methods

In mathematical models, deterministic and stochastic (or probabilistic) models are placed on the antipodes in the theoretical approaches to estimate building energy performance of occupant behaviors. The typical deterministic model uses preset parameters that are optimized for previously designed environmental states of buildings and brings invariant values of occupancy-related schedules. Therefore, the deterministic model always produces the same results based on initial conditions if the model uses a static state.

Conversely, the stochastic model embraces variable states with the randomness of occupant behaviors in buildings by adopting probability distributions. For example, the LBNL research group developed a web-based occupancy simulator (LBNL 2018) using stochastic models to simulate occupancy profiles in buildings and create detailed occupancy schedules for designed spaces. Such generated schedules are useful to emulate occupancy diversity and randomness in buildings. However, in the convention of stochastic models, there are no representative approaches for code-compliance (i.e., the ECB and the Appendix G methods in Standard 90.1-2019) to propose the stochastic nature of occupancy modeling. Also, this model could generate different occupancy schedules for each building depending on their attributes of a population for occupancy modeling (i.e., size, location, building type, etc.), which creates uncertainty of stochastic models that obstructs to develop generally acceptable occupancy-related schedules.

2.3.3. Agent-based Methods

The agent-based model is an emerging occupant modeling technique since there are several benefits for simulating the influence of individuals' dynamic actions and interactions of autonomous agents with the building (O'Brien et al. 2013, O'Brien et al. 2018 and IEA-EBC, Annex 66 2018). This model has the definite advantage of considering both experimental and mathematical approaches for the prediction and representation of individual occupants' behaviors as agents in simulations. For stochastic modeling, numerous approaches can have been used. Annex 66 researchers (IEA-EBC, Annex 66 2018) organized occupant behavior modeling approaches from the previous literature that reported that Markov and Hidden Markov chains were suitable for time-dependent data sources, and Mixed-effects models can be used for diversity among occupants. Also, data mining techniques (i.e., decision tree, clustering) recently shows a growing trend for occupant behavior modeling.

2.3.4. Summary

There have been numerous models for occupant behavior modeling. Such models have tried to improve the prediction of occupant behavior in buildings and reduce the uncertainty and discrepancies in building energy simulations against actual energy use of the existing buildings. In a literature review, occupant behavior simulation frameworks are basically categorized as four types depending on their size, resolution, and complexity: 1) Deterministic, 2) Non-probabilistic, 3) Probabilistic/Stochastic, and 4) Agent-based models. Also, based on their state conditions of time flow, the dynamic and the static models can be applied for occupancy modeling analysis.

Deterministic static models typically provide fixed schedules that assume no changes during the projection hours. This characteristic is useful for practical projects and transparent processes, such as code-compliance building energy modeling (i.e., Standard 90.1-2016 User's Manual). On the other hand, dynamic stochastic models offer relatively flexible schedules that can reflect the interactions with buildings during the projection period. This model uses mathematical approaches (i.e., regression, Markov chain model) as shown as probability, which could over- or under-estimate the influence of occupant behaviors in commercial buildings depending on their data population characteristics and analysis models.

Therefore, for this study, it is required to develop a realistic and feasible occupancy modeling method for occupancy-based building modeling credits to make up the problems of the currently adopted and used deterministic models for code-compliance in Standard 90.1-2016.

2.4. Challenges for Introducing Occupancy Predictions and Modeling Methods

In this chapter, technical or descriptive barriers are addressed based on O'Brien et al. (2018), Tian et al. (2018), and Belazi et al. (2018) presented challenges that must be settled to introduce occupancy-based control credits in Standard 90.1-2019. The challenges for this study are categorized as the following:

- Challenge 1: The necessity of defining related parameters of occupancy modeling for the Standards
- Challenge 2: The necessity of defining occupancy-related provisions and modeling methods in the Standards (i.e., Standard 90.1 and 189.1)
- Challenge 3: The inevitability of updating over- or under-estimated occupancy related schedules for simulations and no credits for supporting more energy use reduction potential due to occupancy-based building controls in the Standards
- Challenge 4: Limitations of occupancy modeling in the current building energy performance programs (i.e., EnergyPlus, DOE-2.1e, eQUEST, and TRNSYS)
- Challenge 5: Uncertainty analysis of input variables for occupancy-based controls in building energy performance simulations

2.4.1. Challenge 1: No Consensus of Occupancy-Related Parameters for the Standards

These days, the evolution of technologies such as the Internet of things (IoT) expedites the faster spread and integration of technologies in the field of architectural design and construction. For this reason, sensing technologies to control lighting and HVAC systems are not a stranger any longer. However, there has not been a common consensus of the scope of occupancy modeling and simulation parameters so far to precisely quantify the influence of occupant behavior in building energy use and provide credits of its energy use reduction potential due to optimized control and operations. To date, only a few researchers started to discuss this topic in their research to improve code-compliance (i.e., O'Brien et al. 2018).

However, to define the related parameters of occupancy modeling, it is required to exhaustively understand total building energy use, modeling assumptions, and parameters of occupant behavior. Although it is difficult to clearly diagnose occupant behavior and its impact on building energy use, hundreds of researchers in the working groups (i.e., IEA-EBC Annex 53, Annex 66, and Carleton University, Canada) found that occupant behavior significantly affects the results of building energy predictions from operable windows, window shading adjustment, lighting switching control, thermostat control, appliance use, and occupant diversity from the literature review (IEA-EBC, Annex 66 2018).

However, currently, the performance compliance paths of Standard 90.1-2019 do not define energy modeling methods for the representations of occupancy-based building controls. The Appendix G only contains credits of occupancy sensors for the lighting system controls in the table G 3.7, pp333-335 that provide "Occupancy Sensor Reductions (OSR)" (See Appendix B, credits for lighting occupancy sensors). Therefore, there are no exhaustive ways except designers or engineers who want to develop and adjust their proposed design model for occupancy modeling based on their practical expertise and experience.

Table 1 shows a list of occupancy-related parameters mentioned in Standard 90.1-2019 (ASHRAE 2019). The existing code-compliant occupancy modeling methods do not fully cover occupancy-related parameters, which exclude personal conditions (i.e., Clothing level, metabolic rate) and reactions (i.e., personal thermostat control). Standard occupancy modeling typically depends on the simulation schedules to model occupancy behavior. O'Brien et al. (2018) pointed out that occupancy modeling requires comprehensive and scrupulous studies of individuals' adaptive behaviors for better understanding. Therefore, to develop elaborated occupancy models for conventional buildings, it is required to develop concurred occupancy-related parameters for performance code-compliance.

Table 1. Occupancy-Related Parameters in Standard 90.1-2019

Paths	Section	Covered
Prescriptive	5 Building Envelope	• N/A
	6 HVACs	• Thermostat set points and controls (setback, on/off) • Ventilation system controls
	7 Service Hot Water	• N/A
	9 Lighting	• Lighting controls (occupancy sensors)
Performance	11 Energy Cost Budget (ECB)	• Schedules: occupancy, receptacle (plug) loads, elevators, lighting, thermostat setpoints, hot water • Controls: thermostat, lighting, ventilation
	Appendix G	• Schedules: occupancy, receptacle (plug) loads, elevators, lighting, thermostat setpoints, hot water • Controls: thermostat, lighting, ventilation

2.4.2. Challenge 2: The necessity of Defining Occupancy-Related Provisions and Modeling Methods

The current performance paths (i.e., ECB and Appendix G methods) in Standard 90.1-2019 neglect occupant behavior-related parameters and thus handle them only as types of schedules or control methods to conduct a comparative analysis between the baseline and the proposed design models. A single assumption for occupancy parameters (i.e., schedules) is mandated to compare energy use reduction potential against the baseline model. Even though Standard 90.1-2019 includes provisions of the credits for occupancy-based lighting controls, if the credits integrate other occupancy-related parameters (i.e., HVAC, ventilation, and application), it could show more energy use reduction beyond the current code models. However, since full occupancy-based control modeling is not currently described enough in the Standard requirement to cover the characteristics of occupant behavior. Therefore, more research is required to seek a method to define occupancy modeling provisions and credit methods for Standard 90.1-2019.

2.4.3. Challenge 3: The Necessity of Updating the Current Code Schedules and Introducing Credits for Occupancy-Based Building System Controls

So far, researchers (Hoes et al. 2009, Yan et al. 2015) have argued that the current schedules cannot represent actual occupant behavior in office buildings, particularly in occupancy diversity and presence rate. What is serious in this regard is that these code schedules are commonly used for developing code-compliant models and practical works using building performance simulations (BPS). These bring about over- or under-estimated results of predictions using building energy simulations. Although Standard 90.1-2019 allows exploiting different schedules for the proposed design, it is unattainable without the approval from the related authorities. Thus, such a reason may enforce the use of fixed code schedules on architects or engineers for occupancy modeling. For example, Gaetani et al. (2016) verified the results from the survey that most modelers use default schedules for building energy modeling.

Therefore, to compensate for the vulnerability of interactions between occupants and buildings in current deterministic schedules for code-compliance, it is inevitable to update occupancy related schedules. Otherwise, credits of more energy use reduction potential due to occupancy-based controls in the standards could not be considered to provide benefits and offset the vulnerability of flexibility in the current deterministic schedules. There are three types of approaches to representing occupancy rate and credits in load calculations.

2.4.3.1. Full-Time Equivalent Occupancy (FTEO) (2nd Review)

U.S. Green Building Advisory Committee (GBAC) developed an occupancy-based Energy Use Intensity (EUI) that was based on the lately suggested notion of Full-Time Equivalent Occupancy (FTEO) to provide an improved understanding of occupant-related building energy use. This study appraised about how much occupancy impacts building energy use and EUI using a standard office building. This metric could be useful in buildings that have dramatic changes in occupancy to acquire more accurate results in building energy performance evaluation. The concept of FTEO is "the number of assigned occupants may not represent actual occupancy level in a building, due to different factors including telework, alternative work schedules, and attendance at outside meetings or events" (Selvacanabady and Judd 2017).

$$\text{FTEO} = \frac{Total\ Annual\ Occupied\ Person\ Hours}{1645\ Hours}$$

- 1,645 hours = 35 hours/week × (52 weeks/year – 5 weeks regulatory vacation)
- Regulatory vacation: federal holidays + average annual leave hours/year

2.4.3.2. Occupancy Load Factor (OLF)

Haberl and Komor (1989) conducted a study of a shopping mall to ameliorate commercial building energy audits. This study discovered unexpected energy use in unoccupied hours in a comparative analysis between calculated base-level energy use and actual energy use using Occupancy Load Factor (OLF) and Electric Load Factor (ELF). Unexpected electricity use in unoccupied hours could appear when monthly ELF outpaces monthly OLF. The equations of OLF and ELF can be defined as below (ASHRAE 2015b):

$$\mathrm{OLF} = \frac{Occupied\ Hours\ in\ Period}{24\ \times Days\ in\ the\ Period}$$

$$\mathrm{ELF} = \frac{kWh\ (for\ the\ Period)}{kW(Max\ in\ Period) \times Hours\ in\ Period}$$

In these equations, the occupancy rate can be simply presented in an average occupied hour during the projected period to diagnose energy waste in buildings.

2.4.3.3. Occupancy Reduction Factor (ORF)

The Appendix G method in Standard 90.1-2016 proposed a new measure to calculate the performance rating method for Lighting Power Density (LPD) allowance, which could be used for occupancy sensor-based lighting controls. For example, if lighting systems in an enclosed office are controlled by occupancy sensors, the maximum LPD of the enclosed office is 30 percent more than conventional enclosed offices (ASHRAE 2016a, 2019).

Before this introduction, similarily, Thornton et al. (2011) used the same measure to provide occupancy schedule reduction credits for estimating potential energy use reduction of Standard 90.1-2010 compared to Standard 90.1-2004. This study assessed 153 Addenda (44 Addenda to 90.1-2004 and 109 Addenda to 90.1-2010), and of them, occupancy sensors and LPD reduction-related Addendum were Addendum x to 90.1-2007, Addendum aa to 90.1-2007, and Addendum cf to 90.1-2007. The proposed lighting power deduction based on the previous literature had a format as below Table 2 (Thornton et al. 2011, Table 5.45).

Table 2. Manual-On Occupancy Sensor Lighting Power Reduction

Prototype	LPD reduction (W/ft^2)
Small Office	0.0217
Medium Office	0.0191
Large Office	0.0143

Table 3. Occupancy Sensor Control Lighting Reduction by Space Type

Space types	Occupancy Sensor Reduction Estimate
Pre-K to 12 Classrooms	32%
Storage and Supply (50-1,000ft^2)	48%
Office (private up to 250ft^2)	22%
Restrooms	34%
Dressing/Fitting Rooms	10%

$$Schedule\ Reduction\ Fraction = Space\ Type\ Fraction \times Occupancy\ Sensor\ Reduction$$

2.4.4. Challenge 4: Limitations of Occupancy Modeling in the Current Building Performance Simulation Programs

In general, building energy simulation programs take the lead in occupancy modeling for code-compliance to quantify energy use reduction potential from the proposed design. Many simulations for compliance models prefer to use deterministic modeling approaches since Standard 90.1-2019 is not ready to cover dynamic or stochastic modeling approaches. There are three ways to develop occupancy models in building energy simulation programs (O'Brien et al. 2018a, LBNL 2018):

1. Adjust or customize existing schedules
2. Use advanced functions in building energy simulation programs or plug-in applications (i.e., obFMU[1], LBNL)

[1] The obFMU is an occupant behavior FMU developed by the occupant behavior research team at the LBNL. This tool co-simulates with EnergyPlus v8.3.0 based on a DNAs (drivers-needs-systems-actions) ontology. The objective

3. Generate occupant schedules using simulators (i.e., Occupancy Simulator, LBNL)

An international survey of occupant behavior (IEA-EBC, Annex 66 2017d) identified the current needs, practice, and capabilities of occupant modeling by users. This survey contains two parts: (1) current practice and stance of simulation users respecting occupancy modeling and (2) available functions of occupant modeling in current building performance simulation (BPS) programs. A total of 274 valid responses from 37 countries showed that simulation users applied simplified and varied assumptions that are different in the actual phenomenon of occupant behavior in buildings because of insufficient time or lack of understanding as significant barriers. Also, to evaluate occupancy modeling in the commonly used building performance simulation programs (e.g., EnergyPlus, DOE-2, eQUEST, TRNSYS), six domains were discussed: occupant movement/presence, controls of lighting, window, and HVAC systems, other internal heat gains related with occupant behavior (i.e., domestic hot water), and other domains related with occupant behavior (i.e., blinds). The survey reported that deterministic functions could produce adequately consistent results from simulations, whereas stochastic functions could generate varied results depending on their conditions.

Also, the Annex 66 (IEA-EBC, Annex 66 2018,2017d; Cowie et al. 2017) surveyed occupant modeling functionality in eight widely used building performance simulations (i.e., DeST, EnergyPlus, ESP-r, TRNSYS, IDA-ICE, IES-VE, Pleiades + Comfie, and DOE-2.1e). It comes up with facts that most of building performance programs offer relatively steady functionalities of deterministic occupant modeling, which are typically modeled employing

---

of this tool is to simulate occupant behavior at each time step using XML format and consider other environmental condition using the co-simulation program.

prescribed schedules and rule-based controls. On the contrary, the stochastic modeling functionality of occupants is not prevalent in the present simulations that are available using two types of approaches: user-defined models and defined occupant models from the programs. For example, the representation of occupant stochastic models in the survey can be built up in their user-defined models, such as using the external function (i.e., DOE-2.1e), source code/EMS/co-simulation (i.e., EnergyPlus v8.3), and source code modification (i.e., ESP-r v12.3, TRNSYS 17 v5.3.0). The recommendation of this study to simulate stochastic occupant models is to develop a co-simulation for the current simulation tools.

For more details, Appendix E describes the most used whole-building energy simulation programs and provides an abridged table for occupancy modeling functions in the programs.

2.4.5. Challenge 5: Uncertainty Analysis of Input Variables for Occupancy-Based Controls in Building Energy Performance Simulations

In general, there is always some uncertainty in whether or not the input variables for a simulation represent the actual conditions in a building. Numerous variables influencing energy use in buildings are complicated and inherently uncertain. For example, the uncertainty of occupant behavior and building envelope materials can affect the results of energy performance analysis. Therefore, previous researchers have tried to identify different uncertainty modeling approaches and conduct the uncertainty analysis to identify the impact of input variables on building energy performance simulations, including Tian et al. (2018) and Belazi et al. (2018).

Tian et al. (2018) offered a systematic review of uncertainty analysis from four perspectives: uncertainty data sources, forward and inverse methods, application of uncertainty analysis, and available software. First, this study concluded that an uncertainty analysis's data sources should provide a firm foundation for identifying variations of uncertainty factors. The study showed that forward uncertainty analysis typically used three types of approaches (i.e., Monte Carlo, non-sampling, and non-probabilistic) depending on the purpose and specific application of building analysis. For the inverse analysis, the study concluded that recent studies focused more on Bayesian computation due to the full use of prior information about unknown variables. Fourth, the study concluded that uncertainty analysis in building energy assessment can be applied to analyzing several variables, including weather data, thermal properties, HVAC system sizing, occupant behavior, and variations of sensitivity indicators.

Belazi et al. (2018) performed an uncertainty analysis for hot, moderate and cold weather conditions using the building envelope (i.e., external walls, floor and roof U-values). The results revealed that there is a large variation of energy use because of uncertainties related to occupant behavior and building properties. The study concluded that uncertainty analysis of input data identified that occupant behavior variables have a considerable impact in hot climates compared to variables related to building envelope materials. On the other hand, for cold climate, the study found that the impact is more significant for building envelope variables than occupant behavior variables.

Therefore, in occupancy-based controls, a complicated relationship of occupancy variables impact the results in building energy simulations. In general, previous studies have utilized sensitivity studies to determine which input parameters impact the simulation output so special attention can be paid to accurately portraying these parameters. Therefore, the impact of uncertainty should be considered in occupancy modeling when analyzing the impact of occupancy on energy use between different input variables.

2.5. Occupancy-related Influencing Variables and Impact on Building Design

In building energy simulations, occupant-related variables are significant to determine the type of occupant behaviors and predict potential influence in building energy use. In building simulations, occupant behaviors could trigger the changes of building operation settings related to particular occupant behavior variables. Typically, occupant behavior is interactions between occupants and buildings, which would be affected by the physical, biological, social, and psychological environment. The prediction of these interactions requires a multilateral effort into solving problems with technical strategies. Therefore, the determination of occupancy variables in simulations is challenging due to the difficulty of considering all their conditions in the modeling stages.

Thereby, this study limited the scope of occupant-related influencing variables, focusing on building systems (i.e., heating, cooling, ventilation, lighting, and appliances). In other words, occupant-related influencing variables in this study address usage profiles of occupants related to building systems and other triggers (i.e., biological, social, and psychological environment) were not included in the scope of the study. The following chapters describe occupancy-related variables from primary research projects of occupancy-based building controls.

2.5.1. IEA-EBC Annex 53

IEA-EBC Annex 53 (IEA-EBC, Annex 53 2013a,b) studied occupant behavior and energy modeling to improve understanding of the total energy use in residential and office buildings. To interpret the relationship between occupant behavior and building energy use in office buildings, IEA-EBC Annex 53 investigated six types of analysis models: 1) Psychological models; 2) Average value models; 3) Deterministic models; 4) Probabilistic models; 5) Agent-based models; 6) Action-based models.

As for the types of analysis models, psychological models were defined to describe the occupant behavior themselves and related actions in building energy use. Average value models employed the occupant-related influential factors, which significantly affect the total building energy use. Deterministic models have the classification of families to provide deterministic input values for energy simulations. Probabilistic models calculate the probability of specific actions using parameters and equations. Agent-based models regard occupants as individuals with rule-based self-regulating decisions (e.g., memory, self-learning). In action-based models, occupant behaviors were defined as actions (i.e., movement, control action) that could tune up occupant-related conditions, such as occupant location, window condition, lights, air-conditioners and come up with results for occupant movement and control actions separately.

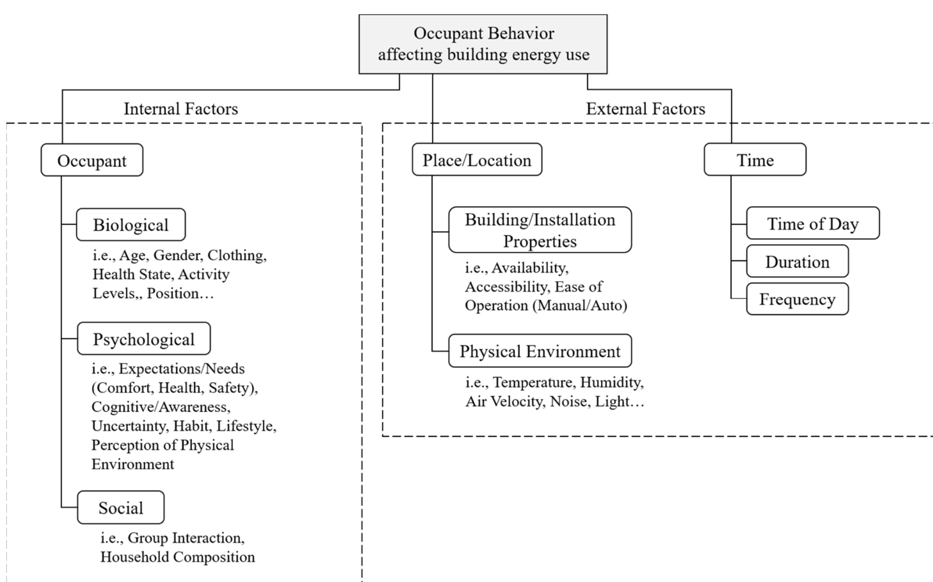


Figure 9. Influencing Factors of Energy-related Occupant Behavior (Adapted from Figure 2.3 in IEA-EBC, Annex 53 2013a)

This project also identified occupant-related driving factors in energy use and attempted a quantitative analysis of occupant-related factors in energy modeling. Figure 9 shows a scheme developed by IEA-EBC Annex 53 that is an interaction between the occupant and building systems driven by influencing parameters that could be categorized as internal (biological, psychological, and social) and external parameters including building/installation properties, physical environment, and time.

2.5.2. IEA-EBC Annex 66

IEA-EBC Annex 66, a follow-up study of Annex 53, has explored occupant behavior simulation in commercial buildings. The Annex 66 reviewed mathematical and statistical methods of occupant behavior in commercial buildings and developed an XML schema (i.e., obXML) to incorporate occupancy modeling into building energy performance programs (i.e., EnergyPlus) (LBNL 2018).

In the process of developing an occupant behavior XML (obXML) schema, as a subtask under the Annex 66, the LBNL (Hong et al. 2015a,b) developed DNAS (Drivers-Needs-Actions-Systems) ontology to standardize occupant behavior. The DNAS is a methodology of occupant behavior to have a better understanding of occupant in building energy use. Each capital letter of the DNAS indicates: 1) Drivers: environmental factors; 2) Needs: occupant-related physical and non-physical requirements; 3) Actions: interactions between systems/activities and occupants; and 4) Systems: equipment or mechanisms to restore comfort environment in the building.

To propose the DNAS framework, researchers reviewed several simulation models of occupant behavior, which investigated typical building components, characteristics, metrics, and simulation outputs from the previous literature, as shown in Table 4 and Table 5 (Hong et al.

2015a,b). In the DNAS framework, parameters forcing occupant's actions were newly defined as drivers that promote the interactions with building systems to change the indoor environmental conditions from discomfort to comfort.

Table 4. Typical Building Components and Characteristics of Occupant behavior

Group	**Components and characteristics**
Building Type	Building type (i.e., office)
Envelope design	Building envelope, thermos-physical characteristics Façade orientation and height Window geometry and height Type of window device (manual/motorized/automated) Type of shading device (manual/motorized/automated)
Space	Type of office (open space, cubicle, private vs. shared office) Space layout, geometry, location
Systems	Type of ventilation system (natural, mechanical, mixed-mode, night ventilation) Type of HVAC/AC system Type of lighting control (manual/automatic)
Controls	Type of indoor temperature control Internal loads, occupancy schedules

Table 5. Typical metrics and simulation outputs of Occupant behavior

Techniques	**Metrics**
Windows	air change rate(n/h), losses (kWh/m^2), thermal comfort, indoor air quality
Shade/blinds	Mean Shade Occlusion (MSO), Shade Movement Rate (SMR), visual/thermal comfort, glare, discomfort index
Lighting system	daylight, Illuminance level (lux), Light switch frequency, visual comfort
Thermostat	primary energy consumption for space heating (kWh/m^2), internal gains, thermal comfort
Space occupancy	occupancy rates, nominal occupancy profiles, vacancy activity, transition probability, presence/absence probability and distribution, frequent pattern detection
Plug loads	Occupancy patterns, operational schedules

2.5.3. IEA-EBC Annex 79

The ongoing IEA-EBC's project Annex 79: *Occupant-centric building design and operation* for 2018-2023 period seeks for new approaches to integrate an understanding of occupant behaviors into building design and operation levels, which will encourage that the representation of real building's operation can be appropriately modeled for designers and building managers with guidelines. The objective of this project is to include: 1) development of new scientific insights of adaptive occupant behavior based on manifold independent indoor environmental parameter; 2) a better understanding of interactions between occupant and buildings; 3) applications of big data techniques (i.e., machine learning) for promoting the active use of generated data of occupant, building and sensing technologies; 4) development of recommendations of occupant modeling to improve the current building codes and standards; 5) development of test cases to verify new methods and models for occupant-centric building design and operation (IEA-EBC, Annex 79 2018,2019).

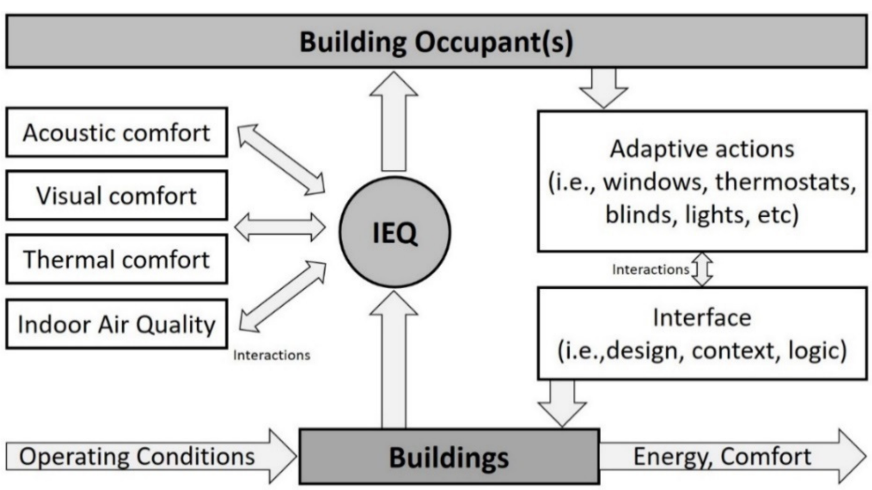


Figure 10. The Annex 79: Advanced building modeling of occupant behavior

Figure 10 (adapted from IEA-EBC, Annex 79 2019) shows their perspective to understand advanced modeling and related variables of occupant behavior for design and operation stages. This figure describes that this project mainly considers building energy performance, occupant comfort and indoor air quality as performance metrics and such performance metrics can be interacted based on adaptive occupant behaviors (i.e., windows, thermostats, blinds, lights) and building designs (i.e., design, logic, context).

2.5.4. Impact of Occupancy-Based Controls on Building Design

With the technology evolution, occupancy-based control is becoming a new normal to monitor and operate building systems in commercial buildings. For example, in high-efficient buildings, numerous technologies of OBC can improve building operations and energy efficiency, which is closely related to human interactions with buildings, including HVAC, lighting, plug loads, operable window and shading, automated system, human operation, and distributed energy resources. Smart HVAC systems collect and interpret occupant usage from various sensors to optimize the system operation without loss of occupant comfort. Also, smart HVAC controls can reduce energy consumption when interior zones are unoccupied and improve Smart lighting systems incorporate daylighting, advanced occupancy, and dimming functions to eliminate overlit spaces or energy waste in unoccupied spaces using occupancy sensors (King and Perry 2017). Such technology is mainly involved with building performance (i.e., building automation, energy management, HVAC control) and indoor comfort (i.e., CO2/environmental monitoring, lighting) (IFSEC Global 2017). However, with the increased demand of green buildings (i.e., LEED-certified buildings) and high-efficient buildings, when developing building design, designers also started to consider occupancy-based controls of building performance in building designs, such as window design, exterior envelope shading design, indoor shading device control, and HVAC system thermal zone design and operation. However, it has challenges to diffuse occupancy-based control in building designs. For example, the current Standard 90.1-2019 does not allow to use of different schedules from occupancy sensors in performance paths (ASHRAE 2019) and also, there are several problems, including integration/interoperability of different systems, installation and maintenance costs, and cultural resistance to new technology among staffs (IFSEC Global 2017). Despite the pros and cons, occupancy-based controls are helpful to ensuring energy performance for energy-efficient buildings and integrated designs for green buildings.

2.5.5. Summary

In summary, IEA-EBC's research projects (i.e., the Annex 53, 66, 79) have identified occupancy-related variables and forwarded the understanding of occupant behavior in buildings. These projects have provided new insights about the influence of occupant behavior in building energy use, modeling methods in building performance simulation programs, and integration of occupant behaviors with building systems in design and operation stages. Also, researchers investigated occupant-related variables from the previous literature, which was significant to select occupancy variables and limit the research scope of occupant behaviors in this study. In addition, occupancy-based control would affect energy-performance based building designs for architects and building owners. The integration with IoT and smart technology can provide more options for designers who want to develop building design, considering occupant and built environment, to save energy and cost.

However, these projects and studies focused on the identification of total energy use (IEA-EBC, Annex 55 2013a,b), field study methods, modeling and evaluation methods, cases studies (IEA-EBC, Annex 66 2018; Wagner et al. 2018; Park et al. 2019), occupancy schedule tool development (Chen et al. 2018; Feng et al. 2015) and integrated occupancy model development with building energy simulation (IEA-EBC, Annex 66 2018; Hong et al. 2015a,b). Also, a recent research project, IEA-EBC Annex 79 concentrated on occupant-centric building design and operation (O'Brien et al. 2020b). This is in contrast to the previous and ongoing studies that recently began occupancy modeling research to apply it into practice or building codes and standards (O'Brien et al. 2018b; O'Brien et al. 2019; O'Brien et al. 2020a). These studies did not give analyzing an OBC method for different building systems (i.e., PSZ, PVAV), different building envelope materials (i.e., lightweight, heavyweight), and designs (i.e., window-to-wall ratio) in different climates (i.e., hot and cold climate zones). Therefore, there is a need to consider the impact of different or varying occupancy-related variables and the impact on building design.

3. SIGNIFICANCE AND LIMITATIONS OF THE STUDY

3.1. Significance of the Study

This study investigated occupancy modeling approaches and evaluated the potential influence of Occupancy-Based Controls (OBC) using simulation to reduce building energy loads for building systems. From the literature review, the previous topics mostly focused on field measurement methods, predicting actual occupancy schedules, data-driven occupant modeling strategies, integrated occupancy model development with building energy simulation tools, OBC application in building design and operation. In contrast, the previous studies gave little attention to analyzing the impact of occupancy-based controls on different building systems (i.e., PSZ, PVAV), different building envelope materials (i.e., lightweight, heavyweight), and designs (i.e., window-to-wall ratio) in different climates (i.e., hot and cold climate zones). Therefore, this study concentrated on identifying the impact of occupancy-based building controls in different weather conditions, different building types (i.e., lightweight, heavyweight) for different system types (i.e., PSZ, PVAV) with varying window-to-wall ratios.

3.2. Limitations of the Study

This study has the following assumptions and limitations to accomplish the research objectives, which include:

1) The reference buildings of this study were small sized office buildings. Therefore, the results of this study might differ in other sized buildings (e.g., medium, large).

2) The energy models in this study simulated only selected two different building systems (i.e., PSZ, PVAV) with occupancy-driven smart controls in small office buildings. Therefore, the results may not be applicable to other HVAC system types.
3) This study used office building designs based on the U.S.DOE/PNNL prototype office buildings for Standard 90.1-2016. Therefore, other office shapes or offices with multiple floors may show different results.
4) This study limited the scope of occupancy-based building controls to specific simulation schedules (e.g., occupancy, lighting, equipment) only. Other occupancy-based building control variable options (e.g., operable windows, varying thermostat control, and varying set-back control) were not modeled in this study.
5) This study calculated the energy performance only in two representative climate zones (i.e., hot-humid, cold-humid) in the U.S. The impact of occupancy-based building controls in the other climate zones would need to be studied in future research.
6) This study assumes that occupancy-based building controls can be integrated into building systems, and their sensors can immediately and accurately capture occupant behaviors to send the correct signal to the control building systems. Thus, the simulations did not assume a time delay in building system controls.
7) Occupancy-based control schedules used in this study included different usage intensities from 100% to 0% in office buildings. The usage rates of occupancy-based control schedules assumed evenly-distributed usages during open office hours on weekdays.
8) This study used five-zone models for modeling convenience in energy performance calculations. More detailed zoning models would show improved accuracy in the impact of occupancy-based controls by space type.

9) This study adopted Standard 90.1-2016 models because the latest code adoption by the state of Texas is Standard 90.1-2016, and the latest prototype office models that were developed by the PNNL in collaboration with the DOE were for Standard 90.1-2016.
10) This study assumed that all input parameters were correct and did not attempt to determine how the results would differ from variations in the inputs (i.e., a sensitivity analysis).

4. RESEARCH METHODOLOGY

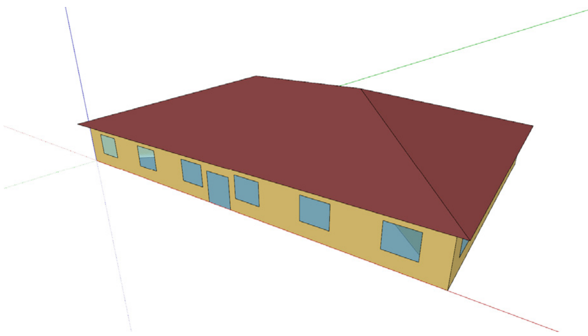
This chapter describes the research methodology to develop reference office building models and evaluate the impact of Occupancy-Based Controls (OBC) in order to develop the appropriate credits for improving code-compliance in the performance methods. To achieve the research goals, the following tasks are proposed: 1) Perform a literature review; 2) Develop the representative office building reference models based on the previous prototype building energy models for code-compliance; 3) Investigate the influence of OBC using energy models in different building design and system conditions (e.g., lightweight and heavyweight envelope materials, PSZ and PVAV systems); 4) Propose the novel credits of OBC modeling for hot-humid and cold-humid climate zones to cover energy use reduction potential of OBC in lighting, equipment, ventilation, heating and cooling loads in simulation models.

For each task, research methods were designed based on the previous literature review. Chapter 4.1 describes prototype office building models developed by the PNNL. Chapter 4.2 outlines the procedure of the reference small office building models in DOE-2.1e. Chapter 4.3 provides an approach to evaluate the impact of OBC in small office buildings. The evaluations of OBC were conducted using the sensitivity analysis of the occupancy-related schedules in hot-humid and cold-humid climate zones. Chapter 4.4 presents the approach to developing modeling credits for OBC in building energy performance simulations.

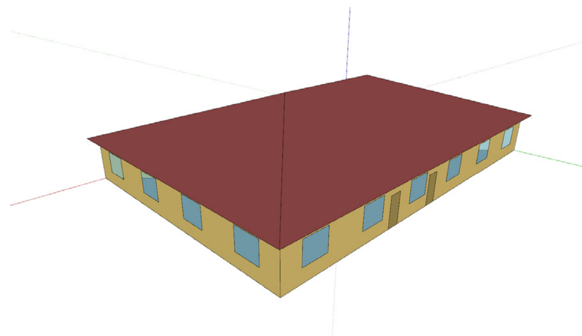
4.1.Commercial Prototype Building Models

The Department of Energy (DOE) has supported the development of the commercial prototype building model for code-compliant modeling (PNNL and U.S.DOE 2018). This prototype model represents 80% of the floor area of U.S. commercial buildings in all climate zones, which was developed in collaboration with the PNNL in order to back up Standard 90.1 and IECC. Currently, the DOE offers 16 prototype building models across 17 representative cities in 8 climate zones in the U.S. The commercial building prototype models contain small, medium, and large types of commercial building energy simulations that are suitable for new construction or retrofits of HVAC systems in existing buildings. The large office model has 498,588 ft^2 floor area and 12 floors, and the medium office model has 53,628 ft^2 floor area and 3 floors, and the small office model has 5,500 ft^2 floor area and one floor (Deru et al. 2011). In this study, small office models were selected to clarify and simplify the analysis process of potential energy use reduction due to occupancy-based controls. As of January 2020, Standard 90.1-2016 is the latest version in the code-adoptions by the state for commercial buildings. Also, the latest prototype office building models were for Standard 90.1-2016 in EnergyPlus ver 8.0. Thus, the prototype models for Standard 90.1-2016 were used in this study for building performance evaluations.

Figure 11 shows the modeling image of the PNNL small prototype office model plugged in Sketchup software for energy performance simulations in hot-humid and cold-humid climate zones. Sketchup was used to check the accuracy of the building's geometry and dimension in EnergyPlus. The prototype small office model assumed a simplified rectangular shape (aspect ratio 1.5) with an attic roof and contains HVAC systems, including an air-source heat pump (i.e., gas furnace back-up) systems for space heating and cooling. For thermostat controls, setpoints were defined as 75°F for cooling and 70°F for heating. As for ventilation design, ASHRAE Standard 62.1-2013 was used for simulations (ASHRAE 2013). Other requirements (e.g., envelope properties) and input parameters followed minimum requirements in Standard 90.1-2016.



(a) south-east view



(b) north-east view

Figure 11. Modeling Views of Small Office Building Prototype Model in EnergyPlus

Therefore, the analyses using the prototype models can generate acceptable results to represent the U.S. office buildings and calculate reasonable energy use reduction potential for occupancy-driven building energy simulations. This study developed small office reference models in DOE-2.1e based on the PNNL prototype models in EnergyPlus. This study simulated energy models for Houston, TX and Chicago, IL, as representative cities for climate zone 2A (hot-humid) and 5A (cold-humid) that can show the comparison about the influence of occupancy-based building controls in hot and cold climates. However, in Standard 90.1-2016 prototype models, since representative cities for climate zone 2A and 5A are Tampa, FL, and Buffalo, NY, the modeling locations were modified to reflect geographic information in Houston and Chicago.

4.2. Development of DOE-2.1e Small Office Reference Model

This study developed the small office reference models in DOE-2.1e simulation based on the PNNL office building models for Standard 90.1-2016 (PNNL and U.S.DOE 2019) to test the building energy performance of occupancy-based building controls in two different Climate Zones (CZ) in the U.S.: CZ 2A- the hot and humid (i.e., Houston) and CZ 5A- cold and humid (i.e., Chicago). DOE-2.1e software was selected due to an advantage to intuitively understand the structure of simulation modeling and provide simplified subdivided output formats for occupancy model analysis (e.g., load components, hourly report). In simulation modeling and calculations, there are some differences between DOE-2.1e and EnergyPlus v8.0 simulations. For example, DOE-2.1e is based on Building Description Language (BDL) (LBL 1991) and can directly develop coding in FORTRAN language. Whereas EnergyPlus utilizes a modular simulation system for modeling components (Kreider et al. 2001). The modular type simulation tool may be challenging for users to figure out the modeling structure at a look because users should consider the complicated relations between component modules.

Thus, this study used DOE-2.1e to develop small office reference models. Reference DOE-2.1e models shared the building information with the original PNNL prototype models in EnergyPlus ver 8.0 (PNNL and U.S.DOE 2018), including the building dimensions, material properties, and building systems (i.e., HVAC, lighting, ventilation systems). However, there were partial modifications in DOE-2.1e reference models from the original PNNL models due to the following reasons: 1) input parameter type differences between two simulation programs (e.g., system parameters), 2) outdated simulation library, 3) To evaluate the impact of OBC in simulations (e.g., off daylighting, off infiltration). The following chapters addressed the procedure of the DOE-2.1e reference model development for this study.

Table 6. Summary for Small Office Building Reference Models in DOE-2.1e

Category			Model Description
Building summary	Program & Form	Location	Zone 2A: Houston, Texas (hot-humid) Zone 5A: Chicago, Illinois (cold-humid)
		Available fuel types	Electricity
		Building Type	Office
		Building Prototype	Small Office
		Total Floor Area	5500 ft^2 (90.8 ft x 60.5 ft)
		Building shape	Rectangle (1.5 : 1)
Building summary	Program & Form	Number of Floors	1
		Window Fraction (Window-to-Wall Ratio)	24.4% for South and 19.8% for the other three orientations (Window Dimensions: 6.0 ft x 5.0 ft punch windows for all façades)
		Window Locations	Evenly distributed along four façades
		Shading Geometry	None
		Azimuth	Non-directional
		Thermal Zoning	Perimeter zone depth: 16.4 ft. Four perimeter zones, one core zone and an attic zone. Percentages of floor area: perimeter 70%, core 30%
		Floor to floor height	10 ft
		Floor to ceiling height	10 ft
		Glazing sill height	3 ft (top of the window is 8 ft high with 5 ft high glass)
Architecture	Exterior walls	Construction	Wood-frame walls (2X4 16" o.c.) 1" Stucco + 5/8" gypsum board + wall Insulation+ 5/8 in. gypsum board
		U-factor and/or R-value	Requirements in Standard 90.1-2016 (Table 10) Non-residential; walls, above-grade, wood-framed
		Tilts and orientations	Vertical
	Roof	Construction	Attic roof with wood joist: Roof insulation + 5/8 in. gypsum board
		U-factor and/or R-value	Requirements in Standard 90.1-2016 (Table 10) Nonresidential; roofs, attic
		Tilts and orientations	Hipped roof: 10.76 ft attic ridge height, 2 ft overhang-soffit
	Window	Dimensions	Based on window fraction, location, glazing sill height, floor area and aspect ratio
		Glass-Type and frame	Hypothetical window with weighted U-factor and SHGC
		U-factor & SHGC (all)	Requirements in Standard 90.1-2016 (Table 10) Nonresidential; Vertical Glazing
		Visible transmittance	Same as above requirements
	Foundation	Foundation Type	Slab-on-grade floors (unheated)
		Construction	8" concrete slab poured directly on to the earth
		Thermal properties for ground level floor: U-factor and/or R-value	Requirements in Standard 90.1-2016 (Table 10) Nonresidential; slab-on-grade floors, unheated
		Thermal properties for basement walls	N/A
		Dimensions	Based on floor area and aspect ratio

Table 6. Summary for Small Office Building Reference Models in DOE-2.1e (continued)

Category			Model Description
HVAC & DHW	System Type	Heating type	Air-source heat pump
		Cooling type	Air-source heat pump
		Distribution and terminal units	Single zone, constant air volume air distribution, one unit per occupied thermal zone
	HVAC Control	Thermostat Setpoint	75 °F cooling/70 °F heating
		Thermostat Setback	85 °F cooling/60 °F heating
		Supply air temperature	Maximum 104 °F, minimum 55 °F
	Service Water Heating	SWH type	Storage tank
		Fuel type	Electric
		Thermal efficiency (%)	Requirements in Standard 90.1-2016
		Tank Volume (gal)	40
		Water temperature setpoint	140 °F

4.2.1. DOE-2.1e Model Development

The small office reference models in DOE-2.1e were developed in modifications based on the model configuration and inputs of the PNNL commercial prototype models for Standard 90.1-2016 (PNNL and U.S.DOE 2018). DOE-2.1e coding for the reference model development was processed in a step-by-step from architectural design to building systems in Building Description Language (BDL). The developed reference models were compared with the modified PNNL prototype models. To compare the result between DOE-2.1e and EnergyPlus, the simulation reports were carefully selected because two programs have different output variables and formats in the output reports of total loads and load components. The proposed reference DOE-2.1e models were used to investigate the influence of occupancy-based building controls in building energy performance simulations (BEPS) and develop occupancy-based building control modeling credits for code-compliance in Chapters 6.

4.2.1.1. Weather Data

The weather data is a significant factor in the energy performance predictions, especially for calculating the heat gain and heat loss on the building envelope and HVAC system operations to respond to environmental condition changes. There are numerous types of weather data (e.g., Typical Meteorological Year (TMY), Test Reference Year (TRY), and Weather Year for Energy Calculations 2 (WYEC2)) to represent the regional weather conditions at specified locations. Energy modelers should avoid using single year, such as Test Reference Year-type (TRY) weather data, because a single year cannot describe typical long-term weather conditions (e.g., 20-30 years) (EnergyPlus 2019c). To run simulations in DOE-2.1e and EnergyPlus, this study used the latest TMY3 data for Houston (#722430) and Chicago (#725300) for both simulation programs. The epw TMY3 files were downloaded from the EnergyPlus website and NREL website (EnergyPlus 2019b; Wilcox and Marion 2008). Then, TMY3 weather data in Houston, TX and Chicago, IL were converted for DOE-2.1e using the eQ_WthProc (JJH 2018) that is a software to convert EnergyPlus epw weather data into eQUEST and DOE-2 bin readable weather data.

Table 7. Locations and TMY3 weather data for Houston,TX and Chicago,IL

	Houston	**Chicago**
TMY3 Weather Station	#722430	#725300
Climate Type	Hot and humid (2A)	Cold and humid (5A)
Latitude	30 ^{o}	41.98 ^{o}
Longitude	-95.4^{o}	-87.9 ^{o}
Elevation	29.0m	201.0m
Time Zone	-6	-6
Hours	8,760hrs	8,760hrs

4.2.1.2. Simulation Schedules

In energy modeling, simulation schedules define building system operations and occupant usage schedules, which has a critical influence on building energy consumption and energy usage profile in buildings.

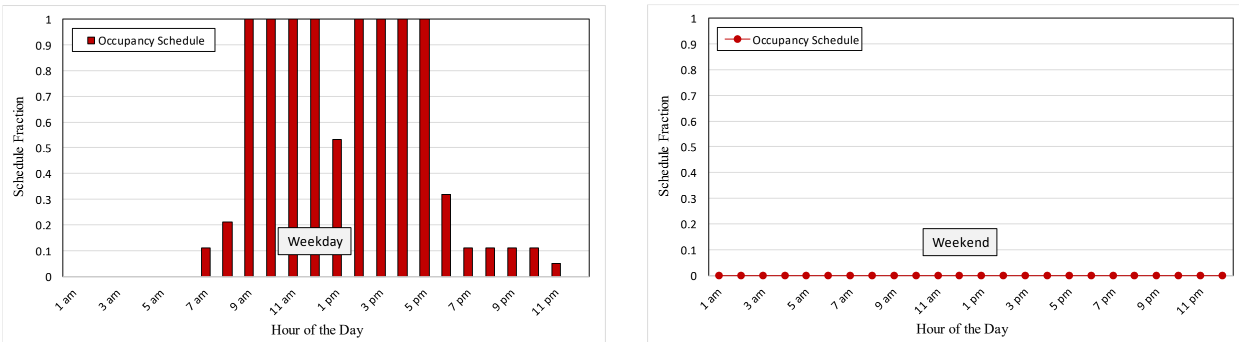
In reality, occupancy schedules in buildings vary due to different activities and usage profiles, which results in different building system operation patterns with more or less energy use to control the indoor environment in office buildings. However, in energy simulations, typical occupancy schedules generally assumed fixed values for occupancy profiles based on different building types and sizes. For example, occupancy schedules can be defined as a fraction of the nominal occupancy (i.e., the value between 0 and 1) for each hour during business hours, non-business hours (i.e., weekends, holidays). A schedule value of 1 indicates 100% occupancy in the space at that time, and a schedule value of 0 represents 0% occupancy at that hour (i.e., unoccupied). Also, standard simulation schedules (e.g., occupancy, lighting, and equipment) in many detailed simulation models are categorized only by building type and size without the considerations of usage diversity in reality. For instance, for code-compliant modeling, the ECB method (Section 11.4.1.1) in Standard 90.1-2019 requires hourly-based occupancy schedules for whole-building energy simulation programs and that the proposed design schedules must be identical with the baseline design schedules. In another performance path, the Appendix G method describes that different proposed schedules can be used by the designer with the approval of the local code authority (ASHRAE 2016a, 2019).

To apply occupancy schedules in the DOE-2.1e reference models, it is necessary to understand the interface configuration between DOE-2.1e and EnergyPlus that might differ depending on the simulation tools.

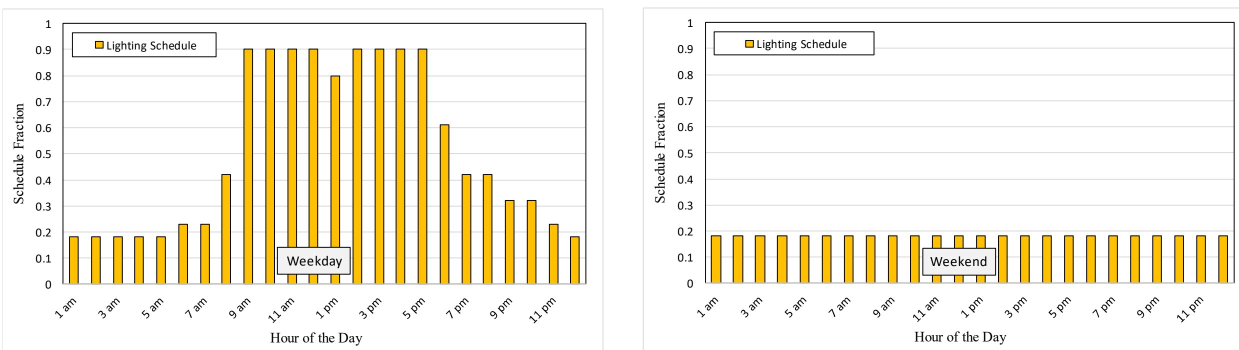
Table 8. Schedule Designs for DOE-2.1e and EnergyPlus

<table>
<tr><th>Description</th><th>DOE-2.1e</th><th>EnergyPlus</th></tr>
<tr><td>Method</td><td>BDL FORTRAN coding</td><td>Schedule spreadsheet in IDF editor</td></tr>
<tr><td>Basic Schedule Level</td><td>Day, Week, Annual</td><td>Day, Week, Annual</td></tr>
<tr><td>Day Schedule</td><td>24 hours in a day</td><td>24 hours in a day</td></tr>
<tr><td>Week Schedule</td><td>Individual schedules for 7days (Monday to Sunday) or
Weekday and weekend schedules or custom day designations</td><td>Individual schedules for 7days (Monday to Sunday) or
Weekday and weekend schedules or custom day designations</td></tr>
<tr><td>Annual Schedule</td><td><Example>
INFIL-SCH =SCHEDULE
THRU MAR 31 (ALL) (1,24) (1)
THRU OCT 31 (ALL) (1,24) (0)
THRU DEC 31 (ALL) (1,24) (1)</td><td><Example>
<table>
<tr><th>Obj15</th><th>Obj16</th><th>Obj17</th><th>Obj18</th></tr>
<tr><td>Exterior_Lgt_189_1</td><td>ALWAYS_OFF</td><td>HVACOperationSch</td><td>BLDG_LIGHT_SCH</td></tr>
<tr><td>Fraction</td><td>Fraction</td><td>on/off</td><td>Fraction</td></tr>
<tr><td>Through:12/31</td><td>Through: 12/31</td><td>Through: 12/31</td><td>Through: 12/31</td></tr>
<tr><td>For:Weekdays</td><td>For: AllDays</td><td>For: Weekdays Sun</td><td>For: Weekdays</td></tr>
<tr><td>Until: 9:00</td><td>Until: 24:00</td><td>Until: 06:00</td><td>Until: 5:00</td></tr>
<tr><td>0.5</td><td>0</td><td>0</td><td>0.05</td></tr>
<tr><td>Until: 24:00</td><td></td><td>Until: 22:00</td><td>Until: 6:00</td></tr>
<tr><td>1</td><td></td><td>1</td><td>0.1</td></tr>
<tr><td>For:Saturday</td><td></td><td>Until: 24:00</td><td>Until: 7:00</td></tr>
<tr><td>Until: 9:00</td><td></td><td>0</td><td>0.090560114</td></tr>
</table></td></tr>
<tr><td>Special Days</td><td>Holiday, summer design day, winter design day</td><td>Holiday, summer design day, winter design day</td></tr>
<tr><td>Schedule Types</td><td>Occupancy, lighting, equipment, infiltration, Domestic Hot Water (DHW), fan/ elevator, heating and cooling temperature</td><td>Occupancy, lighting, equipment, infiltration Domestic Hot Water (DHW), fan/ elevator, heating and cooling temperature</td></tr>
</table>

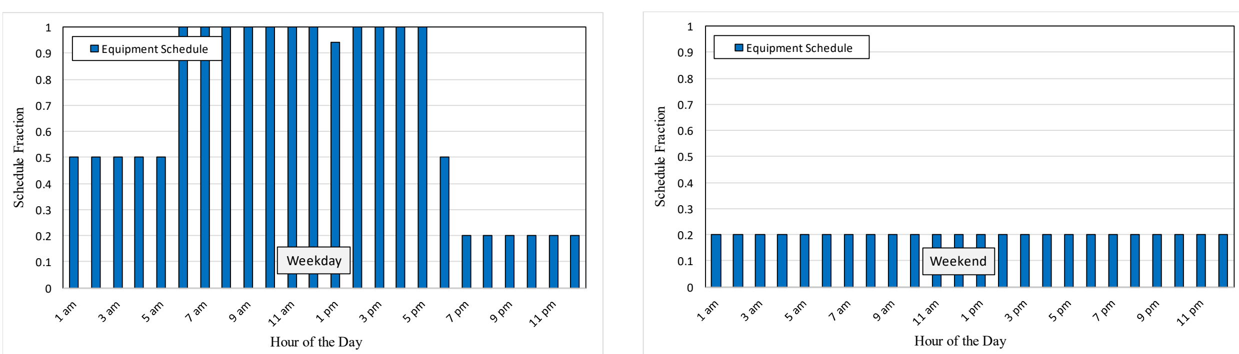
In simulation schedules, several types of input values (i.e., occupancy, fan, cooling, and heating temperature) are modeled based on the fractions in each schedule: any number, fraction, temperature (°F), on/off, humidity (%), and control type (EnergyPlus 2013, PNNL and U.S.DOE 2018). Between two simulation programs, DOE-2.1e and EnergyPlus have slightly different input formats in the simulations as an example in Table 8. However, those two programs have similar schedule structures and input value types. Also, in both simulation tools, the forms of schedules typically show pre-determined characteristics for weekdays or weekends/holidays. This is because current simulation schedules mainly model prescribed schedules (i.e., fixed) and rule-based controls. Therefore, the use of stochastic schedules or real-time schedules is limited in energy modeling using the current simulation tools (See Chapter 2.4.4). Table 8 summaries the schedule design features in DOE-2.1e and EnergyPlus.



(a) Occupancy Schedules

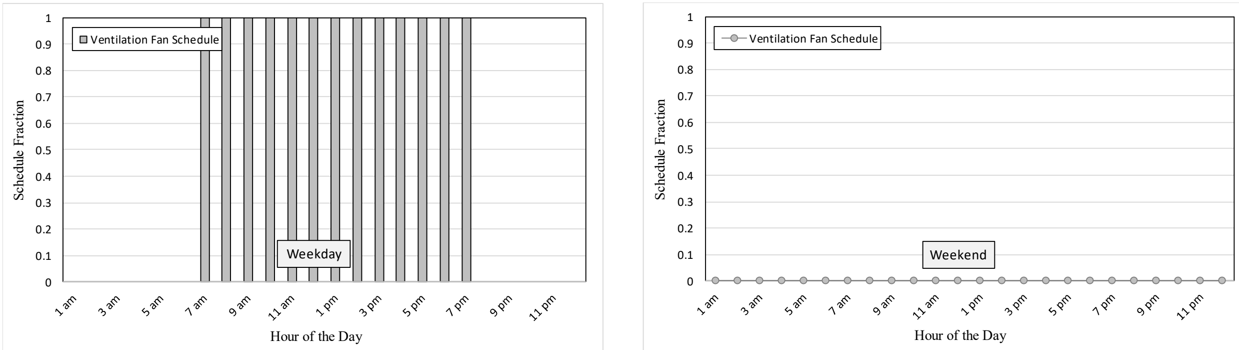


(b) Lighting Schedules

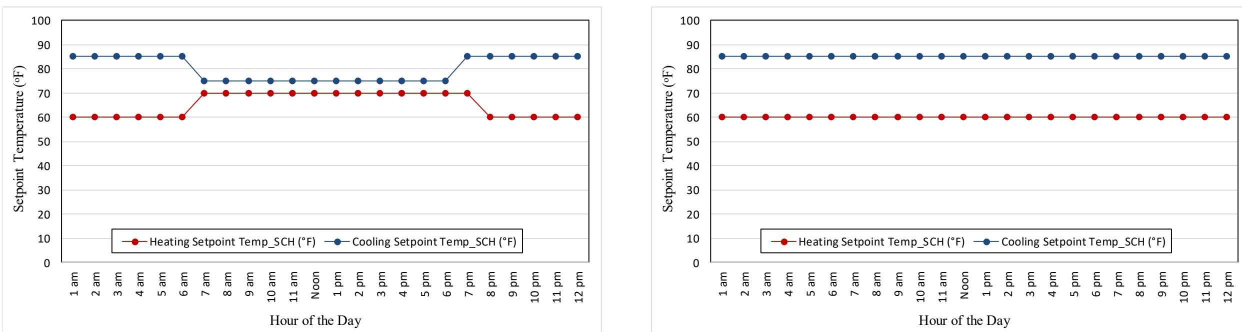


(c) Equipment Schedules

Figure 12. Simulation Schedules for Code-Compliant Modeling



(a) Ventilation Fan Schedules



(b) Thermostat Setpoint Temperature Schedules

Figure 13. Vent Fan and Setpoint-Temperature Schedules for Code-Compliant Modeling

To develop the DOE-2.1e reference office models, this study selected the Standard 90.1-2016 schedules (ASHRAE 2017b) as the baseline schedules without modifications that are shown in Figure 12 and Figure 13. Then, in addition to the Standard 90.1-2016 schedules, to compare the impact of OBC according to different space usage rates in office buildings, 100% to 10% OBC schedules in-office hours (9 AM-5 PM) for occupancy, lighting, equipment, ventilation fan, and thermostat set-point schedules were developed to evaluate minimum and maximum reduction from varying building system operations due to occupancy usage diversity.

4.2.1.3. Building Envelope and Fenestration

In the developing process of building envelopes and windows in the simulations, DOE-2.1e and EnergyPlus use different parameters and input methods to express the envelope material properties and constructions for their architectural design and thermal properties. Table 9 shows the details of the input parameters for modeling the building envelope in DOE-2.1e and EnergyPlus. To develop the building envelope, DOE-2.1e exploits a layer command to represent internal/external walls, floors, ceilings, roofs that are made up of assemblies using thickness, conductivity, density, specific heat, and resistance to describe the thermal properties of each material. Similarly, EnergyPlus makes use of layers expressed as constructions.

Table 9. Input Parameters for Building Envelope Modeling in DOE-2.1e and EnergyPlus

Type	**DOE-2.1e**	**EnergyPlus**
Material	• Type: Roof, Internal/External wall, Ceiling, Floor • Parameter: Thickness, Conductivity, Density, Specific heat, Resistance	• Type: Roof, Internal/External wall, Ceiling, Floor • Parameter: Roughness, Thickness, Conductivity, Density, Specific heat, Thermal absorptance, Solar absorptance, Visible absorptance
Material: No Mass	N/A	• Type: Door, Carpet, Air wall, Insulation • Parameter: Roughness, Thermal resistance, Thermal absorptance, Solar absorptance, Visible absorptance
Window: Glazing	• Type: glazing • Parameter: panes (1-3), glass type code, shading coefficient (SC), glass conductance, visual transmittance, frame conductance, frame absorptance, spacer type code, inside/outside emission	• Type: glazing • Parameter: Optical data type, thickness, Solar transmittance, Front/backside solar reflection at normal incidence, Visible transmittance at normal incidence, Front/backside visible reflection at normal incidence, Infrared transmittance at normal incidence, Front/backside infrared hemispherical emissivity, conductivity

Table 9. Input Parameters for Building Envelope Modeling in DOE-2.1e and EnergyPlus (cont.)

Type	DOE-2.1e	EnergyPlus
Construction	• Type: Door, Ceiling, Roof, Internal/External wall, Floor, Window • Parameter: Layers (Material, Thickness, Inside film resistance), U-value, Absorptance, Roughness	• Type: Door, Air wall, Ceiling, Roof, Internal/External wall, Floor, Window • Parameter: Layers (Material)
Building Surface	• Type: Roof, External wall, Plenum wall • Parameter: Dimension, Construction, Azimuth, Tilt, Ground reflectance, Location, Shading surface/division, Sky/ground form factors, Infiltration coefficient, Solar fraction, Inside visible reflectance, Inside Solar absorptance, Outside emission,	• Type: Roof, Ceiling, Floor, Internal/External wall, Plenum wall • Parameter: Surface type, Zone name, Boundary condition, Sun/Wind exposure, View factor to ground, Dimension
	• Type: Interior wall, Air wall • Parameter: Area, Location, Construction, Wall type, Solar fraction, Inside visible reflection, Azimuth, Inside Solar absorptance	
	• Type: Underground wall/floor • Parameter: Area, Dimension, Construction, Tilt, U-Effective, Multiplier, Solar fraction, Inside visible reflection, Inside Solar absorptance	
Fenestration Surface	• Type: Window, Door • Parameter: Dimension, Glass type, Frame, Shading design/schedule, Ground form factor, Shading division, Infiltration coefficient, Solar transmittance schedule, Visible transmittance schedule, Glare control	• Type: Window, Door • Parameter: surface type, building surface for window, View factor to ground, Shading control, Frame and divider, Multiplier

Therefore, in this study, the DOE-2.1e model's envelope constructions were developed based on the inputs of the PNNL small office prototype models for Standard 90.1-2016. Some SI input parameters in the PNNL models were converted to IP units using conversion factors for modeling in DOE-2.1e. Table 10 shows building envelope component properties for small office buildings in Houston, TX and Chicago, IL. Table 11 to Table 12 represent building envelope components and material layers for the DOE-2.1e models in Houston, TX and Chicago, IL.

Table 10. Summary of Small Office Model Construction

#	Type	Houston (2A)			Chicago (5A)		
		U-Value ($Btu/hr\text{-}ft^2\text{-}F$)		SHGC	U-Value ($Btu/hr\text{-}ft^2\text{-}F$)		SHGC
1	Roof	0.526	0.0257	-	0.526	0.0202	-
2	Ceiling	0.027	(0.027)	-	0.021	(0.021)	-
3	External wall	0.087 (0.089)		-	0.050 (0.051)		-
4	Interior wall	0.442		-	0.442		-
5	Ground floor*	0.415 (F-0.730)		-	0.415 (F-0.520)		-
6	Window**	0.52 (0.54)		0.249 (0.25)	0.367 (0.38)		0.365 (0.38)
7	Glass door**	0.52 (0.54)		0.249 (0.25)	0.367 (0.38)		0.365 (0.38)
8	Opaque door	0.370 (0.037)		-	0.370		-

* Note: The numbers in brackets are code-compliance for Standard 90.1-2016. U-value and SHGC were extracted from DOE-2.1e LV-C and LV-D reports. U-values included air films.
* Ground floor is slab-on-grade (unheated) both for Houston and Chicago models, which used 8" concrete slab with carpet pad. As of August 2020, DOE updated the prototype models using F-factor for underground calculations. Before then, U-value used for underground calculations. The construction of F-factor insulation can be found in Standard 90.1-2016, Table A6.3.1.
** Hypothetical window with weighted U-factor and SHGC used based on the PNNL prototype models. The weighting process is described in Thornton et al. (2011).

Table 11. Houston (2A): Small Office Model Material Layers

#	Type	Material Layers (Outside to Inside)
1	Attic roof	Asphalt shingles, 5/8" plywood
2	Ceiling insulation	Insulation (R-35.4), 15/8" gypsum board
3	External slab 8" with carpet	7 7/8" normal-weight concrete floor, carpet pad
4	Exterior wall	1" stucco, 5/8" gypsum board, insulation (R-9), 5/8" gypsum board
5	Interior wall	½" gypsum board, ½" gypsum board
6	Exterior roof soffit	5/8" plywood
7	Window	Glass 1576, air 2 1/16", Glass 102 (U-value 0.58, SHGC 0.25)
8	Glass door	U-value 0.58, SHGC 0.25
9	Swinging door	Opaque door panel

Table 12. Chicago (5A): Small Office Model Material Layers

#	Type	Material Layers (Outside to Inside)
1	Attic roof	Asphalt shingles, 5/8" plywood
2	Ceiling insulation	Insulation (R-45.98), 5/8" gypsum board
3	External slab 8" with carpet	7 7/8" normal-weight concrete floor, carpet pad
4	Exterior wall	1" stucco, 5/8" gypsum board, insulation (R-17.43), 5/8" gypsum board
5	Interior wall	½" gypsum board, ½" gypsum board
6	Exterior roof soffit	5/8" plywood
7	Window	Glass 8652, air ½", Glass 102 (U-value 0.41, SHGC 0.38)
8	Glass door	U-value 0.41, SHGC 0.38
9	Swinging door	Opaque door panel

4.2.1.4. Internal Heat Gains

In general, internal heat gains in buildings significantly affect building HVAC operations for space cooling and heating. Influential factors for internal heat gains are mainly occupancy, electrical equipment, internal lighting, and other equipment. Table 13 presents default internal heat gain inputs for small office models in DOE-2.1e simulations in this study. In the DOE-2.1e model development, task lighting and other equipment elements are not modeled for internal loads. Input values were mainly extracted from Standard 90.1-2016, User's manual (ASHRAE 2017b), and PNNL small office models for Standard 90.1-2016 (PNNL and U.S.DOE 2018).

Table 13. Internal Heat Gain Inputs in DOE-2.1e and EnergyPlus Simulation Tests

Heat sources	DOE-2.1e	EnergyPlus	Reference
Occupancy	- 450W/person - 200ft^2/person	- 450W/person - 200ft^2/person	ASHRAE (2017b)
Electrical equipment	0.63 W/ft^2	0.63 W/ft^2	ASHRAE (2017b)
Internal lighting	0.79 W/ft^2	0.79 W/ft^2	ASHRAE (2017b)
Task lighting	Not modeled	Not modeled	N/A

4.2.1.5. Heat Transfer on the Ground Surfaces

The ground-coupled floor is a primary path to lose heat in buildings. Previous literature (Andolsun et al. 2010, 2011, 2012) reported that the current simulation programs showed a high degree of variation in the ground-coupled heat transfer (GCHT) calculations in slab-on-grade buildings. Heat loss through the ground may comprise 30-50% of the total heat loss in code or above-code houses, and the variation of heat transfer on the ground surfaces can differ based on insulation on the slabs, simulation model, climate, thermal properties (Andolsun et al. 2010). The estimation of ground coupling is challenging because it contains three-dimensional heat conduction, humidity transport, longtime constants, and heat storage properties of the ground condition (Andolsun et al. 2011).

Table 14. Average Monthly Ground Temperature in DOE-2.1e and EnergyPlus

Month	Houston (CZ 2A, °F)	Chicago (CZ 5A,°F)	Reference
January	69.314	67.838	PNNL and U.S.DOE (2014)
February	69.224	67.604	
March	69.368	67.604	
April	69.512	37.838	
May	69.692	68.180	
June	73.634	72.050	
July	74.300	73.184	
August	74.444	73.526	
September	74.480	73.634	
October	70.448	69.944	
November	69.818	68.954	
December	69.458	68.342	

In prototype models, this study selected monthly ground temperature models for the small office models in Houston, TX and Chicago, IL, which was used in the original PNNL prototype model methods for small office models. Therefore, to match the simulation results, DOE-2.1e models used the same average monthly ground temperatures from the PNNL prototype small office building models in EnergyPlus. For more information about the ground coupled models, Appendix G provides the comparison of the impact of ground-coupling.

4.2.1.6. Thermal Zones for HVAC Systems

In simulation models, the determination of thermal zoning is significant to improve the accuracy of the mathematical predictions because thermal zoning methods can affect sensitive calculation on building elements, such as heat transfer and circulation in building spaces, and building system assignments and operations. In reality, it is difficult to have the same indoor temperature distribution in building spaces due to solar gains in the perimeter zones. Therefore, thermal zoning should be carefully modeled in a modeling procedure by considering building design and system factors (e.g., space type, orientation, occupant density and activities, HVAC types and controls).

Thermal zones have been defined as different names and definitions (e.g., thermal zone, thermal block, HVAC zone) (Shin 2018). For example, Standard 90.1-2013 (ASHRAE 2013b) described an HVAC zone that is "a space or group of spaces within a building with heating and cooling requirements that are sufficiently similar so that desired conditions (e.g., temperature) can be maintained throughout using a single sensor (e.g., thermostat or temperature sensor)." Such thermal zones are operated by a single thermostat sensor with its setpoint temperature and schedule. Moreover, in the same thermal zone, the zone should maintain the same set-temperature during the operating period in simulations. Therefore, to carefully consider thermal zoning, previous studies have developed guides for simulation modeling. From the literature review, Shin (2018) also found common criteria for thermal zoning that contained considerations of (a) solar gains, (b) orientation, (c) occupancy, (d) schedule, and (e) space function.

To determine the thermal zoning model, this study developed simplified single models and five-zone models to compare the simulation estimation accuracy of thermal zoning based on the small office building models in DOE-2.1e. Also, an attic roof is not conditioned as a thermal zone, and the return air path was set to “direct” without the use of ducts in DOE-2.1e simulations. Table 15 and Table 16 represents the thermal zoning model summary for single-zone models and five-zone models. The depth of the perimeter zone for five-zone models was assumed as 15ft with four perimeter zones, one core zone, and an attic zone. The percentages of floor areas are 70% of perimeter zones and 30% of the core zone.

Table 15. Single Zone Model Summary for DOE-2.1e Models in Houston and Chicago

Zone	Area [ft²]	Conditioned [Y/N]	Volume [ft³]	Gross Wall Area [ft²]	Window Glass Area [ft²]	90.1-2016 Lighting[2] [W/ft²]	People [ft²/person]	Number of People	Plug and Process [W/ft²]
Space1-1	5,503	Yes	55,065	3,030	643	0.79	179	31	0.63
Attic	6,114	No	25,437	0	0	0.79	-	0	0.00
Total	5,503		80,502	3,030	643			31	
Area weighted average							179		0.63

Table 16. Five Zone Model Summary for DOE-2.1e Models in Houston and Chicago

Zone	Area [ft²]	Conditioned [Y/N]	Volume [ft³]	Gross Wall Area [ft²]	Window Glass Area [ft²]	90.1-2016 Lighting[2] [W/ft²]	People [ft²/person]	Number of People	Plug and Process [W/ft²]
Space5-1	1,611	Yes	16,122	0	0	0.79	179	9	0.63
Space1-1	1,221	Yes	12,221	909	222	0.79	179	7	0.63
Space2-1	724	Yes	7,250	606	120	0.79	179	4	0.63
Space3-1	1,221	Yes	12,221	909	180	0.79	179	7	0.63
Space4-1	724	Yes	7,250	606	120	0.79	179	4	0.63
Attic	6,114	No	25,437	0	0	0.79	-	0	0.00
Total	5,503		80,502	3,030	643			31	

4.2.1.7. Building System Configuration

This chapter investigated system input variables for the small office reference building models to develop system variables in DOE-2.1e. Table 17 shows a building system summary for small office building models in DOE-2.1e, which was based on the PNNL prototype models for Standard 90.1-2016. The reference office model used a packaged single-zone model (PSZ) for space cooling and heating. The energy efficiencies were 4.12 (COP) for cooling and 3.36 (COP) for heating both in Houston, TX and Chicago, IL. Designed thermostat setpoint temperatures were 75°F of cooling and 70°F of heating, respectively, during the daytime with set-back controls. The outdoor air ventilation rate was 0.085 CFM/ft^2 in Standard 62.1-2013, which is equal to 17 CFM/person in office spaces (ASHRAE 2013b). Also, the missing or different parameters that were not provided by EnergyPlus were selected from the default values in the DOE-2 reference manual (LBL and LASL 1980a,b).

Table 17. Input Summary for Small Office Building Systems

		Houston (2A)	**Chicago (5A)**
System Type	Heat Source	Heat pump	Heat pump
	HVAC system	Packaged single-zone system (PSZ)	Packaged single-zone system (PSZ)
HVAC Sizing	Air Conditioning	Autosized to design day	Autosized to design day
	Heating	Autosized to design day	Autosized to design day
HVAC Efficiency	Air Conditioning	4.12 (COP)	4.12 (COP)
	Heating	3.36 (COP)	3.36 (COP)
HVAC Control	Thermostat Setpoint	75°F Cooling/70°F Heating	75°F Cooling/70°F Heating
	Thermostat Setback	85°F Cooling/60°F Heating	85°F Cooling/60°F Heating
	Supply Air Temperature	Maximum 104°F, Minimum 55°F	Maximum 104°F, Minimum 55°F

Table 17. Input Summary for Small Office Building Systems (con't)

		Houston (2A)	Chicago (5A)
HVAC Control	Economizers	$T_{oa} > 65$°F (required high-limit setting for 2A)	$T_{oa} > 65$°F (required high-limit setting for 5A)
	Ventilation	Standard 62.1-2013 (outdoor air CFM/person=17)	Standard 62.1-2013 (outdoor air CFM/person=17)
	Vent Fan Schedules	Code Schedules	Code Schedules
	Supply Fan Total Efficiency (%)	0.56	0.56
Supply Fan	SWH Type	Storage tank	Storage tank
	Fuel Type	Electric	Electric
	Tank Volume (gal)	40 gal	40 gal
Service Water Heating	Water Temperature Setpoint	140°F	140°F
	Water Consumption	24hr, 1.0	24hr, 1.0

4.2.2. Result of the Development of DOE-2.1e Reference Models

This chapter describes the results of the development of commercial small office models in DOE-2.1e in order to evaluate the impact of occupancy-based controls. DOE-2.1e simulation software was adopted because it is more intuitive on the simulation interface and coding methods and easy-to-use than EnergyPlus. This point has the advantage in the simulation model-developing process to aid the understanding of the modeling structure and immediate modifications of the simulation models corresponding to the variable changes. Therefore, DOE-2.1e reference office models were developed using the same building dimensions and system conditions in the PNNL prototype office building models in EnergyPlus ver.8.0 for Standard 90.1-2016 (PNNL and DOE 2018). However, there are some modifications in the reference models in DOE-2.1e from the original PNNL prototype models so as to estimate the maximum and minimum impacts of OBC. This is because, in the original prototype models, lighting controls with motion sensors and occupancy schedule reductions were already included. Thus, OBC -related variables were removed in the reference models. Also, other input variables (i.e., external lighting) were also eliminated only to evaluate the impact of OBC in lighting energy use. The results of the reference models in DOE-2.1e models were verified in comparison with modified PNNL prototype models in EnergyPlus for this study. The following results are a comparison in Houston, TX and Chicago, IL. BEPS reports in DOE-2.1e and Annual Building Utility Performance Summary reports in EnergyPlus were used to compare component loads and total building load calculations.

Table 18. Comparison of Building Component Loads and Total Loads in Houston

(Unit: MMBtu/yr)	Lighting	Misc equipment	Space heating	Space cooling	Pump & misc	Vent fans	Total (MMBtu)
EP+ Model (Modified)	53.13	54.51	2.07	29.89	-	21.08	160.68
DOE-2.1e Model	53.14	54.53	2.93	29.90	0.05	21.10	161.66
Difference	0.01	0.02	0.87	0.01	0.05	0.02	0.98
Difference (%)	0.0%	0.0%	42.0%	0.0%	-	0.1%	0.6%

Table 19. Comparison of Building Component Loads and Total Loads in Chicago

(Unit: MMBtu/yr)	Lighting	Misc equipment	Space heating	Space cooling	Pump & misc	Vent fans	Total (MMBtu)
EP+ Model (Modified)	53.13	54.51	11.60	13.55	-	18.99	151.79
DOE-2.1e Model	53.14	54.53	13.95	13.66	0.50	19.08	154.86
Difference	0.01	0.03	2.35	0.06	0.50	0.08	3.07
Difference (%)	0.0%	0.0%	20.2%	0.8%	-	0.5%	2.0%

In comparison between modified prototype models and DOE-2.1e simulation models, total building load differences between modified PNNL prototype models and DOE-2.1e models were 0.6% and 2.0% in Houston and Chicago, respectively, which are within the acceptable ranges for the use. Table 18 and Table 19 represent component loads and differences between modified PNNL prototype models and DOE-2.1e models. In the reference models, area lighting and equipment loads are nearly the same values because these results were mainly determined by simulation schedules and power density (i.e., lighting power density and equipment power density). Also, cooling and ventilation loads were slightly different but produced almost the same result between DOE-2.1e and EnergyPlus. The only exception was heating calculations. DOE-2.1e showed the over-estimation in heating loads than the modified prototype models when applied to the PSZ systems. Based on the reference model development in DOE-2.1e models, this study evaluated the impact of OBC and modeling credits for small office buildings.

4.3.Evaluation of Potential Energy Ese Reduction in Office Buildings

In the literature review, substantial energy use reduction were expected from occupancy-based controls in office buildings. However, the quantity of energy use reduction would vary depending on architectural designs, system designs, and simulation conditions. In this chapter, the procedure of the potential energy use reduction calculations for office buildings was addressed to achieve the research goals.

Firstly, this study selected representative climate zones in the U.S., such as hot-humid (e.g., Houston, TX) and cold-humid (e.g., Chicago, IL). These two cities represent the U.S. south and north areas, which can describe different thermal characteristics of OBC in building energy simulations. To identify and quantify potential energy use reduction in different climate zones, the reference models were developed in the previous chapter using DOE-2.1e that are the reference code-compliant models for OBC in small office buildings. Then, potential energy use reduction were estimated using the sensitivity analysis in DOE-2.1e. OBC schedules (e.g., occupancy, lighting, equipment, ventilation fan) were selected based on the previous literature that could significantly affect building controls and total energy use. Hence, the results of this study can clarify the impact of OBC in office building energy modeling. Based on the simulation results of potential energy use reduction, proposed credits were presented in Chapter 6 to suggest ideas to develop occupancy-based building control credits for a new Standard 90.1 addendum of OBC that could improve the modeling requirement in Standard 90.1 performance paths to be more realistic. The credits would provide energy use reduction calculations in a format using different OBC profiles of schedule and operation rates, which can give the flexibility of the current deterministic schedules in Standard 90.1-2016 and Standard 90.1-2019 that they do not match occupancy modeling with the actual building usages in some cases.

Therefore, potential energy use reduction in this study were calculated based on the following simulation conditions: 1) different climate zones (i.e., Houston, TX and Chicago, IL), 2) different usage profiles (i.e., 100% to 10% usage fractions), 3) different thermal zone orientations (i.e., east, west, south, north, and core zone) 4) different HVAC system types (i.e., packaged single zone (PSZ) system and packaged variable air volume (PVAV) system), and different thermal zoning methods (i.e., single-zone model, five multi-zone model).

As for simulation conditions, the reference small office buildings were computed in Houston, TX and Chicago, IL to predict the impact of OBC in hot-humid and cold-humid regions. Also, simulations used Standard 90.1-2016 schedules as baseline schedules and developed OBC schedules to predict potential energy use reduction from occupancy-based controls. Figure 14 to Figure 19 presents OBC schedules for simulations that applied for typical weekdays. The shapes of OBC schedules show evenly distributed deterministic schedules to cover occupant usage diversity during business hours on weekdays. The weekend schedules used the same schedules with Standard 90.1-2016 schedules that represent unoccupied conditions at the weekends. This is because stochastic schedules are project-customized and, thus, challenging to be generalized. In contrast, although deterministic schedules are fixed and less flexible to various office usage profiles, low flexibility and diversity can be made up using various OBC usage profiles. Also, typical codes and standards have used normalized and deterministic schedules because of the difficulty in the generalization of customized schedules in different buildings. Therefore, 100% to 10% OBC schedules were used to represent different occupancy rates and diversity during the daytime and provide alternatives for energy simulation modeling in the performance paths.

On the other hand, in the office building operations, occupancy-based controls would be ideally applied in a whole building, but sometimes, it would be used only for a particular zone due to different space types and usage in office buildings. Therefore, test simulations assumed total OBC applications for the whole-buildings and individual zone OBC applications in thermal zones. The different OBC application methods could show energy use reduction depending on office building zone orientations.

In test cases of HVAC systems, the reference models used a packaged single zone (PSZ) system with constant air volume (CAV) for small office buildings. However, the CAV system has a limitation in capturing the changes in occupancy rates. Therefore, packaged Variable Air Volume (PVAV) system models were also developed to evaluate maximum energy use reduction potential from occupancy-based building controls in building energy performance simulations.

Besides, thermal zoning methods are significant in energy performance calculations, which would affect the accuracy of the energy use reduction impact in office buildings. Previous studies in Chapter 4.2 described that a multi-zoning model would show separate and sophisticated system controls of different space usages in office buildings. Therefore, to precisely compare reduction impact, single-zone models and five multi-zone models were compared to estimate the different reduction impacts due to thermal zoning.

Last but not least, as for the occupancy-based controls in simulations, this study selected only simulation schedules (i.e., occupancy, lighting, equipment, fan, and thermostat set-temperature schedules) as occupancy-related variables. Other parameters (e.g., operable window, office layouts) remained fixed.

4.3.1. Step.1 Determination of Occupancy-based Building Control Schedules

In the development of occupancy models, the determination of the simulation schedules is an essential task because the OBC schedules define occupant behavior in building system operations, such as HVAC, ventilation, equipment, and lighting systems during weekdays and weekends based on space types and locations.

Typically, simulation schedules in building codes and standards showed a conservative tendency in the modeling requirement. They used a static and deterministic type schedule (e.g., Standard 90.1-2016 User's Manual) and the maximized peak occupancy rate that is 100% during the daytime in a small office building (ASHRAE 2017b). This static and deterministic schedule has an advantage for code-compliance due to easy to use for users, more transparent process, and unbiased schedule shape of most building projects. Also, these strengths would offer complete generality for building performance paths in building codes and standards. Nonetheless, this static and deterministic schedule is now meeting with a rebuttal of occupancy-related energy modeling due to fixed and uniform schedule configurations for energy simulations. Therefore, the right determination of OBC schedules would solve the problems of the current fixed standard schedules by reflecting actual-similar occupancy diversity in energy performance prediction models.

In that sense, to sublate conformity and respect diversity of OBC profiles and diverse operations in simulation models, this study proposed 100% to 10% OBC schedules for occupancy, lighting control, and HVAC systems on weekdays. These OBC schedules would represent occupant diversity for more flexible space usages in a static and deterministic schedule format. Fan control and thermostat setpoint temperatures are also modified, corresponding to the changes in OBC schedules. Weekend and holiday schedules are not modified because the current standard schedules already assume unoccupied and system off conditions for small office buildings.

Table 20. Daily Average Rates of Proposed Simulation Schedules for Weekdays

	Occupancy	Lighting System	Equipment	HVAC Fan
100% OBC	0.38	0.49	0.50	0.38
90% OBC	0.34	0.45	0.46	0.38
80% OBC	0.30	0.41	0.43	0.38
70% OBC	0.26	0.38	0.39	0.38
60% OBC	0.23	0.34	0.35	0.38
50% OBC	0.19	0.30	0.31	0.38
40% OBC	0.15	0.26	0.28	0.38
30% OBC	0.11	0.23	0.24	0.38
20% OBC	0.08	0.19	0.20	0.38
10% OBC	0.04	0.15	0.16	0.38

* 24hour schedule average in weekdays from Standard 90.1-2016 User's manual (ASHRAE 2017b)

Table 20 show daily averaged rates for proposed OBC schedules with Standard 90.1-2016 average schedule rates on a weekday. In Standard 90.1-2016 schedules, average daily rates for a weekday were 0.40 for occupancy, 0.51 for lighting system, 0.67 for equipment system, and

0.54 for HVAC fan. Lighting and equipment usages in Standard 90.1-2016 schedules showed higher usage rates than occupancy rates for 6 pm to 8 am unoccupied hours, which led to higher usage rates in daily averages.

Figure 14 to Figure 20 represents the proposed schedules for evaluating the impact of occupancy-based controls in small office buildings. Small office building open hours were set to 9 am to 5 pm, and no occupant presence was assumed after business hours during weekday. All types of schedules have equally 0.1 intervals between schedule variations of OBC 100% to OBC 10%. Weekend and holiday schedules used the minimum rates for occupancy (0.0), lighting (0.18), equipment (0.20), fan (0.0), and set-back controls for thermostats.

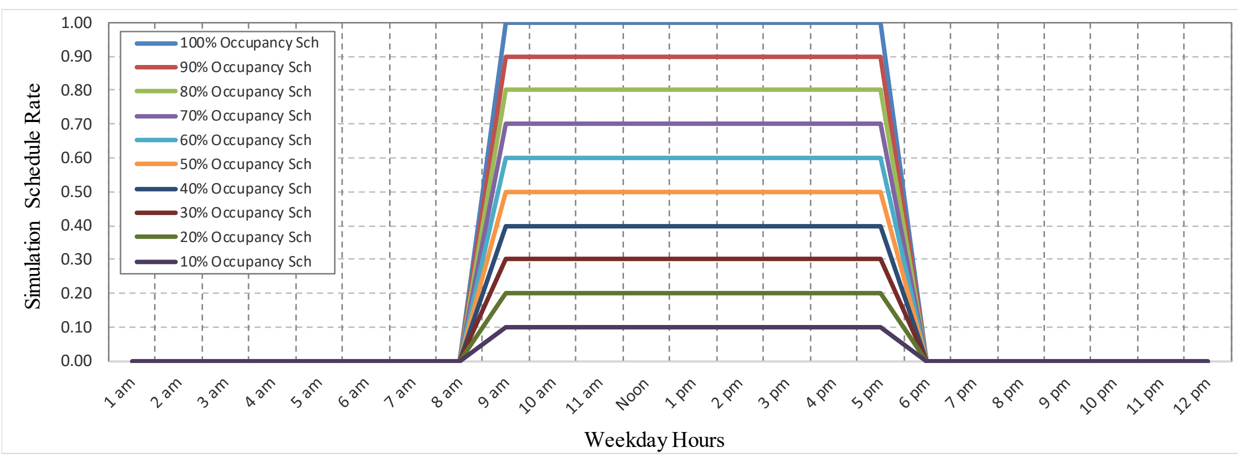


Figure 14. Test Simulation Occupancy schedules (100% to 10%) for Weekdays

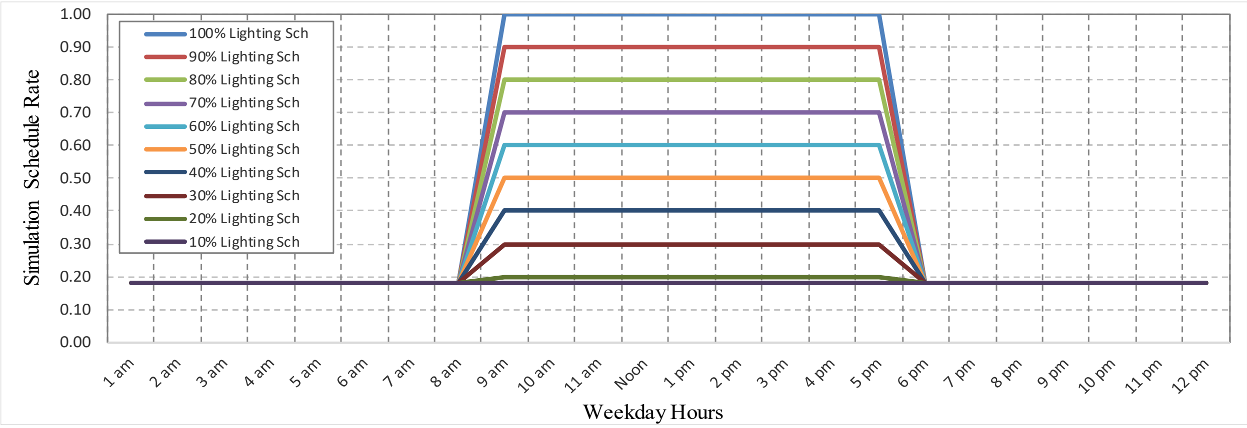


Figure 15. Test Simulation Lighting Schedules (100% to 10%) for Weekdays

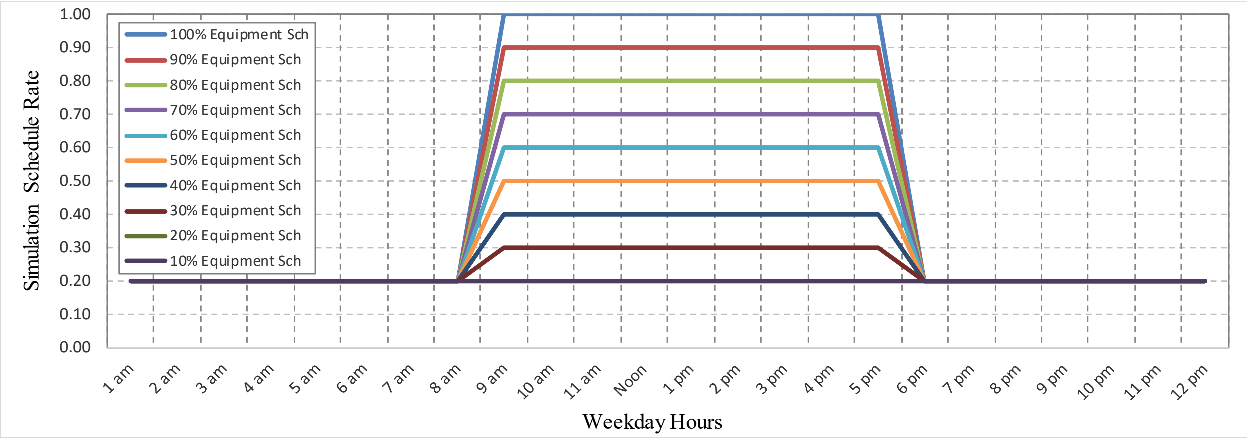


Figure 16. Test Simulation Equipment Schedules (100% to 10%) for Weekdays

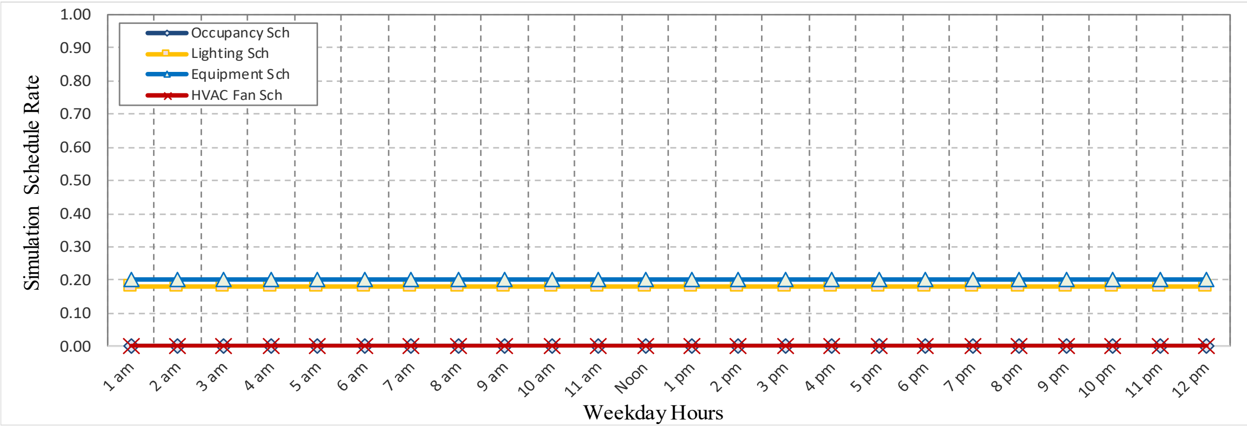


Figure 17. Test Simulation Equipment Schedules (100% to 10%) for Weekends

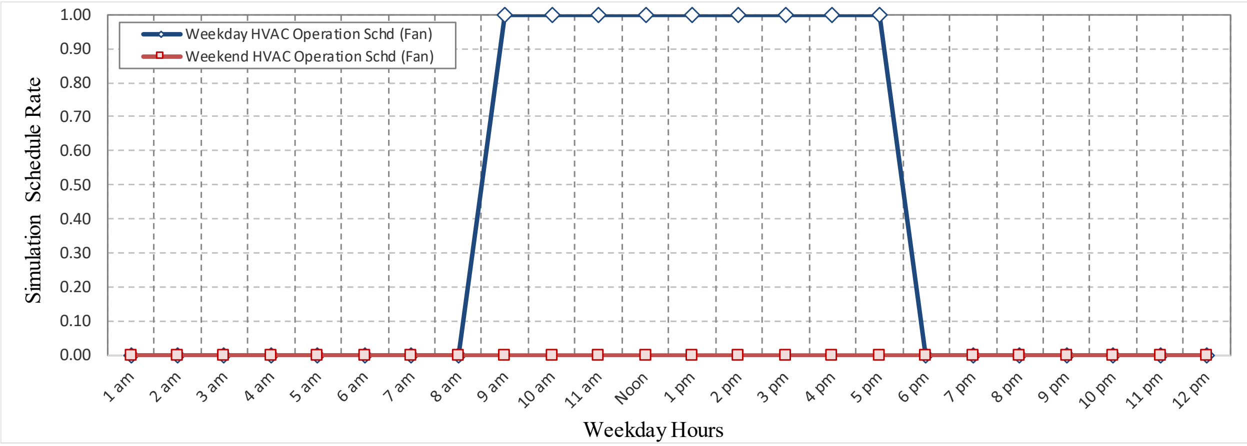


Figure 18. Test Simulation HVAC Fan Schedules (100% to 10%)

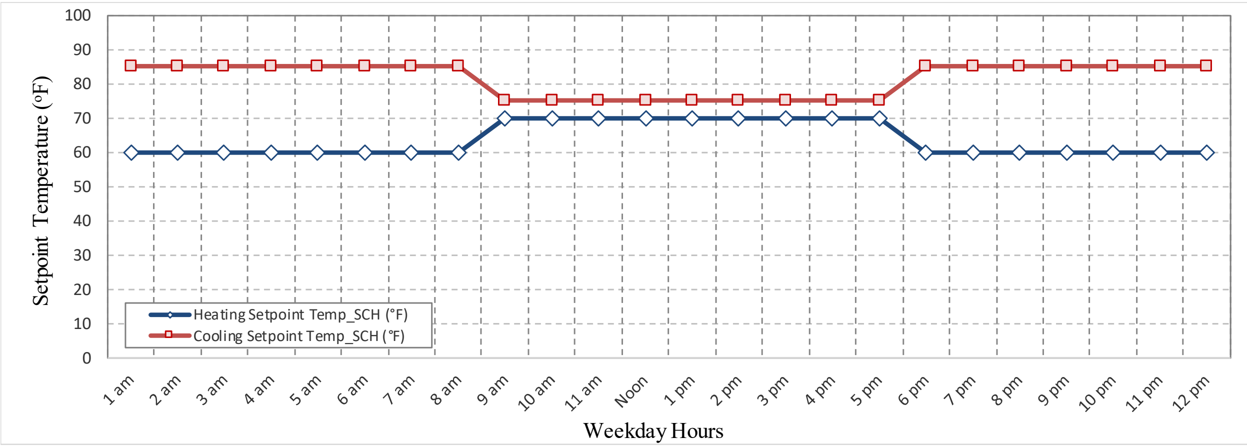


Figure 19. Test Simulation Thermostat Set-temperature Schedules (100% to 10%) for Weekdays

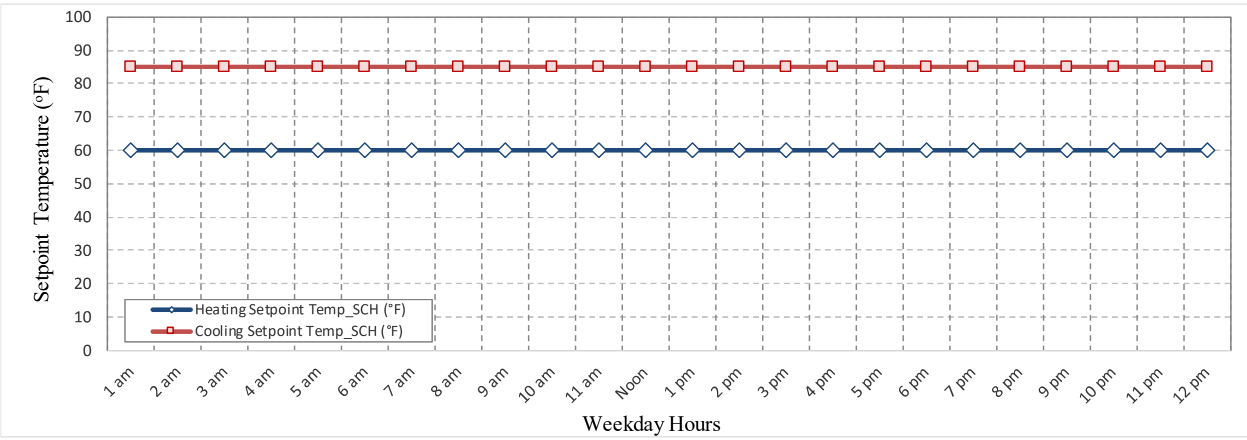


Figure 20. Test Simulation Thermostat Set-temperature Schedules (100% to 10%) for Weekends

4.3.2. Step.2 Development of Variable Air Volume System Models

The original small office model for Standard 90.1-2016 used an air-source heat pump for the heating system and the cooling system. For the distribution and terminal units, the prototype model adopted the PSZ, CAV air distribution system (PNNL and U.S.DOE 2018). However, in general, the CAV system supplies a constant airflow into indoor spaces at variable temperature, which is not sensitive to energy reduction due to the changes in occupant frequency. Contrastively, the VAV system supplies a variable airflow into indoor spaces at a constant temperature that would provide improved energy performance and cost savings, especially in the ventilation systems. This supports the fact that the VAV system showed improved energy performance versus the CAV system in most commercial spaces, especially those with changing occupant loads. Therefore, to observe energy efficiency and reduction from occupancy in different HVAC systems, small office PVAV models were developed in DOE-2.1e for different climate zones (i.e., Houston: 2A and Chicago: 5A). The PVAV models for small office buildings in DOE-2.1e were developed based on the reference models in DOE-2.1e that are the baseline models modified from the PNNL's small office prototype models (PNNL and U.S.DOE 2018). Coding for the VAV systems used the default commands and inputs of the packaged variable air volume systems (PVAV) in the DOE-2 BDL Summary ver. 2.1E (Winkelmann et al. 1993). For the system fan setting for the PVAV systems, the SUPPLY-DELTA-T and SUPPLY-KW used the default values from the DOE-2 documents (Winkelmann et al. 1993, pp101-102). Also, the minimum CFM ratio of 1.0 was eliminated from the VAV system controls to show more energy reduction using flexible air volume controls in each thermal zone. These VAV models were used to simulate the impact of OBC in small office building energy uses.

4.3.3. Step.3 Evaluation of Single-Zone and Multi-Zone Models

Thermal zones in simulation models play a significant role in defining characteristics of heat transfer, system controls, occupant usages, and load calculations. The correct approach for thermal zoning would improve simulation accuracy and resolution of occupancy-based controls in the results. Therefore, in the middle of the OBC evaluation process, single-zone models and five multi-zone models were developed and compared to quantify the impact of the zoning model selection in OBC calculations.

4.3.3.1. Thermal Zoning Considerations

As for basic principles for thermal zoning, thermal zone control is very sophisticated despite its simple appearance in simulations, which is related to several factors (e.g., outdoor temperature, humidity, outdoor air ventilation, internal and external heat gains). Shin (2018) summarized the thermal zoning considerations of HVAC design from previous literature as Table 21.

Table 21. Primary Design Considerations for Thermal Zoning in Building Performance Simulations

Reference	**Considerations for Thermal Zoning**
Bachman (2003)	• Similar solar exposure and orientation • Similar envelope exposure • Similar occupancy type and density • Similar schedules • Shared incremental capacity
McDowall (2006)	• Solar gain • Wall or roof heat gains or heat losses • Occupancy • Equipment and associated heat loads • Freeze protection in cold climates
Grondzik and Kwok (2014)	• Function of thermal zones • Schedule • Orientation

Even though there was still no general quantitative method for thermal zoning, based on the previous literature, this study identified five criteria of HVAC thermal zoning: solar gains, orientation, occupancy, schedule, and space function.

In building energy simulations, the number of thermal zones in a building is important in the analysis of the thermal characteristics (e.g., heating, cooling, thermal comfort) in spaces. In the literature, there have been discussions about the appropriate number of thermal zones, including Georgescu (2014), Shin (2018), Dogan et al. (2014), Im and New (2018) and, Im et al. (2019). Georgescu (2014) described a conventional approach that combines thermal zones with similar load profiles into a single thermal zone to save time and effort in developing a whole-building energy simulation. However, if grouped spaces do not contain sufficient information about similar thermal attributes, it may deteriorate the simulation model accuracy. Shin (2018) stated that a single-zone model may not reflect the localized loads on the north or south exposure that may not be accurately simulated. For example, if a single-zone model has significant south-facing windows, the south face of the thermal zone may have high thermal loads, whereas the north face of the same zone may be less affected by mid-day solar radiation in the winter. However, building energy simulation programs calculate the average loads for the whole zone (e.g., a well-mixed model). Therefore, a single-zone model may not accurately estimate the localized loads on the north or south faces, which causes load cancellation that can create reduced energy cooling or heating demand for a single-zone model in comparison to the multi-zone model. In an extreme case, Dogan et al. (2014) found that a multi-thermal zone model may have as much as 14% higher annual thermal loads (i.e., heating and cooling loads) than a single-zone model of the same building.

The Oak Ridge National Laboratory (ORNL) developed newly-improved thermal zone models (Im and New 2018; Im et al. 2019) for the small and medium office prototype buildings, with model properties based on Standard 90.1. In the current prototype models, only one space type was used for all office building types to calculate energy use, which is "office" space type. However, in typical office buildings, there are many other space types (e.g., conference room, restroom, enclosed office, open office). As part of efforts to overcome these shortcomings, ORNL updated new space types for the small and medium offices and compared energy performance with the original small office models in Standard 90.1-2004 through Standard 90.1-2013 requirements. The results identified that climate zone 2A would have energy use changes of -0.2% to 2.0%, and climate zone 5A would increase by 2.8% to 8.6% energy use in different Standard 90.1 models. The increase of energy use was more apparent in cases of cold climate zones than in cases of hot climate zones throughout all simulations. This study concluded that the new models that added more space types and associated space characteristics in office buildings would show different energy use. Also, in this study, the energy use discrepancies between the simulation models mainly came from detailed space types, space-specific lighting and plug power densities, and ventilation rates.

4.3.3.2. Thermal Zoning Model Development

From the previous literature, it was shown that a detailed thermal zoning model should help analyze the impact of occupancy-based building controls in office buildings. However, thermal zoning development requires a significant effort and time to organize and analyze using simulation models. Thereby, based on the literature, this study selected a five-zone model for Houston and Chicago based on the original small office prototype models. The dimension and zoning of the models followed the small office building prototypes for Standard 90.1-2016. Next, five-zone models were then compared with single-zone models to evaluate the differences in energy performance. The results were used to verify that more thermal zones have the advantage of a detailed analysis for localized energy demand, and specific energy uses by space types. The interpretation of the zoning models allowed for an improved understanding of the significance of thermal zoning in occupancy modeling. To compare the impact in different thermal zoning models, the evaluations were processed in three levels: 1) total building energy use, 2) peak day energy use, and 3) sensitivity analysis of occupancy-based building controls.

4.3.4. Step.4 Evaluation of Energy Use Reduction Impact due to Occupancy-Based Controls

In this step, the five-zone models were simulated to compare building energy use in different architectural and system design conditions (e.g., envelope materials, window design, HVAC system). This process verified the thermal characteristics of occupancy-based controls in different building conditions. To evaluate the energy performance, a sensitivity analysis of occupancy-based building controls (i.e., occupancy, lighting, and equipment schedules) was performed to investigate the influence of the OBC variable in Houston (CZ 2A) and Chicago (CZ 5A). Then, the energy use reduction potential were calculated in building loads using all occupancy-related schedule variables together. This analysis was performed in the small office buildings with the reference model, lightweight and heavyweight envelope designs as well as 10%-40% window-to-wall ratio models. Lastly, the energy use reduction from individual zones occupancy-based operations was simulated to analyze the impact in differently oriented thermal zones in the office building. Based on the result, OBC credits were proposed in Chapter 6 to suggest the solutions of occupancy modeling for Standard 90.1-2019 performance paths.

4.4. Development of Simulation Modeling Credits for Occupancy-Based Controls

In the previous literature, most research focused on the identification and improvement of occupant behavior modeling methods (i.e., IEA-EBC, Annex 66 2018). However, these studies neglected to quantify the impact of occupancy variables in the energy use to develop occupancy modeling credits in standard modeling. Only a few of the previous literature showed examples of occupancy-based modeling credits, such as the PNNL reports (Thornton et al. 2011, Goel et al. 2014) and Appendix G in Standard 90.1-2016. However, these references included only limited credits of occupancy-based modeling for partial building systems (i.e., lighting system). However, a review of the impact of OBC in Chapter 2.2 verified that office buildings possessed more potential to save energy use from various building systems, including lighting, equipment, HVAC, and ventilation systems, when OBC applied and integrated into building systems. Therefore, as the last task, this study performed a process to develop occupancy modeling credits for small office buildings.

In terms of the forms of OBC credits, the energy use reduction impact was quantified using energy use reduction percentages in Houston and Chicago. The total energy use reduction of OBC would be calculated using the proposed equations. OBC rates of load components could then be used to calculate energy use reduction potential for each system component in different building design and system conditions, which can be used to improve Standard 90.1-2019 performance paths.

5. RESULTS: IMPACT OF OCCUPANCY-BASED BUILDING CONTROLS

In general, occupant behavior and activities are key drivers to determine building energy use for system and equipment operations. However, their patterns would vary and be difficult to forecast where, when, and how occupant behavior or events would occur. As a result, the traditional energy simulation modeling using fixed and deterministic schedules is now facing limits in its ability to predict accurate results and reduce a gap of energy use between the proposed design and the actual design. However, most code compliance studies (i.e., Standard 90.1-2016) in the U.S. allow architects and engineers to use only limited modeling of Occupancy-Based Controls (OBC) due to the requirements of the performance paths in the ECB method and Appendix G method. Those modeling requirements basically require identical schedules for both baseline design and proposed design, which constrains the advanced building designs using occupancy-based controls in office building models.

Accordingly, as an effort to resolve such problems, this study presents an analysis of the impact of OBC in small office models in this Chapter. The simulations were performed in Houston, TX and Chicago, IL using TMY3 weather data as the representative cities of hot-humid and cold-humid climate zones in the U.S. This result shows an overlooked aspect of OBC in the current energy modeling methods under code compliance and provides useful information about how to improve modeling requirements for future energy codes. The impact of OBC was calculated based on the sensitivity tests using simulation schedules, building design & materials, HVAC system types & controls, and thermal zone system controls. Energy use reduction contributions to building load components were also analyzed to identify the energy use reduction features of OBC in different U.S. climate zones. The analysis of peak day data shows the most influential energy-related factors of occupancy-based building controls in an entire building and individual thermal zones. These results would be useful to better understand what OBC could do to save energy in office buildings in hot-humid and cold-humid climate zones.

5.1. Impact of Different Thermal Zoning Models

In general, a thermal zone is a unit for controlling the building HVAC systems (e.g., thermostat, equipment, ventilation) in simulations that would significantly affect energy calculations. A rule of thumb for developing thermal zoning models in the previous literature, as discussed in Chapter 4.2.3, was a simplified thermal zoning approach, considering occupancy, orientation, space type, usage profiles, and system type. However, a detailed zoning model would be more beneficial to reflect the actual thermal characteristics of heat gain and transfer by space locations, types, and system operations.

In that sense, this study compares two different types of thermal zoning models (i.e., single, 5-zone models) using the reference models for small office buildings in two locations. The result of the model comparison observed significant differences in the total energy used for heating, cooling, and HVAC fan operations from the single-zone and 5-zone models. Lighting and equipment showed almost the same between the single-zone and 5-zone models. For the tests, thermal zoning models applied packages single zone models with the CAV system and packaged variable air volume models to monitor the system effect of occupancy-based controls in Houston and Chicago. Simulation cases for estimating total energy use in small office buildings are presented in Table 22.

Table 22. Simulation Cases for Total Building Energy Use Analysis

Group	Location	Zoning Model	System Type	OBC Schedule Type (Weekdays)							Average WWR
				Occupant	Light	Equipment	Infiltration	Vent Fan	Set-point	Set-back	
1	Houston	Single zone	PSZ	1) 90.1-2016 2) 100% 24hrs 3) 0% 24 hors	1) 90.1-2016 2) 100% 24hrs 3) 0% 24 hors	1) 90.1-2016 2) 100% 24hrs 3) 0% 24 hors	Off	1.0	H: 70ºF C: 75ºF	H: 60ºF C: 85ºF	21% (default)
2	Houston	Single zone	PVAV	1) 90.1-2016 2) 100% 24hrs 3) 0% 24 hors	1) 90.1-2016 2) 100% 24hrs 3) 0% 24 hors	1) 90.1-2016 2) 100% 24hrs 3) 0% 24 hors	Off	1.0	H: 70ºF C: 75ºF	H: 60ºF C: 85ºF	21% (default)
3	Houston	Five zones	PSZ	1) 90.1-2016 2) 100% 24hrs 3) 0% 24 hors	1) 90.1-2016 2) 100% 24hrs 3) 0% 24 hors	1) 90.1-2016 2) 100% 24hrs 3) 0% 24 hors	Off	1.0	H: 70ºF C: 75ºF	H: 60ºF C: 85ºF	21% (default)
4	Houston	Five zones	PVAV	1) 90.1-2016 2) 100% 24hrs 3) 0% 24 hors	1) 90.1-2016 2) 100% 24hrs 3) 0% 24 hors	1) 90.1-2016 2) 100% 24hrs 3) 0% 24 hors	Off	1.0	H: 70ºF C: 75ºF	H: 60ºF C: 85ºF	21% (default)
5	Chicago	Single zone	PSZ	1) 90.1-2016 2) 100% 24hrs 3) 0% 24 hors	1) 90.1-2016 2) 100% 24hrs 3) 0% 24 hors	1) 90.1-2016 2) 100% 24hrs 3) 0% 24 hors	Off	1.0	H: 70ºF C: 75ºF	H: 60ºF C: 85ºF	21% (default)
6	Chicago	Single zone	PVAV	1) 90.1-2016 2) 100% 24hrs 3) 0% 24 hors	1) 90.1-2016 2) 100% 24hrs 3) 0% 24 hors	1) 90.1-2016 2) 100% 24hrs 3) 0% 24 hors	Off	1.0	H: 70ºF C: 75ºF	H: 60ºF C: 85ºF	21% (default)
7	Chicago	Five zones	PSZ	1) 90.1-2016 2) 100% 24hrs 3) 0% 24 hors	1) 90.1-2016 2) 100% 24hrs 3) 0% 24 hors	1) 90.1-2016 2) 100% 24hrs 3) 0% 24 hors	Off	1.0	H: 70ºF C: 75ºF	H: 60ºF C: 85ºF	21% (default)
8	Chicago	Five zones	PVAV	1) 90.1-2016 2) 100% 24hrs 3) 0% 24 hors	1) 90.1-2016 2) 100% 24hrs 3) 0% 24 hors	1) 90.1-2016 2) 100% 24hrs 3) 0% 24 hors	Off	1.0	H: 70ºF C: 75ºF	H: 60ºF C: 85ºF	21% (default)

* Weekend schedules set to minimum operating conditions of simulation schedules (e.g., occupancy=0.0; lighting=0.18; equipment=0.20; infiltration=off; ventilation fan=0.0; set-point temperature: heating 60ºF, cooling 85ºF).

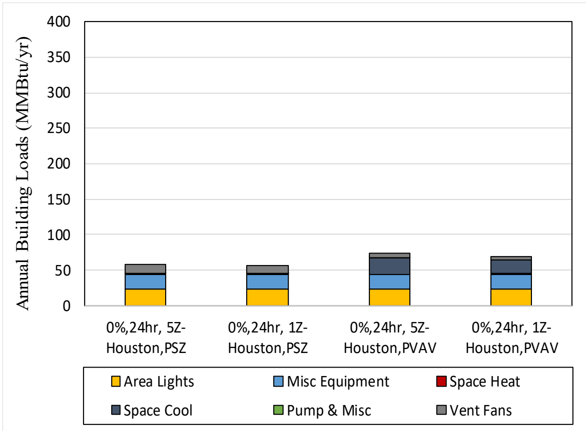
* Window-to-wall (WWR) ratio in small office models is 21% on average. Window fraction is 24.4% for South and 19.8% for the other three orientations (e.g., east, west, north).

5.1.1. Total Building Energy Uses of Different Thermal Zoning Models

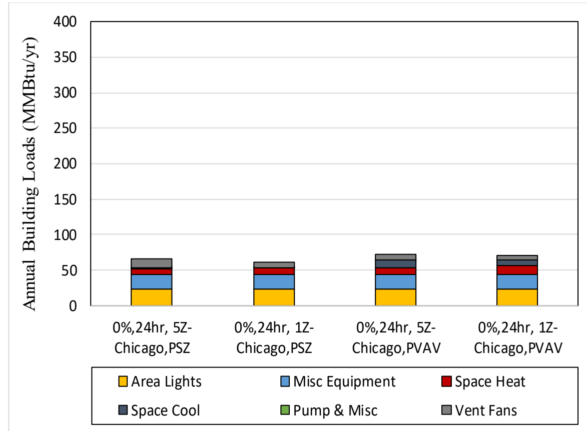
To evaluate the impact of different thermal zoning models in building energy simulations, the total building energy use was simulated using the reference small office models in DOE-2.1e. All test models used the same building dimensions and code-compliance for the climate zones. The independent variables for simulations were the climate zones (i.e., 2A, 5A), the thermal zoning models (i.e., single, 5 zones), the HVAC system type (i.e., PSZ, PVAV), and schedule types (i.e., Standard 90.1-2016 schedules, 100% 24hr operation, 0% 24hr operation schedules).

Figure 21 and Table 23 showed the result of total energy use and load configuration by components. The annual total building energy use (end-use) verified the discrepancies between single-zone and 5 zone models. In cases of the 0% occupancy, 24-hour system operations, the lighting and equipment consumed minimum energy due to the minimum system operations with 0% occupancy. Other load components (e.g., heating, cooling, ventilation fan) were set-back to thermostat temperatures. The result shows annual minimum cooling and heating demand due to weather data and internal heat gain.

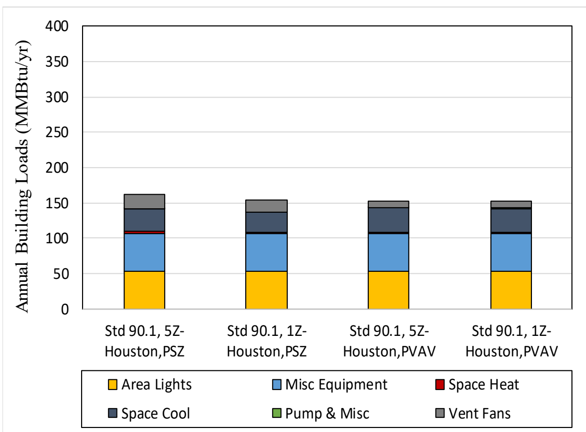
In cases in Houston, using the Standard 90.1-2016 schedules, area lighting and equipment occupied the most significant portions of building load components. The cooling loads and ventilation fan loads were the third and fourth largest loads for the hot-humid climate. Space heating showed smaller energy use than most load components. In cases for Chicago, using Standard 90.1-2016 schedules, heating loads were increased as expected due to cool-humid climate. An interesting observation was that the PSZ systems in the single and 5-zone models used more heating energy than cooling energy. In comparison, the PVAV systems in single and 5 zone models used higher cooling energy than heating energy.



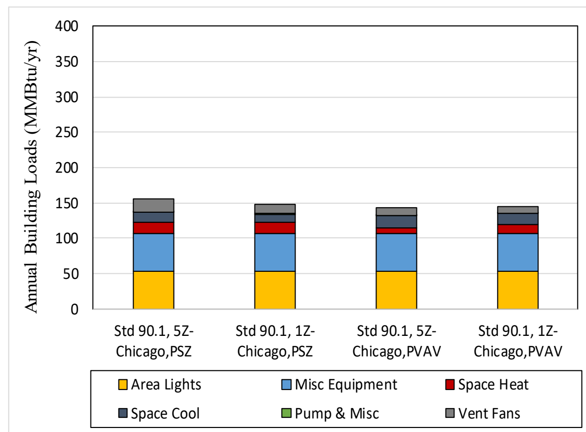
(a) Houston: 0%, 24hrs



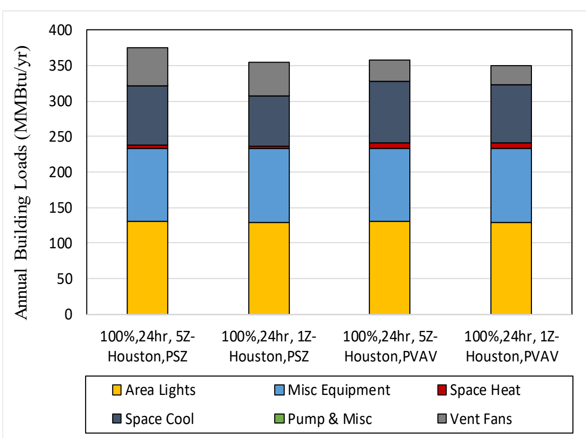
(b) Chicago: 0%, 24hrs



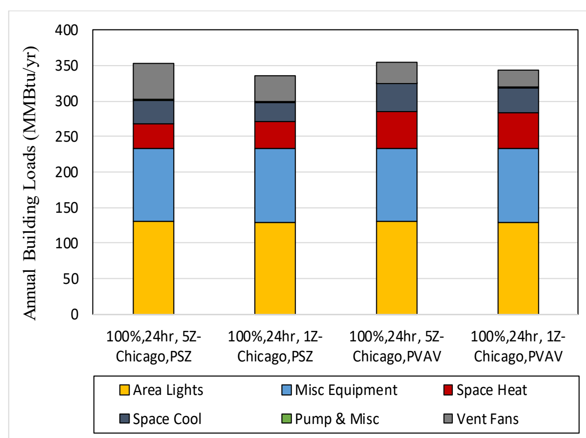
(c) Houston: Standard 90.1-2016



(d) Chicago: Standard 90.1-2016



(e) Houston: 100%, 24hrs



(f) Chicago: 100%, 24hrs

Figure 21. Total Building Energy Use by Thermal Zoning Models

Table 23. Total Building Energy Use by Thermal Zoning Models in Houston and Chicago (Unit: MMBtu)

Simulation Cases	Area Lights	Misc Equipment	Space Heat	Space Cool	Pump & Misc	Vent Fans	Total	5Z vs 1Z Difference(%)
Std 90.1, 5Z-Houston,PSZ	53.1	54.5	3.1	31.6	0.1	19.9	162.3	5.6%
Std 90.1, 1Z-Houston, PSZ	53.1	54.5	1.3	28.0	0.1	16.7	153.7	
Std 90.1, 5Z-Houston,PVAV	53.1	54.5	1.6	33.6	0.1	10.1	153.0	0.3%
Std 90.1, 1Z-Houston,PVAV	53.1	54.5	1.6	33.3	0.1	10.0	152.5	
Std 90.1, 5Z-Chicago, PSZ	53.1	54.5	14.8	13.8	0.5	18.4	155.2	4.6%
Std 90.1, 1Z-Chicago, PSZ	53.1	54.5	14.6	12.1	0.4	13.7	148.4	
Std 90.1, 5Z-Chicago, PVAV	53.1	54.5	7.8	16.8	0.7	10.5	143.6	-0.6%
Std 90.1, 1Z-Chicago, PVAV	53.1	54.5	12.1	15.2	0.6	8.9	144.4	
100%,24hr, 5Z-Houston, PSZ	129.9	103.6	4.8	82.7	0.1	54.5	375.6	6.2%
100%,24hr, 1Z-Houston, PSZ	129.9	103.6	2.6	71.8	0.0	45.8	353.7	
100%,24hr, 5Z-Houston, PVAV	129.9	103.6	7.8	87.0	0.1	29.5	357.9	2.5%
100%,24hr, 1Z-Houston, PVAV	129.9	103.6	7.4	81.7	0.1	26.4	349.0	
100%,24hr, 5Z-Chicago, PSZ	129.9	103.6	34.0	33.7	0.5	51.1	352.9	4.9%
100%,24hr, 1Z-Chicago, PSZ	129.9	103.6	37.4	27.6	0.2	37.7	336.3	
100%,24hr, 5Z-Chicago, PVAV	129.9	103.6	51.5	39.3	0.7	28.8	353.8	3.0%
100%,24hr, 1Z-Chicago, PVAV	129.9	103.6	50.0	35.5	0.6	23.7	343.3	
0%,24hr, 5Z-Houston, PSZ	23.4	20.7	1.8	0.1	0.1	12.7	58.8	4.6%
0%,24hr, 1Z-Houston, PSZ	23.4	20.7	0.1	2.1	0.1	9.9	56.2	
0%,24hr, 5Z-Houston, PVAV	23.4	20.7	0.7	22.8	0.1	6.6	74.2	7.1%
0%,24hr, 1Z-Houston, PVAV	23.4	20.7	1.1	19.0	0.1	5.1	69.3	
0%,24hr, 5Z-Chicago, PSZ	23.4	20.7	8.3	0.6	0.5	12.1	65.7	7.7%
0%,24hr, 1Z-Chicago, PSZ	23.4	20.7	8.7	0.2	0.4	7.6	61.0	
0%,24hr, 5Z-Chicago, PVAV	23.4	20.7	9.5	10.7	0.5	7.0	71.9	2.5%
0%,24hr, 1Z-Chicago, PVAV	23.4	20.7	12.0	8.6	0.5	5.0	70.1	

* Total building energy use extracted from BEPU reports in DOE-2.1e simulations and then SI unit in kWh converted to IP unit in MMBtu

** In 0% 24hr simulation cases, minimum rates for the lighting system and equipment were 0.18 and 0.20, respectively. The minimum occupancy rate was 0.00. Thermostat set-temperatures for heating and cooling used set-back temperatures for 24 hours.

In cases using 100%, 24 hours system operations, all models used almost 2/3 of total energy use for lighting and equipment. In Houston, cooling loads in the single and 5-zone models increased dramatically, which were 11-27 times more than heating loads. In the PSZ systems, the simulation showed more fan energy use for ventilation compared to PVAV systems because PSZ's fan is not as flexible as VAV systems in response to occupant's thermal demand. In the 100%, 24-hour operations, the heating systems in both the single-zone and the 5-zone model used more energy than cooling systems.

The three types of simulation schedules and two different HVAC systems in the single-zone and 5-zone models verified that the lighting and equipment loads were the most energy-consuming loads in the small office buildings in hot-humid and cold-humid climate regions. In addition, heating, cooling, and ventilation fans were weather and system dependent as expected.

The thermal zone models using the Standard 90.1-2016 schedules showed 0.3% - 5.6% differences between the PSZ and PVAV models in Houston and -0.6% - 4.6% differences in the Chicago PSZ and PVAV models. The 5 zone models using a 100%, 24-hour operation resulted in a 2.5% - 6.2% difference for the PSZ and PVAV models in Houston and a 3.0% - 4.9% difference for the Chicago PSZ and PVAV models. The 0% occupancy, 24-hour operation models yielded 4.6% -7.1% differences between the single-zone and 5-zone models in Houston and Chicago and 2.5% - 7.7% differences found in Chicago.

Figure 22 and Table 24 analyzed the end-use load components to determine where the total building energy use differences are coming from in different simulation models. The results found that energy use differences in small office buildings mainly resided in weather-dependent load components (i.e., heating, cooling, ventilation).

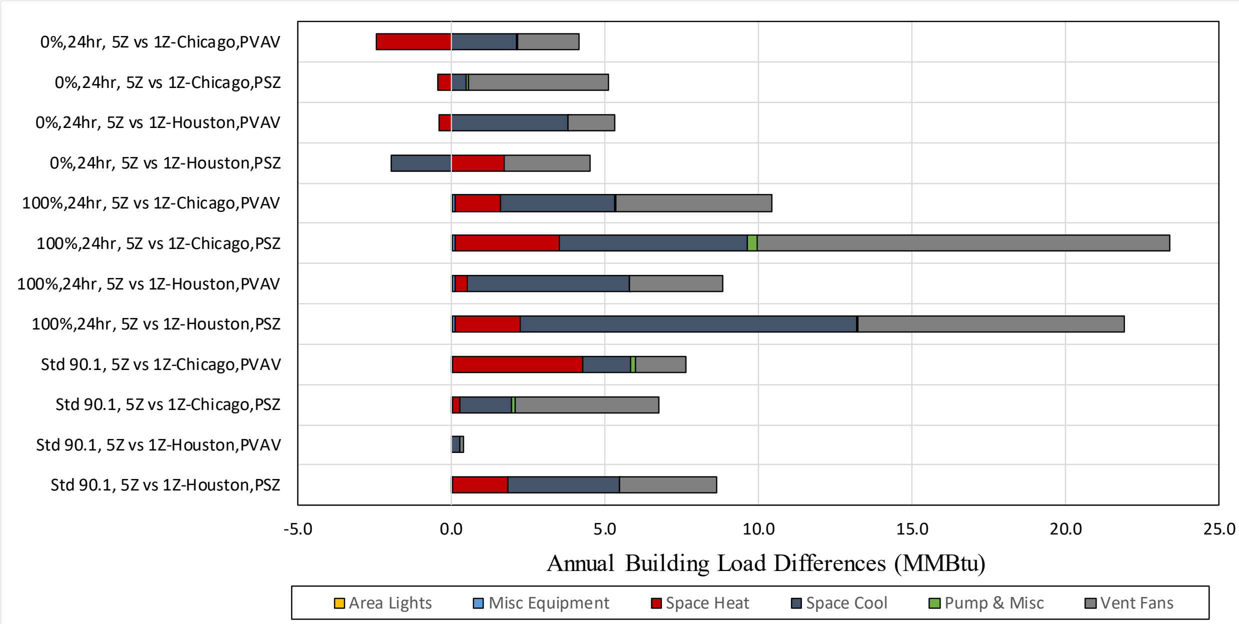


Figure 22. Total Building Energy Use Differences by Thermal Zoning Models

In cases with 0% occupancy and 24-hour operation, the building system operations were set-back to off-hour conditions. Therefore, in all cases of 0% occupancy, 24-hour operation had the same operation inputs of occupancy, system schedules, thermostat schedules. However, outdoor environmental conditions (i.e., external air temperature, humidity) and internal heat gain from minimum lighting and equipment operations made heating and cooling demands, which made the changes of heating, cooling and ventilation fan loads in simulation models using 0%, 24 hours schedule.

In cases where the Standard 90.1-2016 schedule was used, the primary differences came from space cooling and ventilation. The differences in the PSZ system's cooling and ventilation were larger than the PVAV system's energy loads. Space heating energy use showed divergent results depending on regions and system types. The 5-zone PSZ system models in Houston and

Chicago used more space heating energy than single zoning models. In contrast, the 5 zone VAV system models in Houston and Chicago used less space heating energy than single zoning models. Lighting and equipment used the same amount of energy between the single-zone and the 5 zone model in all cases of Standard 90.1-2016 schedules.

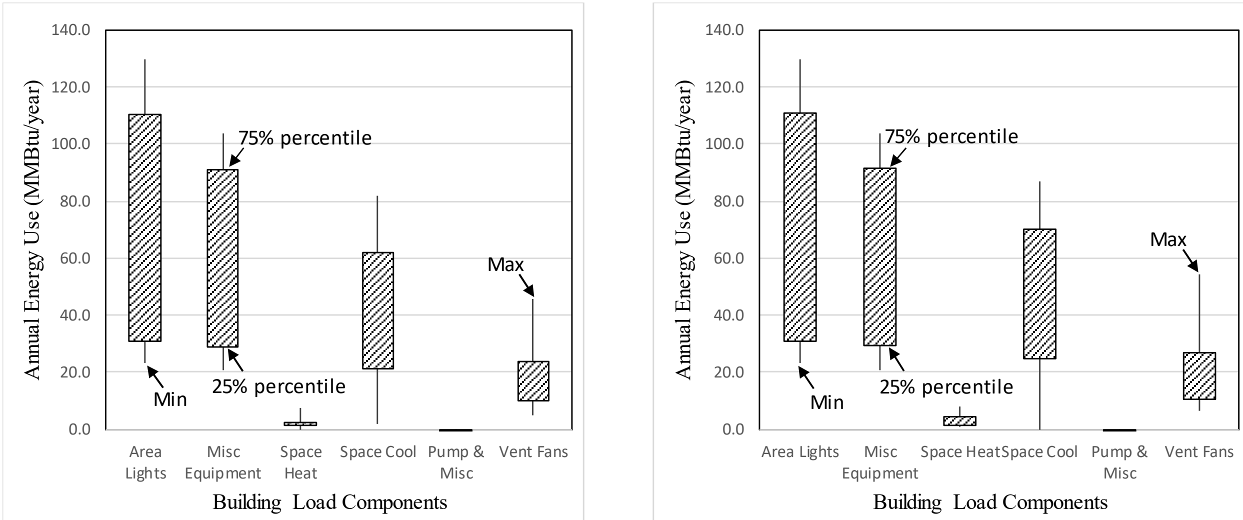
In cases of 100% occupancy, 24-hour operation, the total energy use differences between different thermal zoning models were at least two times larger than Standard 90.1-2016 schedules. Most of the differences in energy use between the single and 5-zone models were from space cooling and ventilation, which occupied 86 to 94 percent of the total energy use differences in all the 100%, 24-hour operation simulations. In space heating, all cases of the 100%, 24-hour operation showed that 5-zone models used more energy than single-zone models except some cases of 5-zones and 1 zone models using CAV systems in Chicago. Since lighting and equipment were weather-independent load components, the differences were very small.

Figure 23 and Figure 24 show the variations of energy use in load components in single-zone and 5-zone models when applied to the three different types of simulation schedules and two types of HVAC systems (i.e., PSZ, PVAV). The results show the lighting and equipment variations in Houston equal to the result in Chicago models. However, the 5-zone models in Houston and Chicago showed larger extents of changes in the heating, cooling, and ventilation fan energy use depending on HVAC system types.

Table 24. Total Building Energy Use Difference by Thermal Zoning Models in Houston and Chicago (Unit: MMBtu)

Base Cases	Area Lights	Misc Equipment	Space Heat	Space Cool	Heat Rejection	Pump & Misc	Vent Fans	Total
Std 90.1, 5Z vs 1Z-Houston,PSZ	0.0	0.0	1.8	3.6	0.0	0.0	3.1	8.6
Std 90.1, 5Z vs 1Z -Houston, PVAV	0.0	0.0	0.0	0.3	0.0	0.0	0.1	0.4
Std 90.1, 5Z vs 1Z -Chicago, PSZ	0.0	0.0	0.2	1.7	0.0	0.1	4.7	6.8
Std 90.1, 5Z vs 1Z -Chicago, PVAV	0.0	0.0	-4.2	1.6	0.0	0.1	1.6	-0.9
100%,24hr, 5Z vs 1Z -Houston, PSZ	0.1	0.1	2.1	10.9	0.0	0.0	8.7	21.9
100%,24hr, 5Z vs 1Z -Houston, PVAV	0.1	0.1	0.4	5.3	0.0	0.0	3.1	8.9
100%,24hr, 5Z vs 1Z -Chicago, PSZ	0.1	0.1	-3.4	6.1	0.0	0.4	13.4	16.6
100%,24hr, 5Z vs 1Z -Chicago, PVAV	0.1	0.1	1.5	3.7	0.0	0.1	5.0	10.4
0%,24hr, 5Z vs 1Z -Houston, PSZ	0.0	0.0	1.7	-2.0	0.0	0.0	2.8	2.6
0%,24hr, 5Z vs 1Z -Houston, PVAV	0.0	0.0	-0.4	3.8	0.0	0.0	1.5	4.9
0%,24hr, 5Z vs 1Z -Chicago, PSZ	0.0	0.0	-0.4	0.4	0.0	0.1	4.6	4.7
0%,24hr, 5Z vs 1Z -Chicago, PVAV	0.0	0.0	-2.4	2.1	0.0	0.1	2.0	1.8

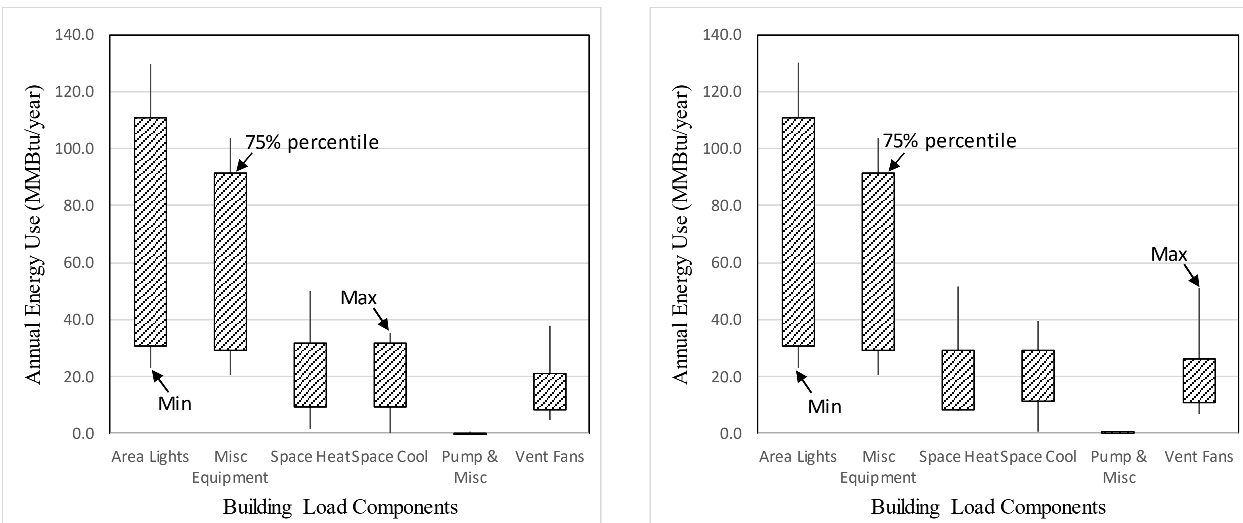
* Total building energy use differences calculated energy use differences in MMBtu between different thermal zoning models using the same HVAC systems
** Total building energy use extracted from BEPU reports in DOE-2.1e simulations and then SI unit in kWh converted to IP unit in MMBtu
*** In 0% 24hr simulation cases, minimum rates for the lighting system and equipment were 0.18 and 0.20, respectively. The minimum occupancy rate was 0.00. Thermostat set-temperatures for heating and cooling used set-back temperatures for 24 hours.



Houston 1 Zone Models

Houston 5 Zone Models

Figure 23. Houston: Energy Use Variations of Load Components in 1 Zone and 5 Zone Models



Chicago 1 Zone Models

Chicago 5 Zone Models

Figure 24. Chicago: Energy Use Variations of Load Components in 1 Zone and 5 Zone Models

5.1.2. Peak Day Building Energy Loads

Peak loads represent peak demands that refer to the maximum energy demand during a particular period, typically a day. Figure 25 shows a concept of peak loads that depicts 24-hour electric utility load curves for summer and winter peak days at a specific location (Aznar 2015). Understanding this concept is significant because a daily pattern of energy use is highly affected by building operating hours and solar gain. In other words, high occupancy intensity and high solar gain (e.g., afternoon) requires more electricity use to control indoor temperature and operate equipment in the summer. Also, these 24-hour load curves can be shown in different load components that are used to understand what is causing the daily load trend changes by the hour.

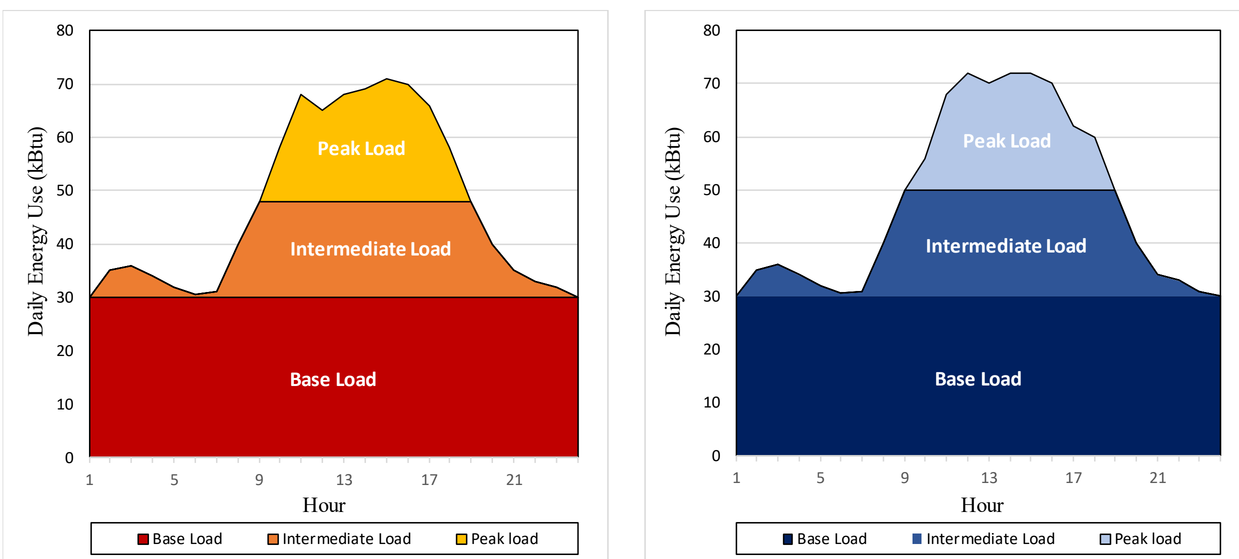


Figure 25. Example Daily Load Curves in Summer and Winter

For estimating the impact in energy use of thermal zoning models, peak day daily energy usage profiles would provide a better perspective of 24-hour energy consumption patterns and energy use reduction contributing components in different simulation conditions. For this, this study used reference small office prototype models for testing PSZ and PVAV systems. The results showed building energy performance, peak day loads by load component, and hourly patterns by HVAC system types and locations (e.g., Houston, TX and Chicago, IL) in single and 5 zone small office building models. The simulation cases for this review are represented in Table 22.

The peak days for this chapter were determined based on the rules shown below to compare simulation models on the same peak days and to better evaluate the occupancy-based controls in energy reduction.

- Peak days were selected based on the building or thermal zone's summer and winter peak days using the LS-A: space peak loads summary report in DOE-2.1e simulations using Houston (#722430) and Chicago (#725300) TMY3 data
- Peak days were selected to be clear days based on cloud amount from TMY3 weather data in the summer and winter, as well as the solar data for the peak day.

Based on the above rules and a simulation period of the calendar year 2019, August 2 (Friday) and February 11 (Monday) were selected for Houston, TX, and September 27 (Friday) and January 23 (Wednesday) were selected for Chicago, IL. For Chicago, the original peak day for winter was January 27 in building total and all five zones. However, since January 27 in 2019 was Sunday, one of the coldest days on weekdays was selected instead for the winter peak day.

Finally, the weather data of peak days in summer and winter are presented in Figure 26 to Figure 29, which include ground temperature (ºF), outdoor temperature(ºF), and total horizontal solar radiation (Btu/ft^2·hr).

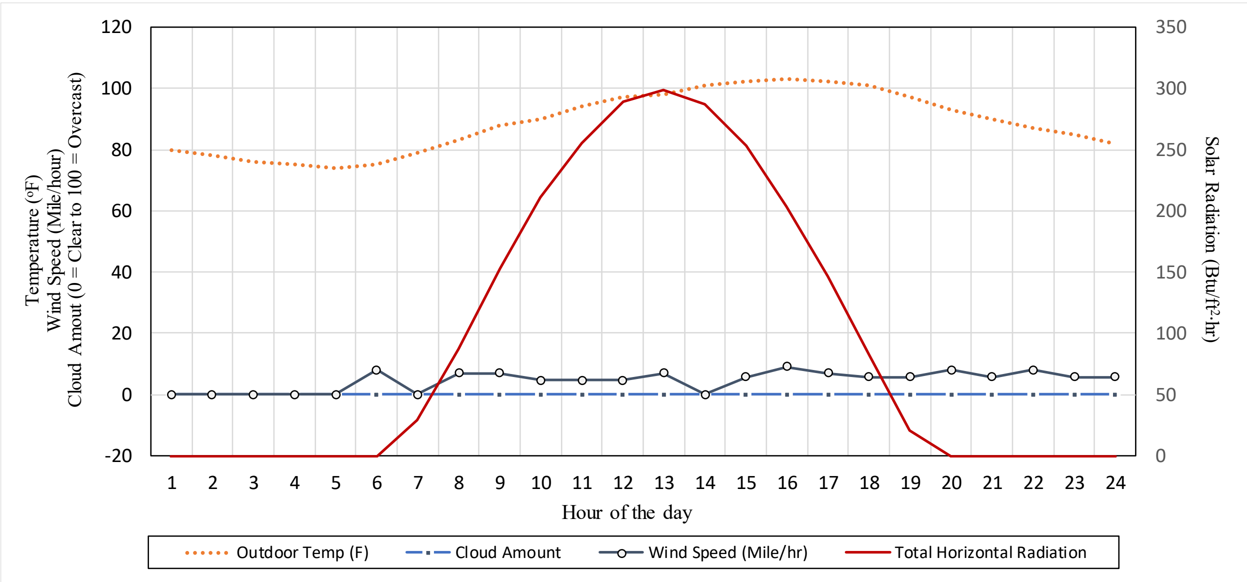


Figure 26. Weather Data for the Summer Peak Load Day (Aug. 2) in Houston, TX

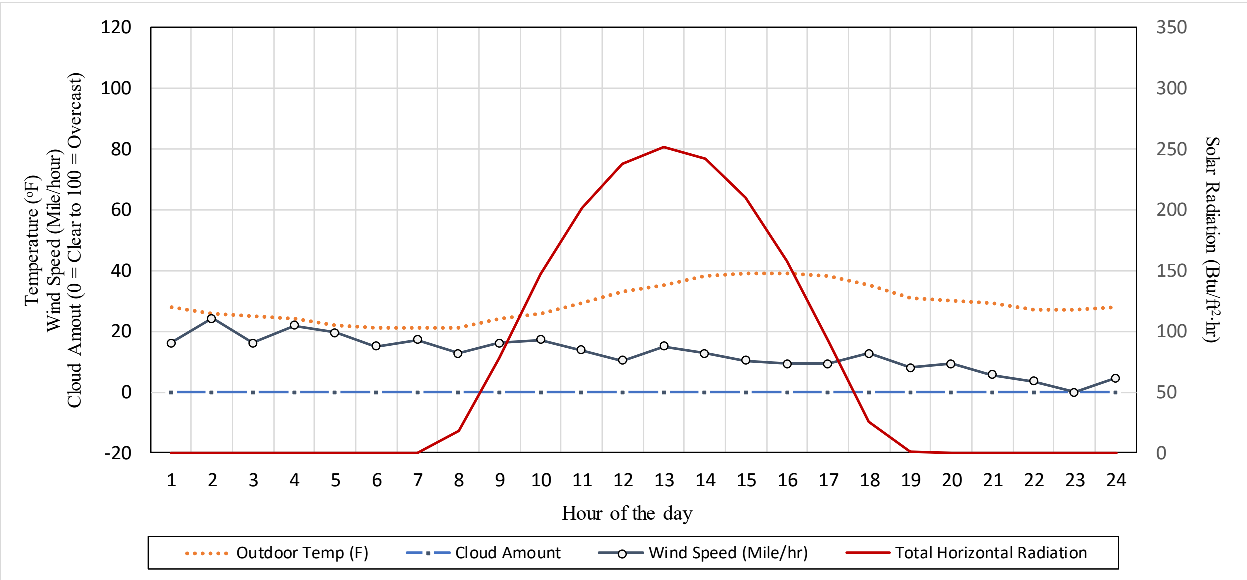


Figure 27. Weather Data for the Winter Peak Load Day (Feb. 11) in Houston, TX

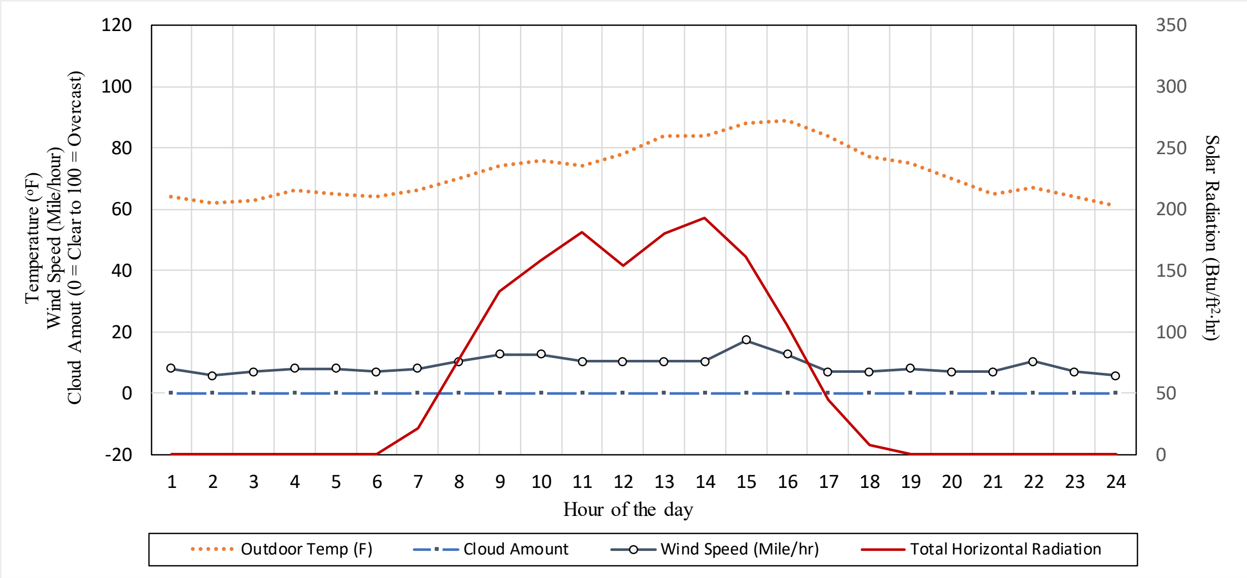


Figure 28. Weather Data for the Summer Peak Load Day (Sep. 27) in Chicago, IL

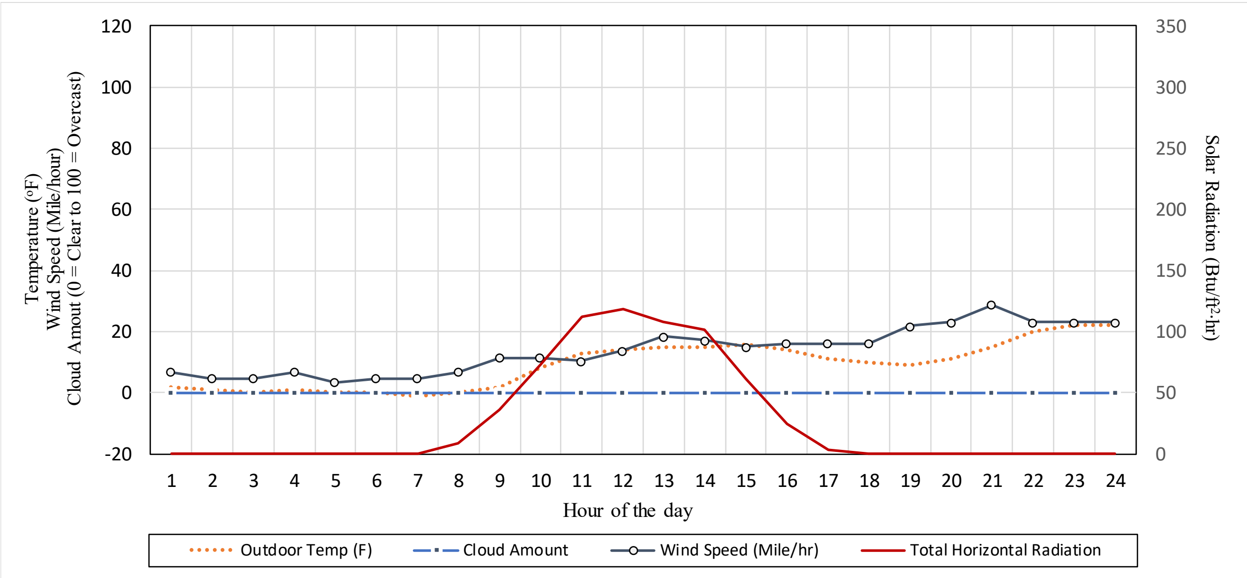


Figure 29. Weather Data for the Winter Peak Load Day (Dec. 20) in Chicago, IL

After the peak days for the corresponding locations are selected, the 24-hourly profiles and space conditions for thermal zones were calculated using the hourly reports in DOE-2.1e.

For the hourly reporting of peak days in Houston and Chicago, an hourly report of outside dry-bulb temperature (ºF) was added in space loads calculations. Also, zonal temperature (ºF), zonal supply fan volume (CFM), heating coil and cooling coil leaving temperatures were hourly calculated in system loads calculations. Lastly, energy use by load components was hourly calculated in plant loads calculations that are end-use energy by load components (i.e., area lighting, equipment, heating, cooling, ventilation) in electricity (kWh).

5.1.2.1. Total Building Energy Use (End-Use) in Peak Days

This chapter compares the total building energy use of single zone and 5 zone models in summer and winter peak days. The result of total building energy use on a peak day was extracted from the hourly plant loads report. Component loads from the plant loads calculations included five components in kWh: area lighting, equipment, heating, cooling, ventilation, which were converted to kBtu/day to compare results in Houston and Chicago.

Table 25, Table 26, Figure 30 and Figure 31 show the result of total building energy use in summer and winter peak days in Houston (Aug 2/Feb 11) and Chicago (Sep 27/Dec 20). About the total building energy use in summer peak days, all 5 zone models represented more energy use than single-zone models in Houston and Chicago, which was 1.7% to 6.3% of total building energy use in each 5 zone model. PSZ systems showed more disparities compared to PVAV systems in both different climate regions.

In terms of total building energy use in winter peak days, 5 zone PSZ models used 1.6% to 18.6% of more energy than the single-zone PSZ models in Houston and Chicago, respectively. Contrastively, 5 zone PVAV system models in Houston and Chicago showed less energy use than single-zone PVAV models in winter peak days.

Table 25. Total Building Energy Use in Summer Peak Days

	Area Lighting Electric (kBtu)	Equipment Electric (kBtu)	Heating Electric (kBtu)	Cooling Electric (kBtu)	Ventilation Electric (kBtu)	Total (kBtu)	Difference (5Z - 1Z Model, %)
1Z,Houston, PSZ	182.1	190.8	0.0	256.1	66.3	695.3	N/A
5Z,Houston, PSZ	182.1	190.9	0.0	283.2	78.8	735.0	5.7%
1Z,Houston, PVAV	182.1	190.8	0.0	267.4	60.4	700.7	N/A
5Z,Houston, PVAV	182.1	190.9	0.0	287.8	62.9	723.7	3.3%
1Z,Chicago, PSZ	182.1	190.8	0.0	137.9	54.3	565.1	N/A
5Z,Chicago, PSZ	182.1	190.9	0.0	154.6	73.0	600.6	6.3%
1Z,Chicago, PVAV	182.1	190.8	0.0	148.7	48.0	569.6	N/A
5Z,Chicago, PVAV	182.1	190.9	0.0	156.4	49.6	579.0	1.7%

Table 26. Total Building Energy Use in Winter Peak Days

	Area Lighting Electric (kBtu)	Equipment Electric (kBtu)	Heating Electric (kBtu)	Cooling Electric (kBtu)	Ventilation Electric (kBtu)	Total (kBtu)	Difference (5Z - 1Z Model, %)
1Z,Houston, PSZ	182.1	190.8	55.9	0.0	66.3	495.1	N/A
5Z,Houston, PSZ	182.1	190.9	135.2	0.0	78.8	587.1	18.6%
1Z,Houston, PVAV	182.1	190.8	183.8	0.0	32.3	589.0	N/A
5Z,Houston, PVAV	182.1	190.9	113.0	0.0	38.5	524.5	-11.0%
1Z,Chicago, PSZ	182.1	190.8	413.8	0.0	54.3	841.0	N/A
5Z,Chicago, PSZ	182.1	190.9	408.2	0.0	73.0	854.2	1.6%
1Z,Chicago, PVAV	182.1	190.8	260.7	0.0	31.0	664.6	N/A
5Z,Chicago, PVAV	182.1	190.9	197.9	0.0	39.4	610.3	-8.2%

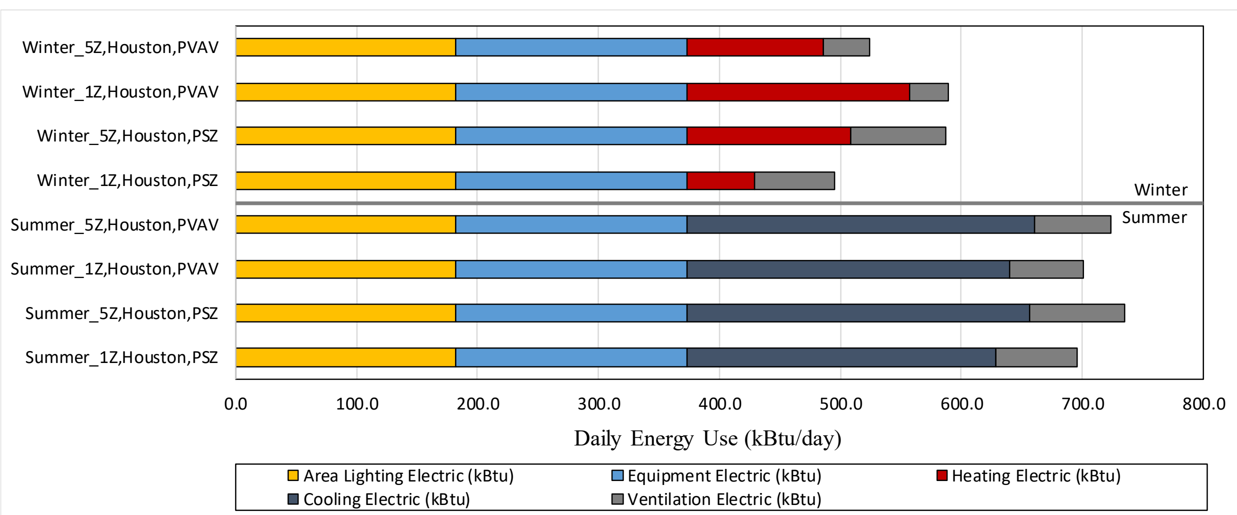


Figure 30. Houston: Total Building Energy Use in Summer and Winter Peak Days

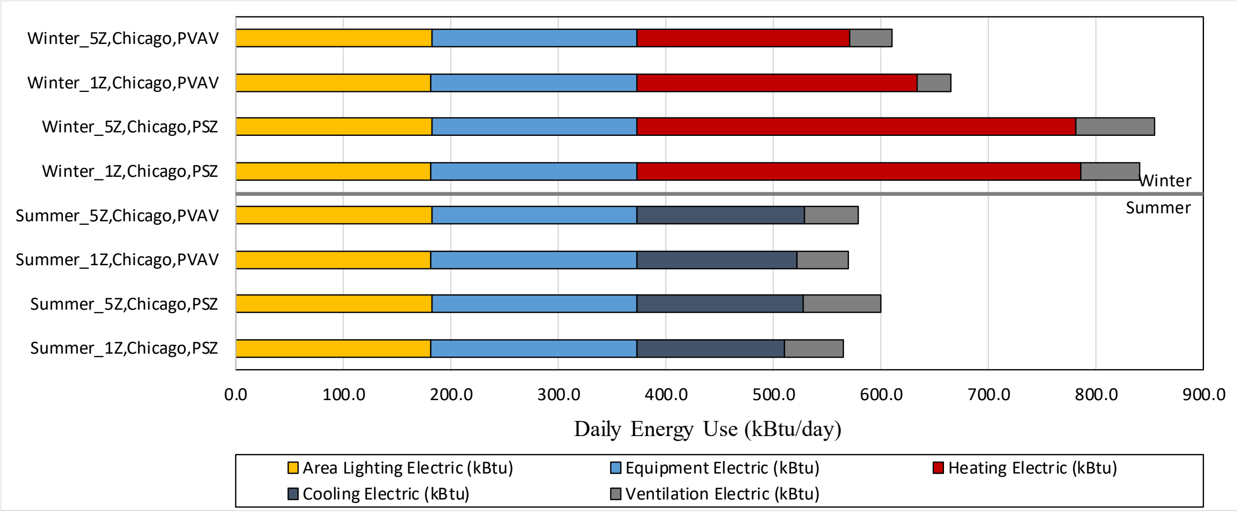


Figure 31. Chicago: Total Building Energy Use in Summer and Winter Peak Days

As for load components, lighting and equipment are operated based on weekday and weekend schedules, which indicates that those components are weather-independent. Thus, the result showed practically no changes between single-zone and 5 zone models in Houston and Chicago. The load differences are represented in weather-dependent load components, such as heating, cooling, and ventilation.

Figure 32 depicts the percentage of changes between single-zone models and 5 zone models by load components. In summer, gaps in different thermal zoning models occurred from cooling and ventilation loads. In PSZ systems, ventilation loads had enormous differences due to constant fan operations in PSZ systems. Relatively, in PVAV systems, cooling loads mainly led to the differences between single-zone and 5 zone models than ventilation loads.

In winter, heating loads were primary variables to create discrepancies in different zoning models. Typically, 5 zone models used less energy than single-zone models except a case of winter_5Z-1Z, Houston, PSZ. Also, two 5 zone PVAV system models showed larger gaps than winter_5Z-1Z, Chicago PSZ model. Winter_5Z-1Z, Houston explained that the PVAV system consumed more heating energy than the PSZ system. In ventilation loads, Chicago models showed more significant discrepancies than Houston models, which implies Chicago single-zone models much more overestimated than Houston single-zone models against 5 zone models.

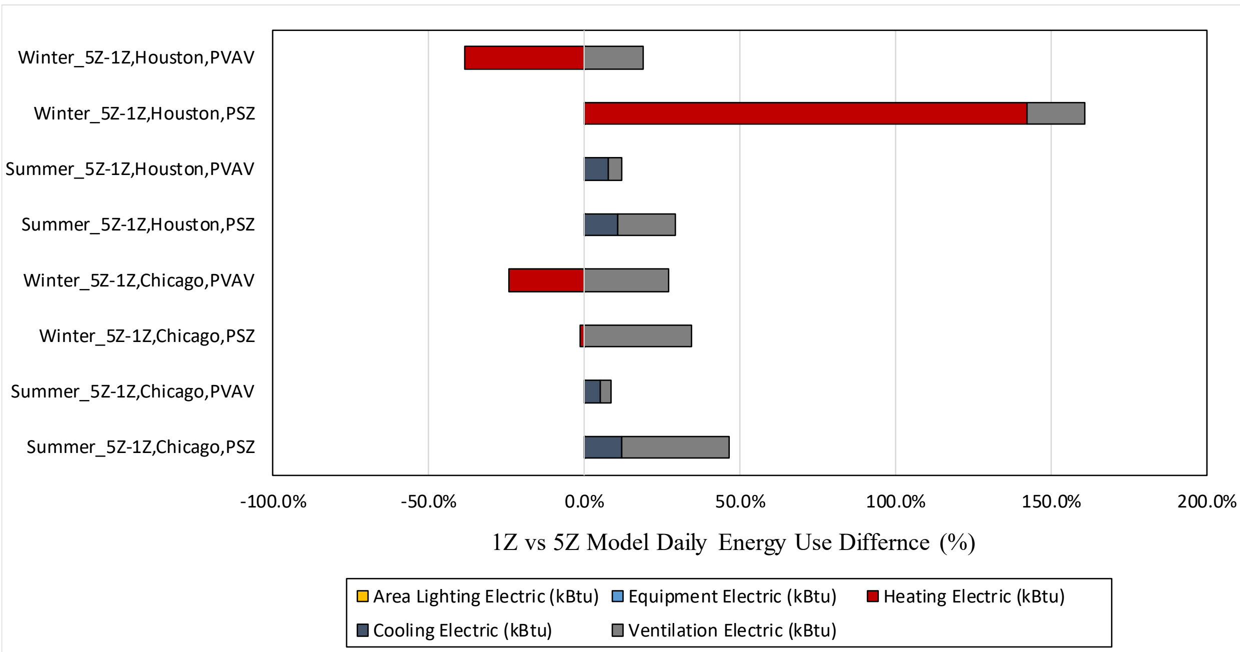


Figure 32. Peak Day Energy Use Difference Between Single Zone and 5 Zone Models (%)

In summary, total building load analysis in summer and winter peak days identified thermal characteristics between single-zone and 5 zone models. The result of total building energy use verified that single-zone models underestimated in summer peak days in both Houston and Chicago. In contrast, in winter, single-zone PSZ system models only underestimated total energy use in Houston and Chicago and single-zone PVAV system models overestimated total energy use in Houston and Chicago.

The underestimation of single-zone models in summer was from cooling and ventilation loads. Also, the underestimation of single-zone models in winter came from heating and ventilation, especially in heating loads of PSZ systems. PVAV single-zone models represented overestimation in heating loads, which led to large discrepancies between single-zone and 5 zone models in Houston and Chicago.

5.1.2.2. Houston: Hourly Building Energy Use (End-Use) in Peak Days

This chapter investigated hourly trends of building energy use by load components in summer and winter peak days using Standard 90.1-2016 schedules. Daily load curves could show shapes and patterns of load components for 24 hours at peak days. Also, the daily load curves would help understand the impact and sensitivity of thermal zoning models to investigate OBC in this study. The result of daily load curves was calculated in the end-use energy from hourly plant loads calculations in DOE-2.1e. Figure 33 and Figure 34 represent summer and winter peak days with outdoor air temperatures in single-zone and 5 models in Houston and Chicago. Lighting, equipment, and ventilation loads consumed energy based on operating schedules during a weekday. On the contrary, cooling and heating loads showed load changes corresponding to weather conditions and system schedules. In cases of PSZ systems in Houston, a single-zone model underestimated cooling and ventilation loads in summer and heating and ventilation loads in winter than a 5-zone model. Notably, in winter, heating load was highly underestimated in the early morning and late afternoon.

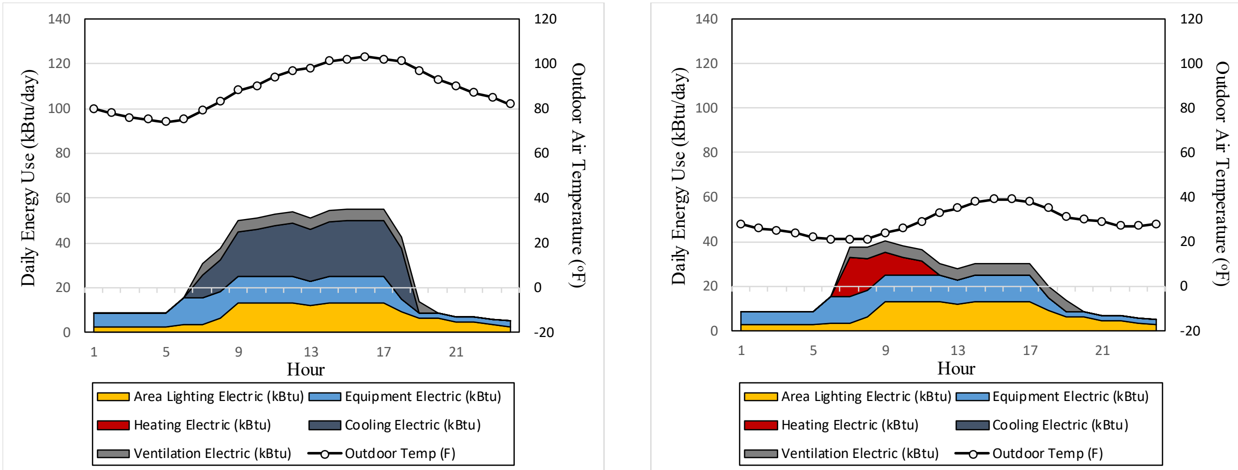


Figure 33. Daily Load Curve: Single Zone Model, Houston, PSZ System

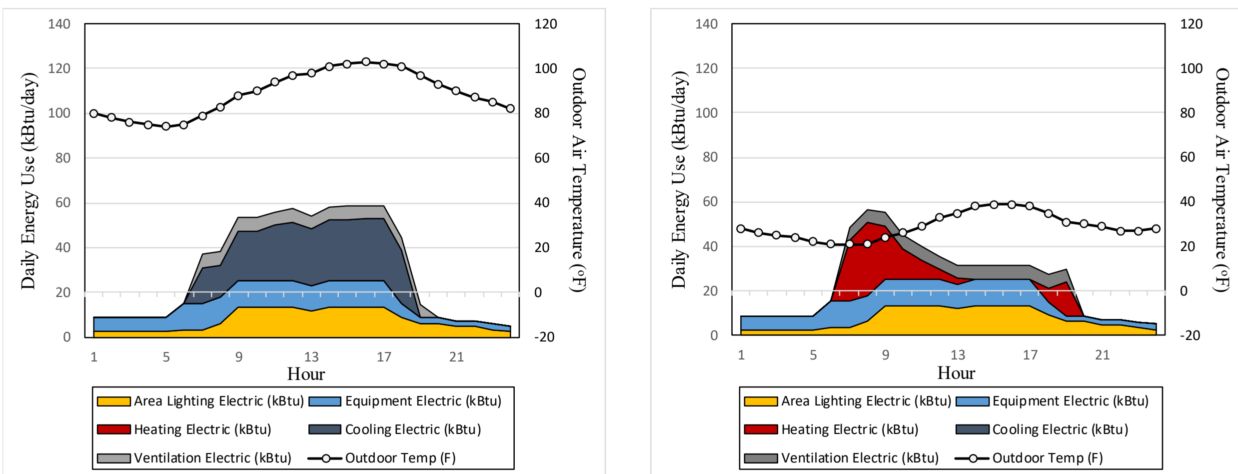


Figure 34. Daily Load Curve: 5 Zone Model, Houston, PSZ System

Figure 35 and Figure 36 describe daily load curves of summer and winter peak days in single-zone and 5 zone models in Houston and Chicago. Lighting, equipment, and ventilation loads followed operating schedules over a weekday, which is not weather-dependent. Contrastively, cooling and heating loads corresponded to the changes in weather conditions.

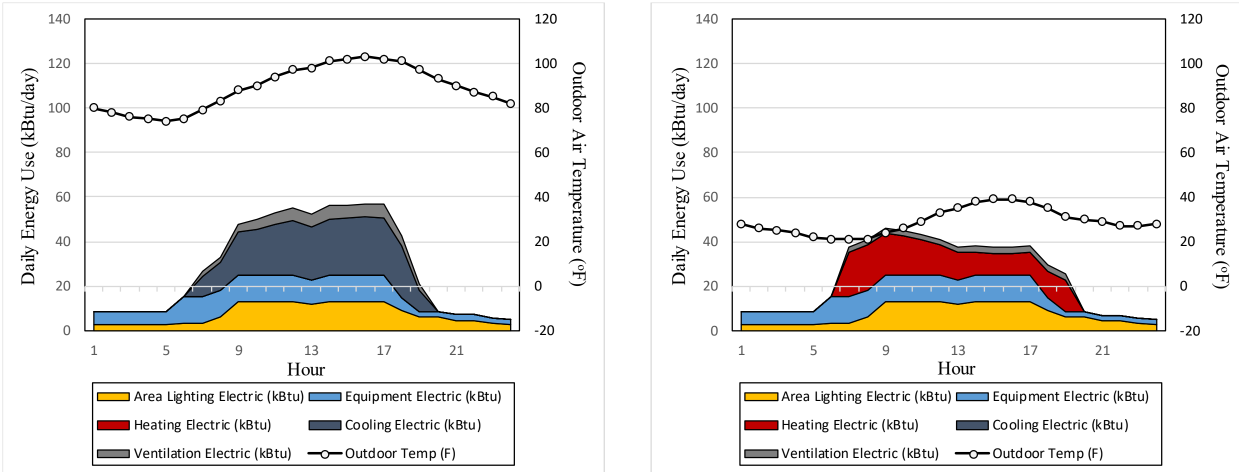


Figure 35. Daily Load Curve: Single Zone Model, Houston, PVAV System

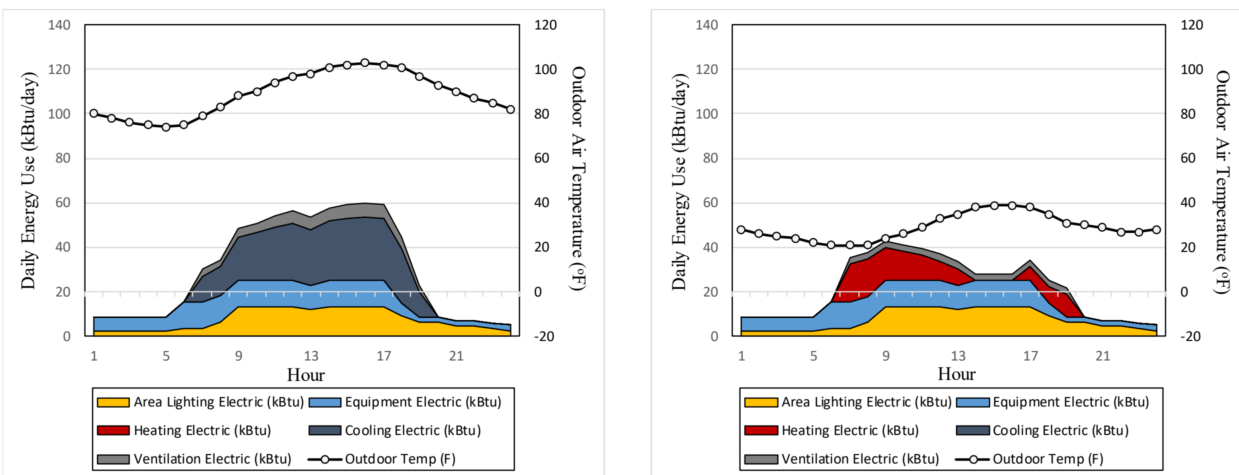


Figure 36. Daily Load Curve: 5 Zone Model, Houston, PVAV System

In cases of PVAV systems in Houston, a single-zone model underestimated cooling and ventilation loads in summer and ventilation load in winter than a 5 zone model. Underestimation in summer occurred in the early morning and late afternoon. However, in winter, a PVAV single-zone model overestimated the heating load than a 5 PVAV zone model, particularly at 1 pm-5 pm. The analysis of daily load curves showed when and where differences occurred in summer and winter.

5.1.2.3. Chicago: Hourly Building Energy Use (End-Use) in Peak Days

In this chapter, hourly trends of building energy use were investigated in Chicago for summer and winter peak days. Daily load curves showed shapes and patterns of load components for 24 hours at peak days. The result of daily load curves was calculated in single-zone and 5 zone models using Standard 90.1-2016 schedules in the end-use energy from hourly plant loads calculations in DOE-2.1e.

Figure 37 and Figure 38 represent summer and winter peak days with outdoor air temperatures in Houston and Chicago. Lighting and equipment loads showed constant energy use between different zoning models that were based on operating schedules during a weekday. The ventilation system worked only in building open hours, which used different amounts of energy depending on HVAC system type and climate region.

On the contrary, cooling and heating loads showed weather-dependent load patterns. The hourly patterns of cooling and heating were similar to cooling and heating coil leaving temperatures, as shown in Chap 5.1.3. In cases of PSZ systems in Chicago, a single-zone model underestimated cooling and ventilation loads in summer and ventilation loads in winter than a 5 zone model. However, in winter, the heating load was highly overestimated during the daytime.

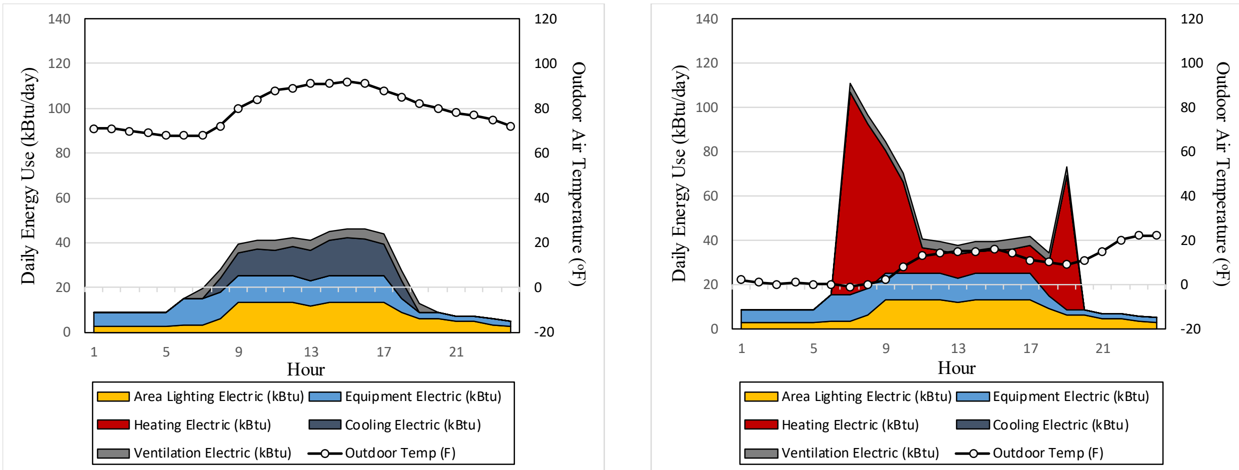


Figure 37. Daily Load Curve: Single Zone Model, Chicago, PSZ System

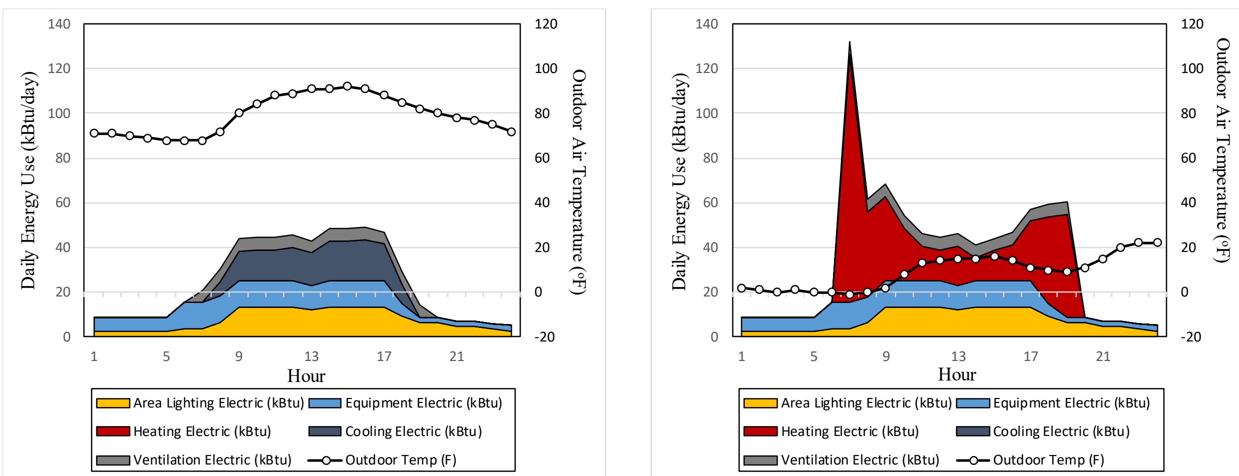


Figure 38. Daily Load Curve: 5 Zone Model, Chicago, PSZ System

Figure 39 and Figure 40 describe daily load curves of single-zone and 5 zone models in summer and winter peak days in Houston and Chicago. Lighting, equipment, and ventilation loads operated based on simulation schedules over a weekday, which is weather-independent. In contrast, cooling and heating loads showed the changes corresponded to weather conditions.

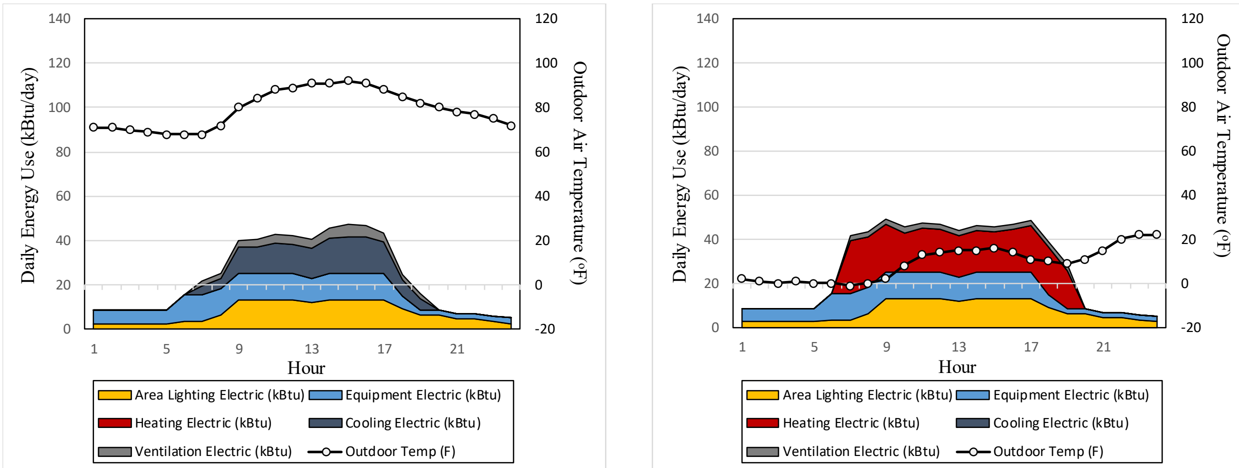


Figure 39. Daily Load Curve: Single Zone Model, Chicago, PVAV System

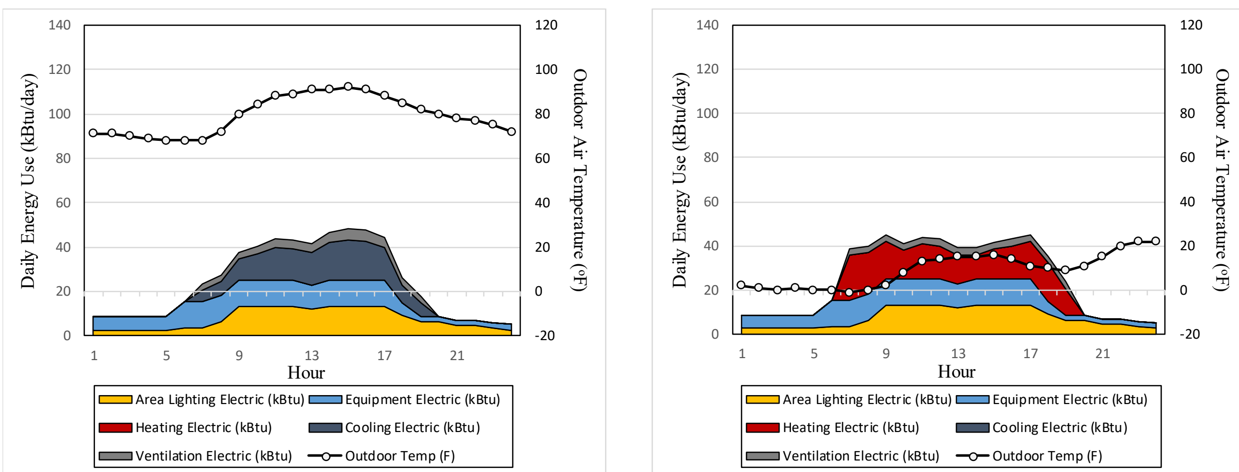


Figure 40. Daily Load Curve: 5 Zone Model, Chicago, PVAV System

In cases of PVAV systems in Chicago, a single-zone model underestimated cooling and ventilation loads in summer and underrated ventilation loads in winter than a 5 zone model. Underestimation in summer occurred evenly throughout the day. However, in winter, a PVAV single-zone model overestimated the heating load than a 5 zone PVAV zone model, particularly at 12 pm-5 pm. The analysis of daily load curves showed when and where differences occurred in summer and winter.

5.1.2.4. Summary

This chapter analyzed the peak day's total building energy use and daily load curve patterns in Houston and Chicago. Houston and Chicago are representative cities of hot/humid and cold/humid climate zones in the U.S. The daily load analysis would show the maximum energy demands during 24 hours in summer and winter peak days.

Annual total building energy use (end-use) verified the discrepancies between single-zone and 5 zone models using three different simulation schedule types: (1) Standard 90.1-2016, (2) 100% and 24-hour operation, and (3) 0% and 24-hour operation. 5 zone models using Standard 90.1-2016 schedules showed 1.7% - 5.6% differences of Houston PSZ and PVAV models and -0.4% - 4.9% differences of Chicago PSZ and PVAV models. 5 zone models using 100%, 24-hours operation resulted in 2.7% - 6.2% differences of Houston PSZ and PVAV models and 3.2% - 5.3% differences of Chicago PSZ and PVAV models. 0%, 24-hours operation models yielded 0.1% differences between single-zone and 5 zone models in Houston and Chicago due to minimum rate operations of lighting and equipment and 0% occupancy during weekday and weekend.

In terms of building energy load analysis in peak days, the amounts of lighting and equipment consumption were fixed based on simulation weekday schedules while heating, cooling, and ventilation fan energy use showed the variability against outdoor air temperature and occupancy schedule. Single-zone models in winter peak days consumed more heating energy than 5 zone models except for winter_1Z Houston, PSZ model. Whereas, single-zone models in summer peak days used less cooling energy than 5 zone models in both Houston and Chicago. As for ventilation fans, PSZ systems typically used more energy than PVAV systems due to constant fan operations. Weather-dependent load components showed fluctuations in daily energy use and patterns depending on daily weather conditions when simulating different combinations of HVAC types and thermal zoning models.

Daily load curves identified how much energy consumed by hours and which load components used by hours in summer and winter. Cooling load curves represented relatively even distribution in Houston and Chicago, including PSZ and PVAV systems. Heating load curves in Houston and Chicago showed significant changes based on the outdoor temperature in winter. In cases of cold and huge daily temperature ranges, PSZ models in Houston and Chicago were energy-intensive in the early morning and late afternoon. Also, the daily cooling and heating curves showed similar patterns with cooling and heating coil leaving temperatures in Chapter 5.1.3.

The comparative analysis of single-zone and 5 zone models verified that the single-zone model would underestimate cooling and ventilation in summer and ventilation in winter. In contrast, in winter single-zone model would overestimate the heating load than a 5 zone PVAV zone model. The single-zone model would miscalculate weather-dependent load components (e.g., heating, cooling, PVAV system ventilation).

5.1.3. Sensitivity in Building Energy Use Reduction from Occupancy-based Controls

In office buildings, occupancy is a critical factor in determining building system usage and operation schedule. However, due to the randomness attribute, occupant behavior causes uncertainty in determining building energy performance. Therefore, to broaden our perspective of how OBC works, this chapter performed simplified sensitivity tests using reference small office models in building energy use from OBC. Currently, there are many measures available to evaluate the impact of OBC, depending on the definitions and simulation environment settings. As part of this effort, this study suggested simplified simulation schedules for 100% to 10% usage rates in Figure 14 to Figure 20. These schedules can show normalized usage rates for daytime depending on average occupancy rates even though it is vulnerable to represent the frequency of occupant presence.

The simulations for computing the impact of occupancy and related schedules and controls were conducted in single-zone and 5-zone models in Houston and Chicago. They are representative regions of hot/humid (2A) and cold/humid (5A) climate zones. OBC schedules were applied to a whole building in single-zone and 5-zone models. Testing simulation cases in Table 26 were determined as part of continuity from the previous sub-chapters in Chapter 5.1 using several independent variables (i.e., location, zoning model, HVAC type, schedule type). Table 28 to Table 35 summarize the annual energy use of occupancy-based controls.

Table 27. Simulation Cases for Quantifying the Impact of Occupancy-Based Controls

Group	Location	Zoning Model	Envelope Material	System Type	OBC Schedule Type (Weekdays, 9AM-5PM)							Average WWR
					Occup	Light	Equip	Infilt	Vent Fan	Set-temp	Set-back	
1	Houston	Single zone	Standard 90.1-2016	PSZ	1.0-0.0	1.0-0.0	1.0-0.0	Off	1.0	H: 70ºF C: 75ºF	H: 60ºF C: 85ºF	21% (default)
2	Houston	Single zone	Standard 90.1-2016	PVAV	1.0-0.0	1.0-0.0	1.0-0.0	Off	1.0	H: 70ºF C: 75ºF	H: 60ºF C: 85ºF	21% (default)
3	Houston	Five zones	Standard 90.1-2016	PSZ	1.0-0.0	1.0-0.0	1.0-0.0	Off	1.0	H: 70ºF C: 75ºF	H: 60ºF C: 85ºF	21% (default)
4	Houston	Five zones	Standard 90.1-2016	PVAV	1.0-0.0	1.0-0.0	1.0-0.0	Off	1.0	H: 70ºF C: 75ºF	H: 60ºF C: 85ºF	21% (default)
5	Chicago	Single zone	Standard 90.1-2016	PSZ	1.0-0.0	1.0-0.0	1.0-0.0	Off	1.0	H: 70ºF C: 75ºF	H: 60ºF C: 85ºF	21% (default)
6	Chicago	Single zone	Standard 90.1-2016	PVAV	1.0-0.0	1.0-0.0	1.0-0.0	Off	1.0	H: 70ºF C: 75ºF	H: 60ºF C: 85ºF	21% (default)
7	Chicago	Five zones	Standard 90.1-2016	PSZ	1.0-0.0	1.0-0.0	1.0-0.0	Off	1.0	H: 70ºF C: 75ºF	H: 60ºF C: 85ºF	21% (default)
8	Chicago	Five zones	Standard 90.1-2016	PVAV	1.0-0.0	1.0-0.0	1.0-0.0	Off	1.0	H: 70ºF C: 75ºF	H: 60ºF C: 85ºF	21% (default)

* 0% schedules refer to minimum operating contisions using weekend Standard schedules.
* Weekend schedules set to minimum operating conditions of simulation schedules (e.g., occupancy=0.0, 0%; lighting=0.18, 18%; equipment=0.20, 20%; infiltration=off; ventilation fan=0.0;
set-temperature: heating 60ºF, cooling 85ºF).
* Window-to-wall (WWR) ratio in small office models is 21% on average. Window fraction is 24.4% for South and 19.8% for the other three orientations (e.g., east, west, north).

Table 28. Houston, Single-Zone PSZ Model: Annual Energy Use from OBC

	Houston 1Zone, PSZ System										
(Unit: MMBtu)	100% OBC	90% OBC	80% OBC	70% OBC	60% OBC	50% OBC	40% OBC	30% OBC	20% OBC	10% OBC	0% OBC
Area Lights	51.0	47.6	44.2	40.9	37.5	34.1	30.8	27.4	24.0	23.4	23.4
Misc Equipment	42.2	39.5	36.8	34.1	31.4	28.8	26.1	23.4	20.7	20.7	20.7
Space Heat	0.3	0.4	0.5	0.6	0.7	0.9	1.1	1.4	1.6	1.7	1.8
Space Cool	24.9	23.5	22.1	20.7	19.3	18.0	16.6	15.3	13.9	13.4	13.0
Heat Rejection	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Pump & Misc	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Vent Fans	11.8	11.2	10.7	10.1	9.5	8.9	8.3	7.7	7.2	7.0	6.8
Total	130.2	122.3	114.3	106.4	98.6	90.7	82.9	75.2	67.5	66.3	65.8

* Schedules for 100% OBC to 0% OBC (no occupancy) controls applied only for weekday based on the schedules in Figure 14 to Figure 20.
** Weekend and holiday calculations used the same schedules with Standard 90.1-2016 schedules.
*** Set-back controls used for heating and cooling systems in unoccupied hours

Table 29. Houston, 5-Zone PSZ Model: Annual Energy Use from OBC

	Houston 1Zone, PSZ System										
(Unit: MMBtu)	100% OBC	90% OBC	80% OBC	70% OBC	60% OBC	50% OBC	40% OBC	30% OBC	20% OBC	10% OBC	0% OBC
Area Lights	51.0	47.6	44.2	40.9	37.5	34.2	30.8	27.4	24.1	23.4	23.4
Misc Equipment	42.2	39.5	36.8	34.1	31.5	28.8	26.1	23.4	20.7	20.7	20.7
Space Heat	1.1	1.2	1.3	1.5	1.7	1.9	2.4	2.9	3.6	3.7	3.7
Space Cool	27.2	25.6	24.0	22.3	20.7	19.0	17.3	15.5	13.8	13.2	12.7
Heat Rejection	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Pump & Misc	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Vent Fans	14.0	13.4	12.8	12.2	11.6	11.0	10.3	9.7	9.1	8.9	8.8
Total	135.6	127.4	119.2	111.1	103.0	94.9	87.0	79.1	71.3	70.0	69.4

* Schedules for 100% OBC to 0% OBC (no occupancy) controls applied only for weekday based on the schedules in Figure 14 to Figure 20.
** Weekend and holiday calculations used the same schedules with Standard 90.1-2016 schedules.
*** Set-back controls used for heating and cooling systems in unoccupied hours

Table 30. Houston, Single-Zone PVAV Model: Annual Energy Use from OBC

	Houston 1Zone, PSZ System										
(Unit: MMBtu)	100% OBC	90% OBC	80% OBC	70% OBC	60% OBC	50% OBC	40% OBC	30% OBC	20% OBC	10% OBC	0% OBC
Area Lights	51.0	47.6	44.2	40.9	37.5	34.1	30.8	27.4	24.0	23.4	23.4
Misc Equipment	42.2	39.5	36.8	34.1	31.4	28.8	26.1	23.4	20.7	20.7	20.7
Space Heat	0.5	0.5	0.5	0.5	0.5	0.4	0.4	0.4	0.4	0.4	0.4
Space Cool	27.3	25.9	24.5	23.1	21.8	20.5	19.3	18.2	17.1	16.8	16.5
Heat Rejection	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Pump & Misc	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Vent Fans	7.8	7.3	6.9	6.4	5.9	5.5	5.1	4.7	4.3	4.2	4.1
Total	128.8	120.9	112.9	105.0	97.2	89.4	81.8	74.2	66.7	65.6	65.3

* Schedules for 100% OBC to 0% OBC (no occupancy) controls applied only for weekday based on the schedules in Figure 14 to Figure 20.

** Weekend and holiday calculations used the same schedules with Standard 90.1-2016 schedules.

*** Set-back controls used for heating and cooling systems in unoccupied hours

Table 31. Houston, 5-Zone PVAV Model: Annual Energy Use from OBC

	Houston 1Zone, PSZ System										
(Unit: MMBtu)	100% OBC	90% OBC	80% OBC	70% OBC	60% OBC	50% OBC	40% OBC	30% OBC	20% OBC	10% OBC	0% OBC
Area Lights	51.0	47.6	44.2	40.9	37.5	34.2	30.8	27.4	24.1	23.4	23.4
Misc Equipment	42.2	39.5	36.8	34.1	31.5	28.8	26.1	23.4	20.7	20.7	20.7
Space Heat	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Space Cool	28.8	27.3	26.0	24.6	23.4	22.2	21.1	20.1	19.1	18.8	18.5
Heat Rejection	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Pump & Misc	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.2	0.2	0.2	0.2
Vent Fans	8.4	8.0	7.5	7.0	6.6	6.2	5.8	5.5	5.1	5.0	4.9
Total	130.6	122.7	114.8	107.0	99.3	91.7	84.2	76.7	69.4	68.3	67.9

* Schedules for 100% OBC to 0% OBC (no occupancy) controls applied only for weekday based on the schedules in Figure 14 to Figure 20.

** Weekend and holiday calculations used the same schedules with Standard 90.1-2016 schedules.

*** Set-back controls used for heating and cooling systems in unoccupied hours

Table 32. Chicago, Single-Zone PSZ Model: Annual Energy Use from OBC

	Houston 1Zone, PSZ System										
(Unit: MMBtu)	100% OBC	90% OBC	80% OBC	70% OBC	60% OBC	50% OBC	40% OBC	30% OBC	20% OBC	10% OBC	0% OBC
Area Lights	51.0	47.6	44.2	40.9	37.5	34.1	30.8	27.4	24.0	23.4	23.4
Misc Equipment	42.2	39.5	36.8	34.1	31.4	28.8	26.1	23.4	20.7	20.7	20.7
Space Heat	7.3	8.0	8.7	9.4	10.2	11.0	12.0	13.2	14.8	15.4	15.9
Space Cool	10.7	10.0	9.3	8.6	8.0	7.3	6.7	6.0	5.3	5.1	4.9
Heat Rejection	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Pump & Misc	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
Vent Fans	9.7	9.2	8.7	8.2	7.6	7.1	6.6	6.0	5.5	5.4	5.2
Total	121.3	114.7	108.2	101.6	95.1	88.7	82.5	76.5	70.8	70.4	70.6

* Schedules for 100% OBC to 0% OBC (no occupancy) controls applied only for weekday based on the schedules in Figure 14 to Figure 20.
** Weekend and holiday calculations used the same schedules with Standard 90.1-2016 schedules.
*** Set-back controls used for heating and cooling systems in unoccupied hours

Table 33. Chicago, 5-Zone PSZ Model: Annual Energy Use from OBC

	Houston 1Zone, PSZ System										
(Unit: MMBtu)	100% OBC	90% OBC	80% OBC	70% OBC	60% OBC	50% OBC	40% OBC	30% OBC	20% OBC	10% OBC	0% OBC
Area Lights	51.0	47.6	44.2	40.9	37.5	34.2	30.8	27.4	24.1	23.4	23.4
Misc Equipment	42.2	39.5	36.8	34.1	31.5	28.8	26.1	23.4	20.7	20.7	20.7
Space Heat	6.9	8.1	9.4	11.1	13.0	15.2	17.1	17.8	17.3	17.2	17.4
Space Cool	12.1	11.3	10.6	9.8	9.0	8.1	7.3	6.5	5.5	5.1	4.8
Heat Rejection	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Pump & Misc	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.4	0.4	0.4
Vent Fans	13.0	12.5	11.9	11.4	10.8	10.3	9.7	9.2	8.6	8.5	8.4
Total	125.7	119.5	113.5	107.8	102.3	97.1	91.5	84.8	76.7	75.3	75.1

* Schedules for 100% OBC to 0% OBC (no occupancy) controls applied only for weekday based on the schedules in Figure 14 to Figure 20.
** Weekend and holiday calculations used the same schedules with Standard 90.1-2016 schedules.
*** Set-back controls used for heating and cooling systems in unoccupied hours

Table 34. Chicago, Single-Zone PVAV Model: Annual Energy Use from OBC

(Unit: MMBtu)	Houston 1Zone, PSZ System										
	100% OBC	90% OBC	80% OBC	70% OBC	60% OBC	50% OBC	40% OBC	30% OBC	20% OBC	10% OBC	0% OBC
Area Lights	51.0	47.6	44.2	40.9	37.5	34.1	30.8	27.4	24.0	23.4	23.4
Misc Equipment	42.2	39.5	36.8	34.1	31.4	28.8	26.1	23.4	20.7	20.7	20.7
Space Heat	7.6	7.5	7.4	7.3	7.3	7.2	7.1	7.0	6.9	6.8	6.8
Space Cool	12.7	11.9	11.2	10.4	9.7	8.9	8.3	7.6	7.1	6.9	6.8
Heat Rejection	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Pump & Misc	0.5	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.7	0.7	0.7
Vent Fans	6.7	6.3	5.9	5.5	5.1	4.8	4.4	4.1	3.8	3.7	3.6
Total	120.7	113.4	106.1	98.8	91.6	84.4	77.2	70.2	63.2	62.2	62.0

* Schedules for 100% OBC to 0% OBC (no occupancy) controls applied only for weekday based on the schedules in Figure 14 to Figure 20.
** Weekend and holiday calculations used the same schedules with Standard 90.1-2016 schedules.
*** Set-back controls used for heating and cooling systems in unoccupied hours

Table 35. Chicago, 5-Zone PVAV Model: Annual Energy Use from OBC

(Unit: MMBtu)	Houston 1Zone, PSZ System										
	100% OBC	90% OBC	80% OBC	70% OBC	60% OBC	50% OBC	40% OBC	30% OBC	20% OBC	10% OBC	0% OBC
Area Lights	51.0	47.6	44.2	40.9	37.5	34.2	30.8	27.4	24.1	23.4	23.4
Misc Equipment	42.2	39.5	36.8	34.1	31.5	28.8	26.1	23.4	20.7	20.7	20.7
Space Heat	4.7	4.7	4.7	4.8	4.7	4.7	4.7	4.6	4.6	4.6	4.6
Space Cool	13.8	13.0	12.3	11.6	10.8	10.2	9.6	9.1	8.6	8.5	8.4
Heat Rejection	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Pump & Misc	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.8	0.8	0.8
Vent Fans	7.7	7.4	7.0	6.6	6.3	5.9	5.6	5.3	5.1	5.0	4.9
Total	120.1	112.9	105.8	98.6	91.5	84.5	77.5	70.6	63.9	62.9	62.8

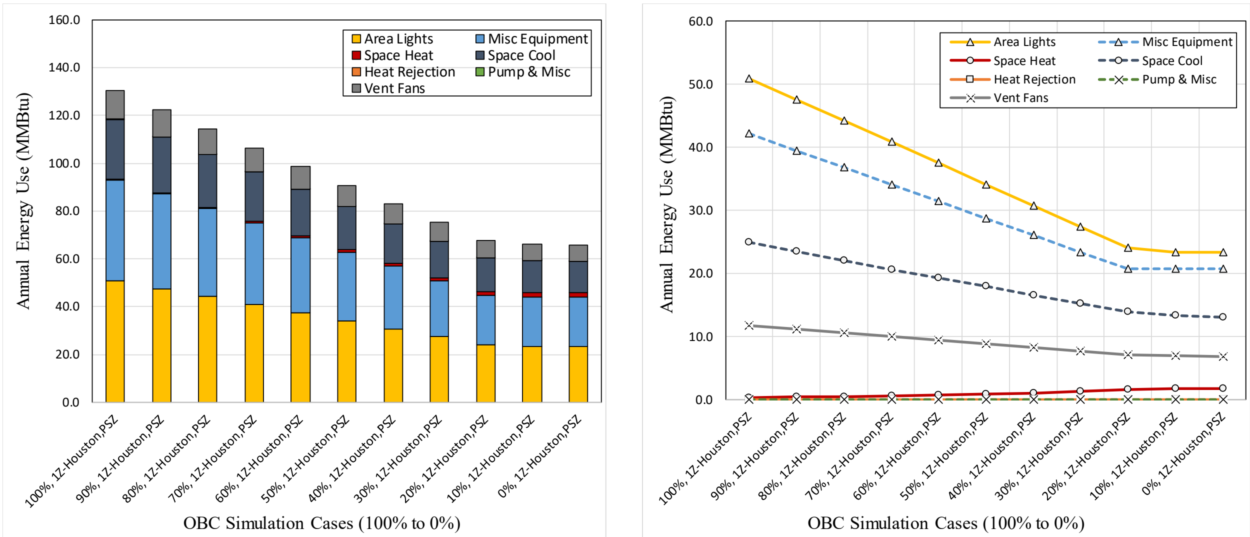
* Schedules for 100% OBC to 0% OBC (no occupancy) controls applied only for weekday based on the schedules in Figure 14 to Figure 20.
** Weekend and holiday calculations used the same schedules with Standard 90.1-2016 schedules.
*** Set-back controls used for heating and cooling systems in unoccupied hours

5.1.3.1. Houston, Packaged Single Zone System, Packaged Single-Zone: 1 Zone vs 5 Zone Models

This study analyzed the discrepancies between single-zone and 5-zone models using the reference small office models in annual total energy use, peak day energy use, and peak day indoor environmental conditions. Lastly, from this chapter, 100% to 0% OBC cases were computed to evaluate the impact of thermal zoning models in energy reduction of occupancy-based controls.

Figure 41 shows the trends of annual energy use and load components in test cases of 100% OBC to 0% OBC in the Houston single-zone PSZ models. Result data is presented in Table 28. 100% OBC consumed 130.2 MMBtu/yr, and 0% OBC consumed 65.8 MMBtu/yr. The potential maximum energy reduction in total building energy use was 64.4 MMBtu/yr, which was calculated as a difference between 100% OBC and 0% OBC results. The tendencies of load components represented a persistent decrease except heating loads that had a gradual increase due to reduced internal heat gain (e.g., occupant, light, equipment).

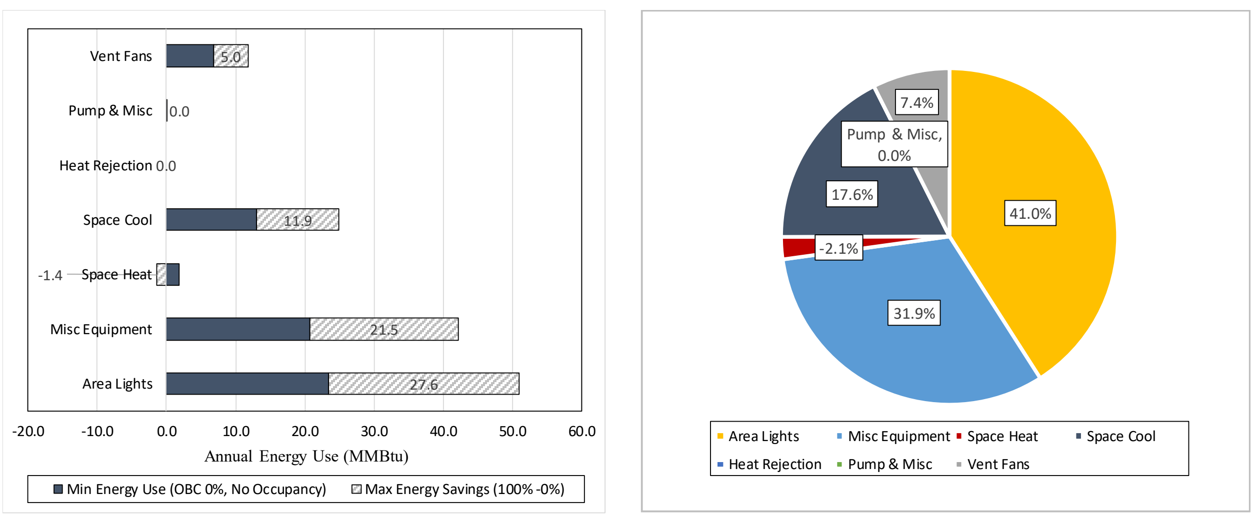
In Figure 42, energy reduction was principally found in lighting and equipment that are the largest energy-consuming components in small office buildings. As for cooling loads, since Houston is hot and humid, the reduction from OBC rate reductions occupied 17.6% of the maximum energy reduction potential. Heating loads showed a slightly negative effect on reducing total energy use due to the loss of internal heat gains from office appliances and people. The energy use reduction of ventilation fans were affected by the demands of the occupancy rate and HVAC operations.



Trends: Total Building Loads

Trends: Load Components

Figure 41. 1 Zone PSZ Model: Annual Energy Use from OBC 100% to 0%, Houston, TX



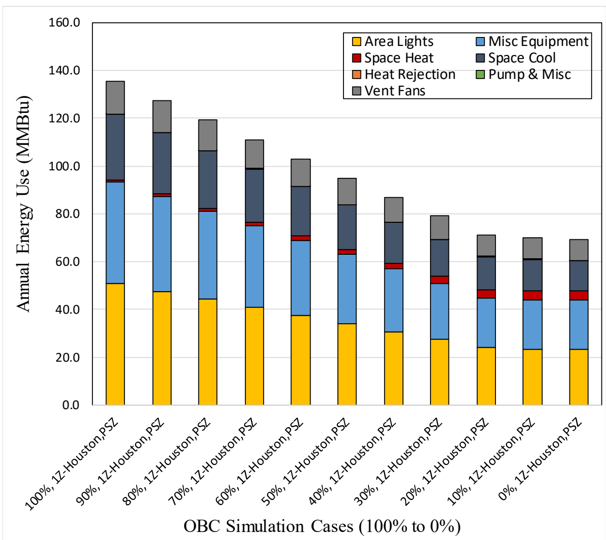
Annual Energy Saving Effect from OBC 100% to 0%

Annual Energy Saving Contribution by Load Component (%)

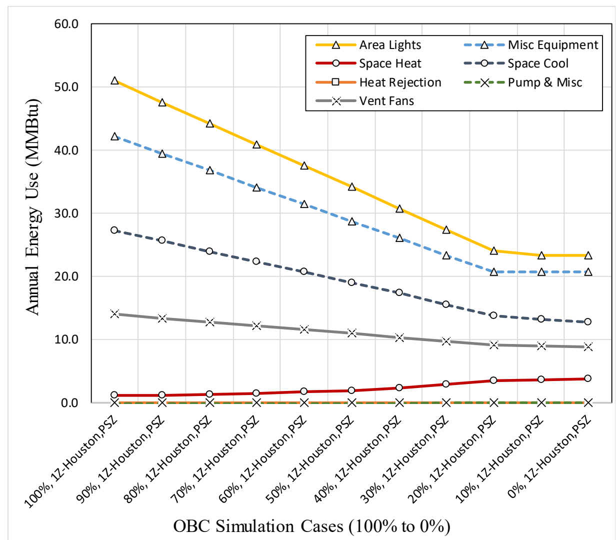
Figure 42. 1 Zone PSZ Model: Energy Reduction Contributions (OBC 100%-0%), Houston, TX

Figure 43 displayed the trends of annual energy use and load components of OBC 100% to 10% test cases in 5-Zone PSZ Models. The tabular result is described in Table 29. 100% OBC consumed 135.6 MMBtu/yr, and 0% OBC consumed 69.4 MMBtu/yr. The maximum energy

Reduction potential in total building energy use was 66.2 MMBtu/yr, which was computed as a difference between 100% OBC and 0% OBC results. The tendencies of load components showed a constant decrease except heating loads that had a gradual increase due to reduced internal heat gain (e.g., occupant, light, equipment).



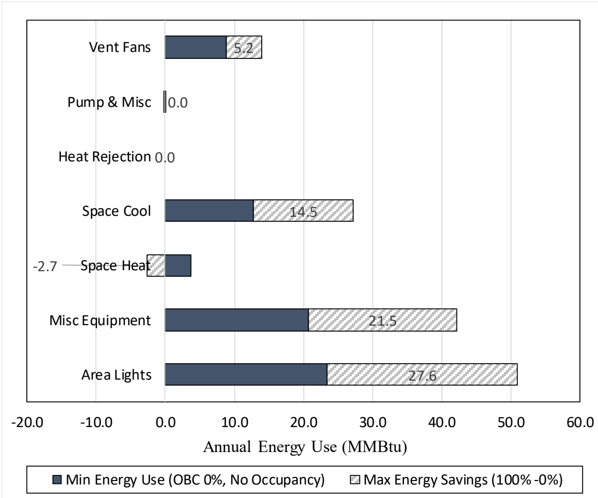
Trends: Total Building Loads



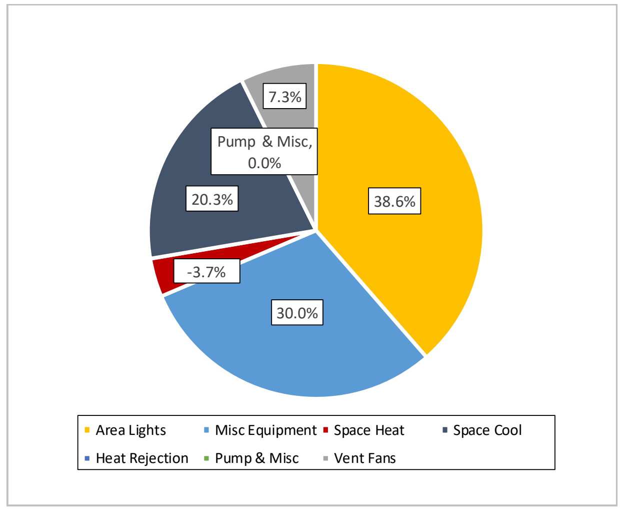
Trends: Load Components

Figure 43. 5 Zone PSZ Model: Annual Energy Use from OBC 100% to 0%, Houston, TX

In Figure 44, energy reduction was mainly from lighting and equipment that used the most considerable energy in small office buildings. As for weather-dependent load components, since Houston is hot and humid, the cooling load reduction from OBC rate changes occupied 20.3% of the maximum energy reduction potential. Heating loads showed a slightly negative effect of -3.7% due to the loss of internal heat gains from people and office appliances. The energy reduction of ventilation fans were influenced by the demands of the occupancy rate and HVAC operations.



Annual Energy Saving Effect from OBC 100% to 0%



Annual Energy Saving Contribution by Load Component (%)

Figure 44. 5 Zone PSZ Model: Energy Reduction Contributions (OBC 100%-0%), Houston, TX

5.1.3.2. Houston, Packaged Variable Air Volume System: 1 Zone vs 5 Zone Models

This chapter evaluated single-zone models and 5-zone models using the reference small office models to compare the impact of thermal zoning models using 100% to 0% OBC rates in energy reduction of OBC.

Figure 45 Figure 41shows the trends of annual energy use and load components in test cases of 100% OBC to 0% OBC in the Houston single-zone PVAV models. The outcome of the simulations is summarized in Table 30. 100% OBC consumed 128.8 MMBtu/yr, and 0% OBC consumed 65.3 MMBtu/yr. The potential maximum energy reduction in total building energy use was 63.2 MMBtu/yr, which was estimated as a difference between 100% OBC and 0% OBC models. The tendencies of load components showed a gradual decrease except heating loads that had a slight increase due to reduced internal heat gain (e.g., occupant, light, equipment).

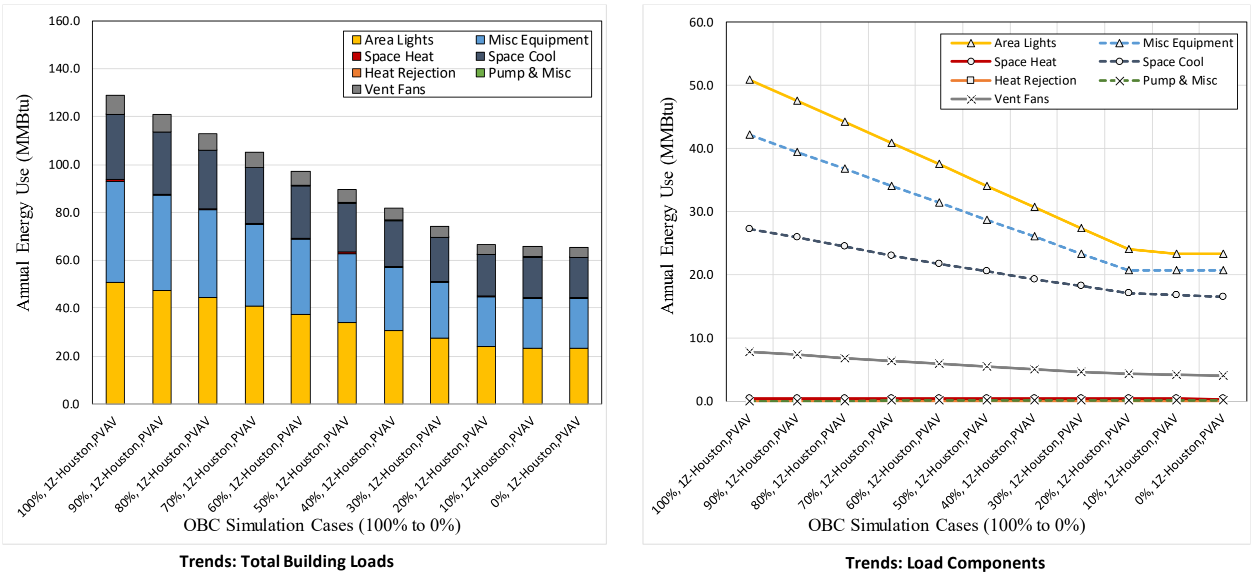


Figure 45. 1 Zone PVAV Model: Annual Energy Use from OBC 100% to 0%, Houston, TX

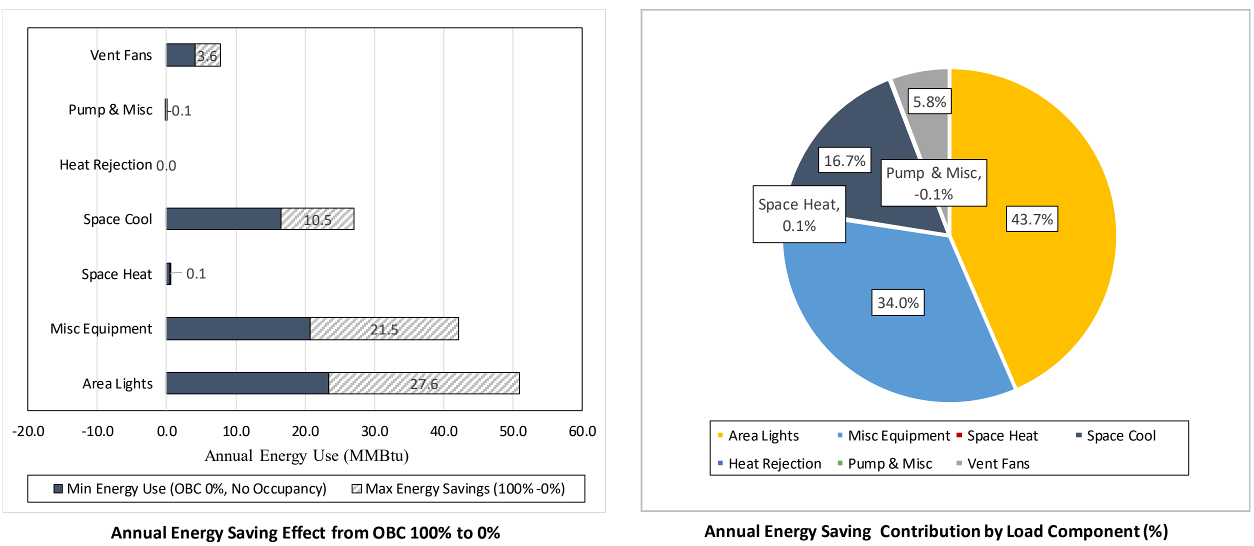
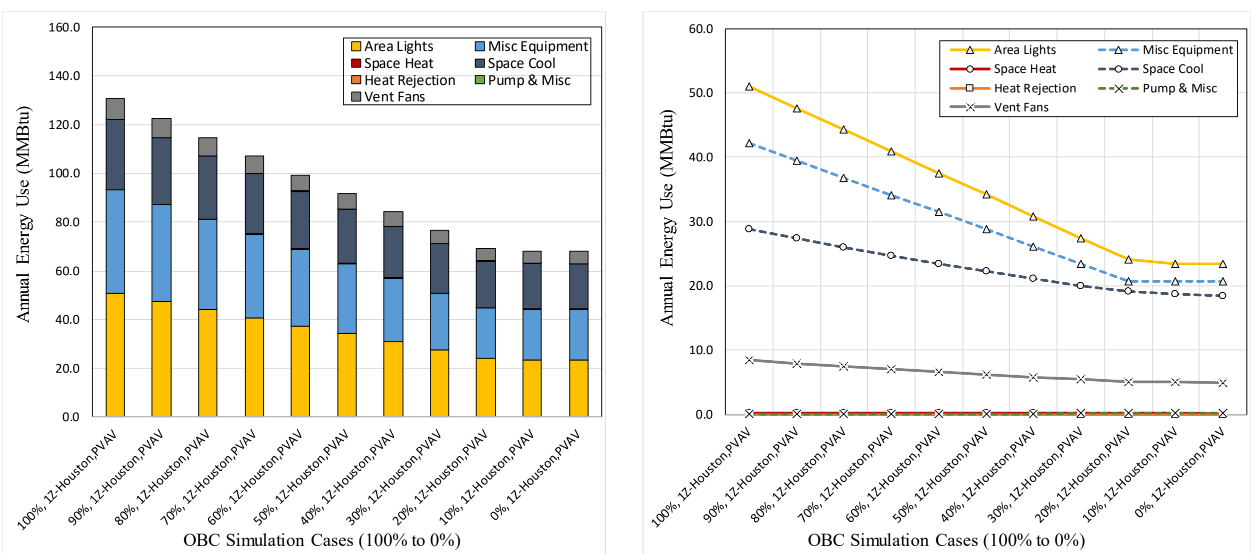


Figure 46. 1 Zone PVAV Model: Energy Reduction Contributions (OBC 100%-0%), Houston, TX

In Figure 46, lighting and equipment are the most significant energy-consuming components in small office buildings, which propelled primary energy reduction. In terms of cooling loads, owing to the hot and humid climate in Houston, the cooling load reduction from

OBC rate reductions also occupied a large reduction that was 16.7% of the maximum energy reduction potential. Heating loads showed a minor effect on reducing total energy use due to the loss of internal heat gains from office appliances and people. The energy reduction of ventilation fans was 5.8% of the total energy reduction in 100% OBC to 0% OBC test cases.

Figure 47 displayed the trends of annual energy use and load components of OBC 100% to 0% test cases in 5-Zone PVAV Models. The tabular result is described in Table 31. 100% OBC consumed 130.6 MMBtu/yr, and 0% OBC consumed 67.9 MBtu/yr. The maximum energy reduction potential in total building energy use was 62.4 MMBtu/yr, which was computed as a difference between 100% OBC and 0% OBC results. The tendencies of load components showed a constant decrease except heating loads that had a gradual increase due to reduced internal heat gain (e.g., occupant, light, equipment).

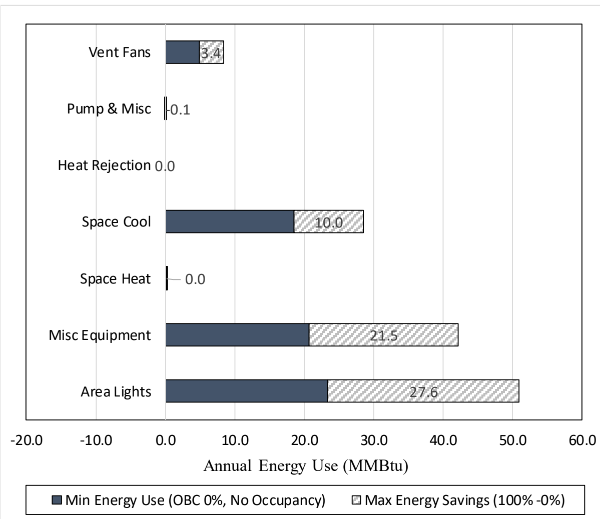


Trends: Total Building Loads

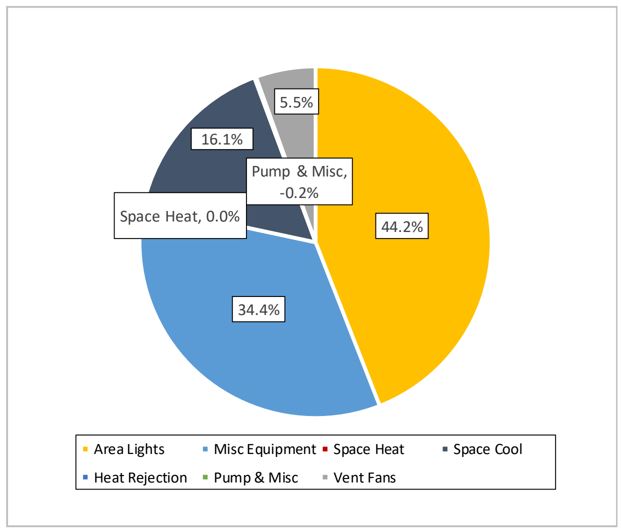
Trends: Load Components

Figure 47. 5 Zone PVAV Model: Annual Energy Use from OBC 100% to 0%, Houston, TX

In Figure 48, most energy reduction came from lighting and equipment that used the most considerable energy in small office buildings. As for weather-dependent load components, since Houston is hot and humid, the cooling load reduction from OBC rate changes occupied 16.1% of the maximum energy reduction potential. The energy reduction of ventilation fans was 5.5% of the total energy reduction in 100% OBC to 0% OBC test cases.



Annual Energy Saving Effect from OBC 100% to 0%



Annual Energy Saving Contribution by Load Component (%)

Figure 48. 5 Zone PVAV Model: Energy Reduction Contributions (OBC 100%-0%), Houston, TX

5.1.3.3. Chicago, Packaged Single Zone System, Packaged Single-Zone: 1 Zone vs 5 Zone Models

Chicago models can reflect energy attributes in cool and humid climate zones in the U.S. Therefore, this chapter performed single-zone models and 5-zone models using the reference small office models to compare the impact of thermal zoning models using 100% to 0% OBC rates in energy reduction of occupancy-based controls.

Figure 49 shows the trends of annual energy use and load components in test cases of 100% OBC to 0% OBC in the Chicago single-zone PSZ models. The outcome of the simulations is summarized in Table 32. 100% OBC consumed 121.3 MMBtu/yr, and 0% OBC consumed 70.6 MMBtu/yr. The potential maximum energy reduction in total building energy use was 51.0 MMBtu/yr, which was estimated as a difference between 100% OBC and 0% OBC models. The tendencies of load components showed a gradual decrease except heating loads that had a slight increase due to reduced internal heat gain (e.g., occupant, light, equipment).

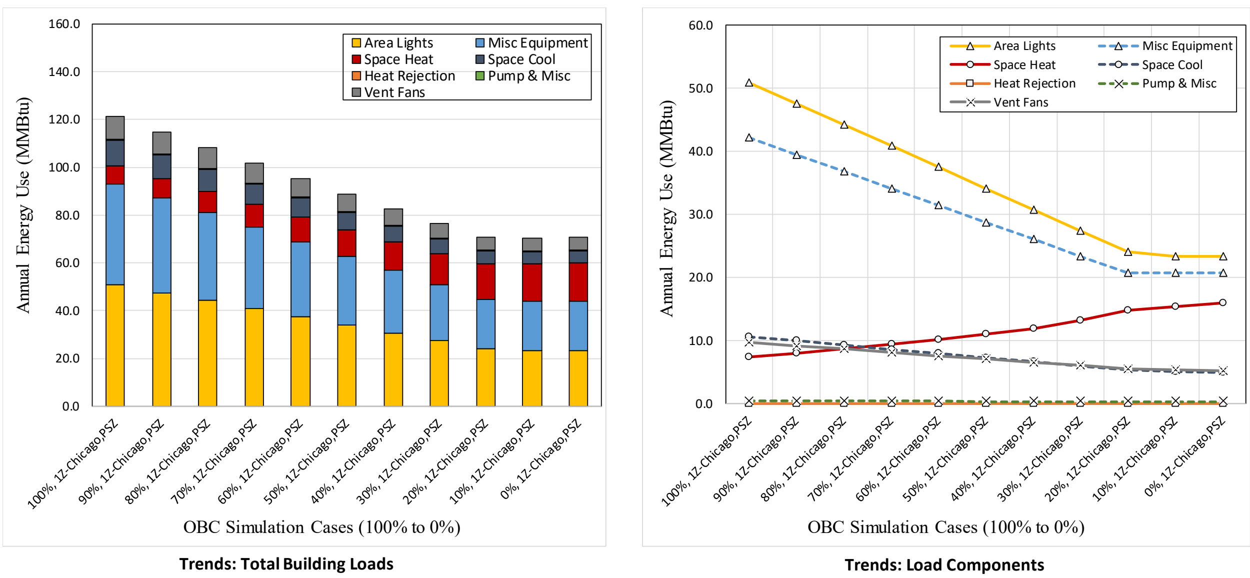
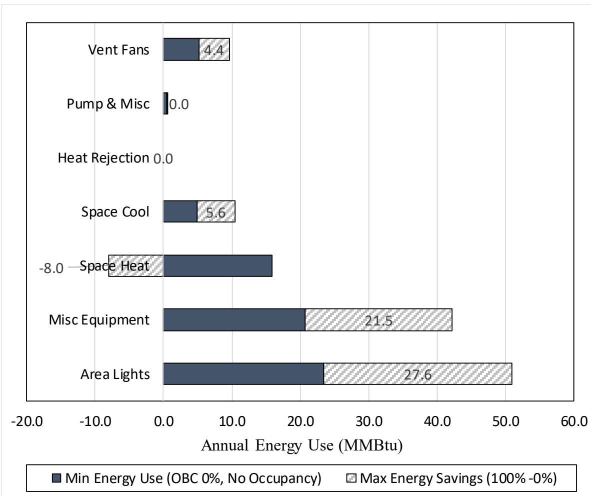
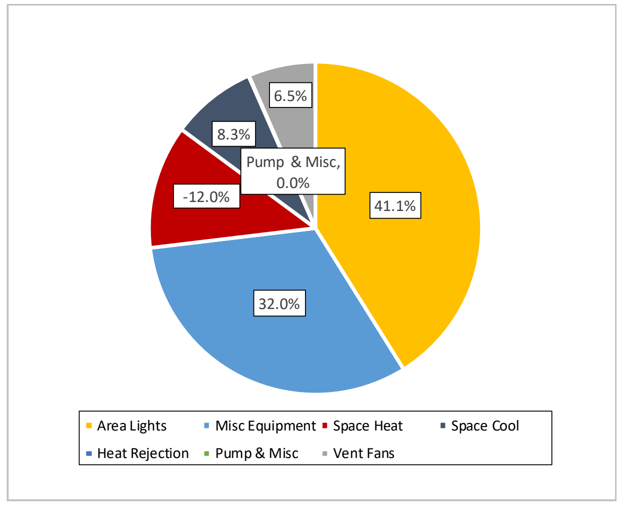


Figure 49. 1 Zone PSZ Model: Annual Energy Use from OBC 100% to 0%, Chicago, IL

In Figure 50, lighting and equipment dominated most energy reduction that are the largest energy-consuming components in small office buildings. As for cooling loads, since Houston is hot and humid, the reduction from OBC rate reductions occupied 8.3% of the maximum energy reduction potential. Heating loads showed a negative effect on total energy use due to the loss of internal heat gains from office appliances and people. The energy reduction of ventilation fans were responsible for 6.5% of the potential total energy reduction.



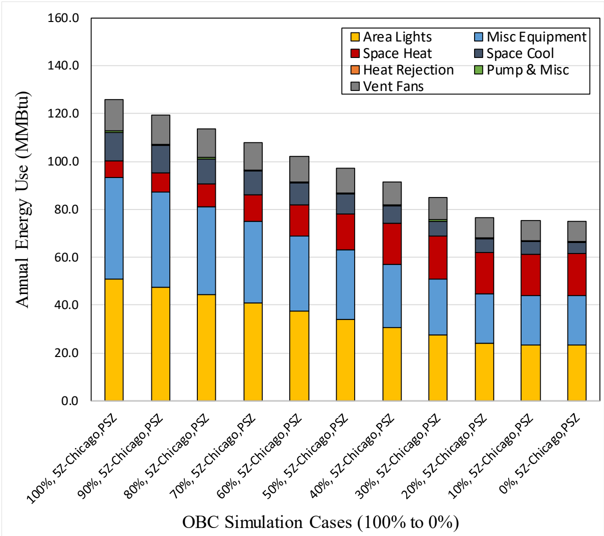
Annual Energy Saving Effect from OBC 100% to 0%



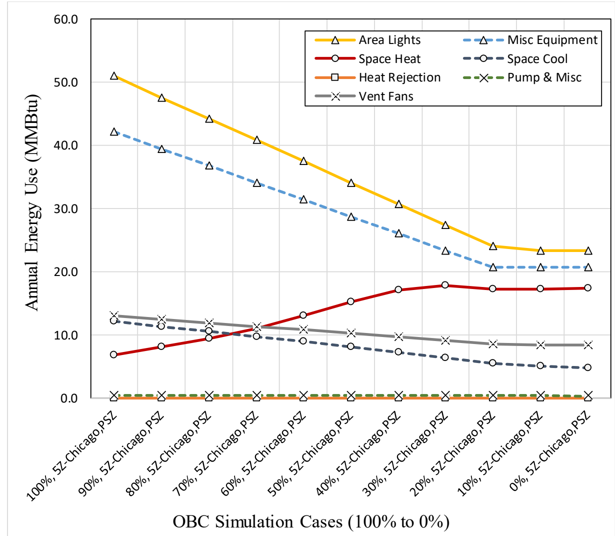
Annual Energy Saving Contribution by Load Component (%)

Figure 50. 1 Zone PSZ Model: Energy Reduction Contributions (OBC 100%-0%), Chicago, IL

Figure 51 showed the trends of annual energy use and load components of OBC 100% to 0% test cases in 5-Zone PSZ Models. The tabular result is arranged in Table 33. 100% OBC consumed 125.7 MMBtu/yr, and 0% OBC consumed 75.1 MMBtu/yr. The maximum energy reduction potential in total building energy use was 50.4 MMBtu/yr, which was computed as a difference between 100% OBC and 0% OBC results. The tendencies of load components showed a constant decrease except heating loads that had a gradual increase due to reduced internal heat gain (e.g., occupant, light, equipment).

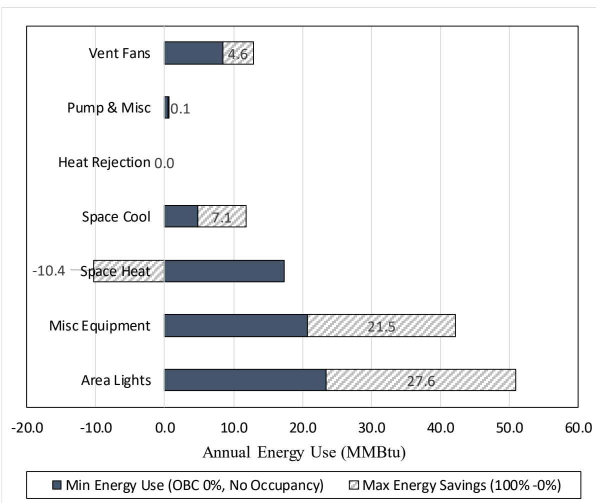


Trends: Total Building Loads

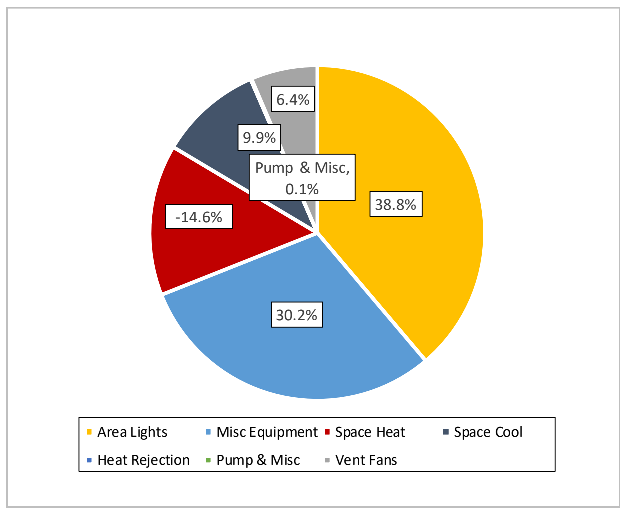


Trends: Load Components

Figure 51. 5 Zone PSZ Model: Annual Energy Use from OBC 100% to 0%, Chicago, IL



Annual Energy Saving Effect from OBC 100% to 0%



Annual Energy Saving Contribution by Load Component (%)

Figure 52. 5 Zone PSZ Model: Annual Energy Use from OBC 100% to 0%, Chicago, IL

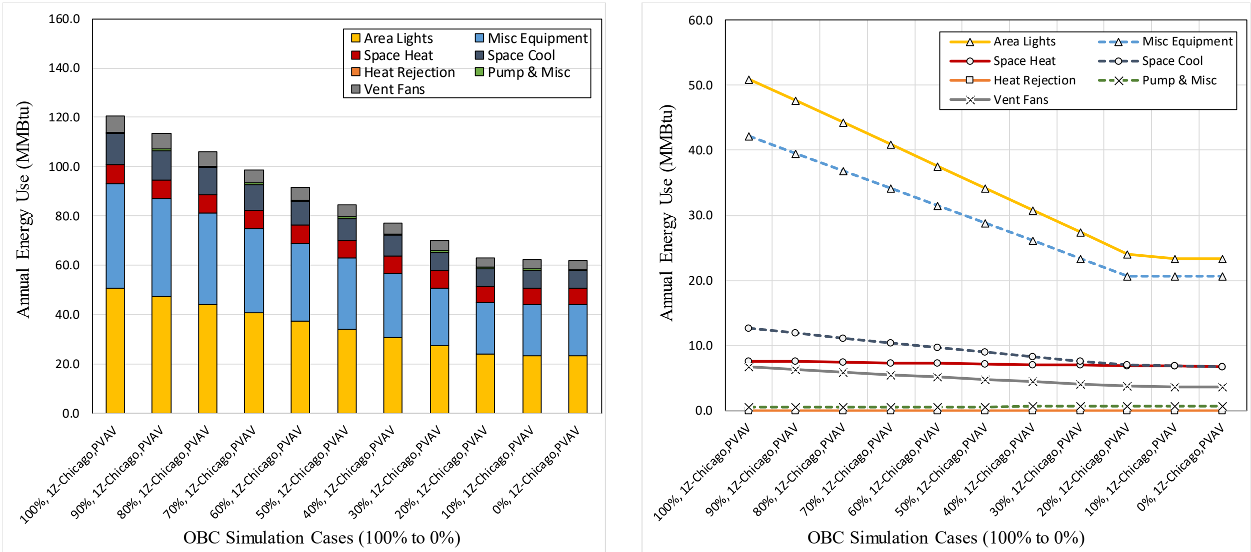
In Figure 52, energy reduction was mainly from lighting and equipment that used the most considerable energy in small office buildings. Also, since Houston is hot and humid, the cooling load reduction from OBC rate changes occupied a large portion that was 9.9% of the maximum energy reduction potential. Heating loads showed a negative effect due to the loss of internal heat gains from people and office appliances. The energy reduction of ventilation fans was 6.4% of the potential total energy reduction in 100% OBC – 0% OBC test cases.

5.1.3.4. Chicago, Packaged Variable Air Volume system: 1 Zone vs 5 Zone Models

This chapter evaluated single-zone models and 5-zone models using the reference small office models to compare the impact of thermal zoning models using 100% to 0% OBC rates in energy reduction of occupancy-based controls.

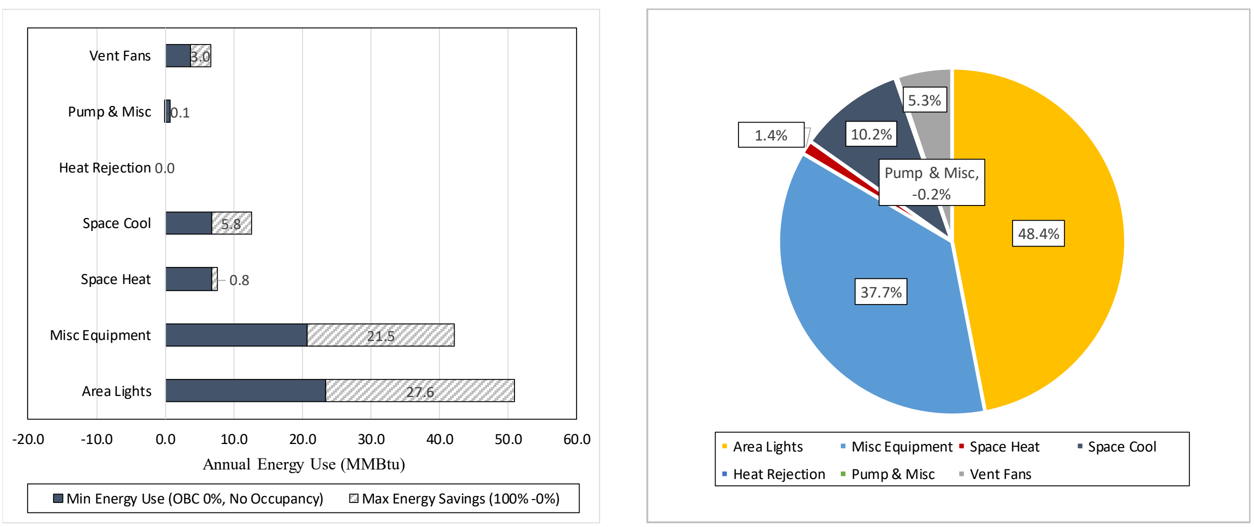
Figure 53 shows the trends of annual energy use and load components in test cases of 100% OBC to 0% OBC in the Houston single-zone PVAV models. The outcome of the simulations is summarized in Table 34. 100% OBC consumed 120.7 MMBtu/yr, and 10% OBC consumed 62.0 MMBtu/yr. The potential maximum energy reduction in total building energy use was 58.5 MMBtu/yr, which was estimated as a difference between 100% OBC and 0% OBC models. The tendencies of load components showed a gradual decrease except heating loads that had a slight increase due to reduced internal heat gain (e.g., occupant, light, equipment).

In Figure 54, lighting and equipment are the most significant energy-consuming components in small office buildings, which propelled primary energy reduction. In terms of cooling loads, owing to the hot and humid climate in Houston, the cooling load reduction from OBC rate reductions also occupied a large reduction that was 10.2% of the maximum energy reduction potential. Heating loads showed a minor reduction effect to reduce total energy use due to the loss of internal heat gains from office appliances and people. The energy reduction of ventilation fans were 5.3% of the total energy reduction in 100% OBC to 0% OBC test cases.



Trends: Total Building Loads | **Trends: Load Components**

Figure 53. 1 Zone PVAV Model: Annual Energy Use from OBC 100% to 0%, Chicago, IL

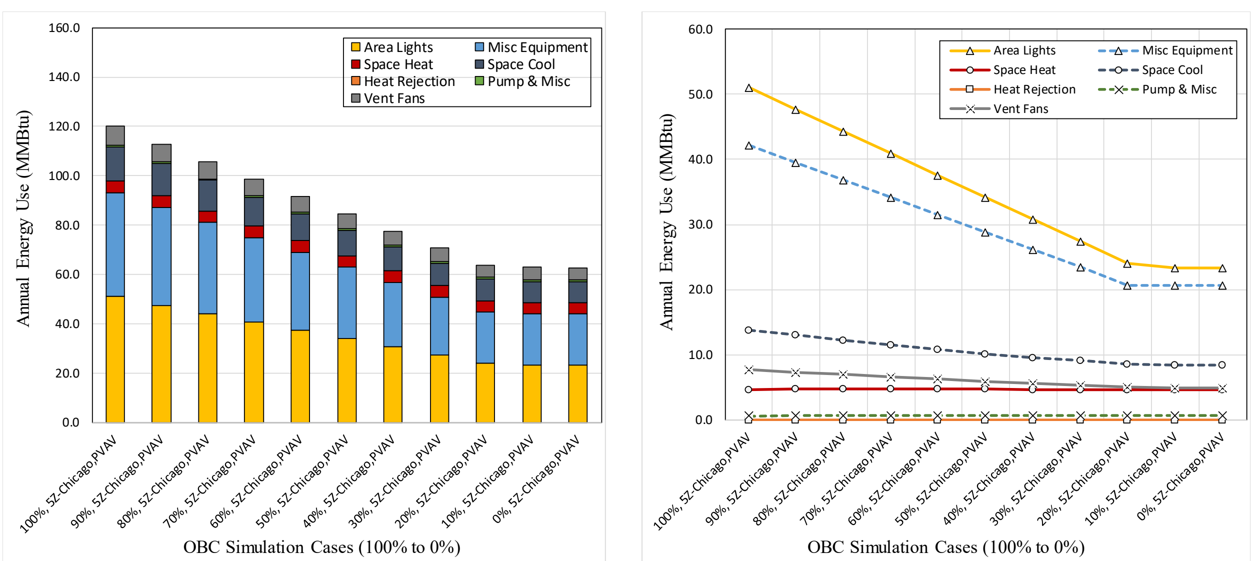


Annual Energy Saving Effect from OBC 100% to 0% | **Annual Energy Saving Contribution by Load Component (%)**

Figure 54. 1 Zone PVAV Model: Annual Energy Use from OBC 100% to 0%, Chicago, IL

Figure 55 showed the trends of annual energy use and load components of OBC 100% to 0% test cases in 5-Zone PSZ Models. The tabular result is arranged in Table 35. 100% OBC consumed 120.1 MMBtu/yr, and 0% OBC consumed 62.8 MMBtu/yr. The maximum energy reduction potential in total building energy use was 57.1 MMBtu/yr, which was computed as a difference between 100% OBC and 0% OBC results. The tendencies of load components showed a constant decrease except heating loads that had a gradual increase due to reduced internal heat gain (e.g., occupant, light, equipment).

In Figure 56, energy reduction were mainly from lighting and equipment that used the most substantial energy in small office buildings. Also, since Houston is hot and humid, the cooling load reduction from OBC rate changes occupied a large portion that was 9.4% of the maximum energy reduction potential. Heating loads showed a minor effect due to the loss of internal heat gains from people and office appliances. The energy reduction of ventilation fans were 4.9% of the potential total energy reduction in 100% OBC – 0% OBC test cases.



Trends: Total Building Loads

Trends: Load Components

Figure 55. 5 Zone PVAV Model: Annual Energy Use from OBC 100% to 0%, Chicago, IL

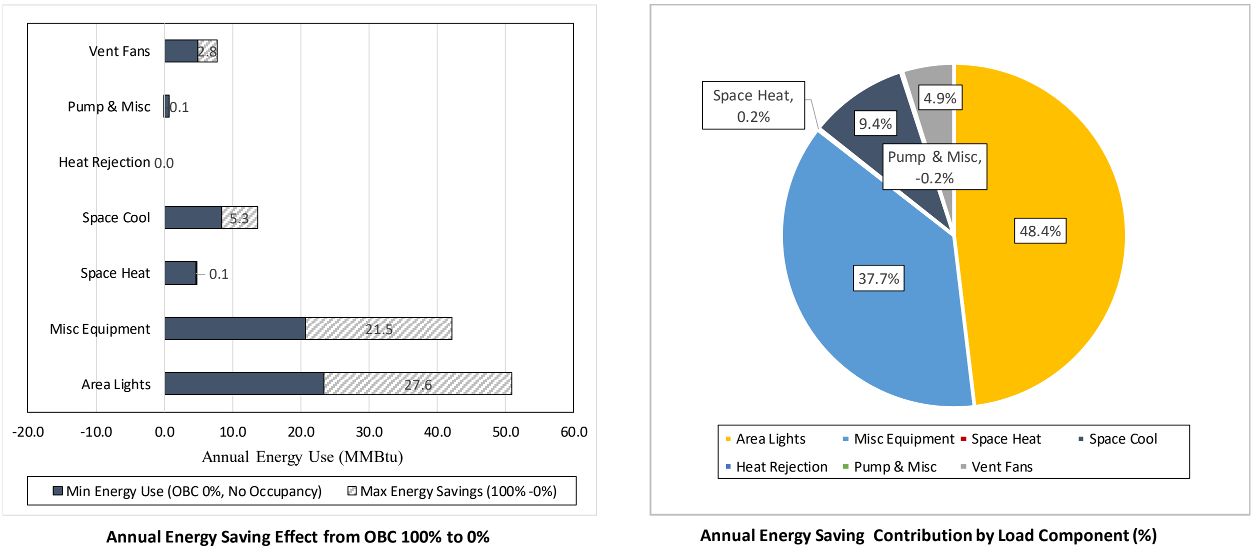


Figure 56. 5 Zone PVAV Model: Annual Energy Use from OBC 100% to 0%, Chicago, IL

5.1.3.5. Summary

This chapter discussed the energy use sensitivity of different thermal zoning models using the reference small office models in occupancy-based controls. In energy calculations, the thermal zoning model is related to numerous parameters that affect building energy performance and consumption. Therefore, different thermal zoning models would bring about a misunderstanding of heat transfer and gain in particular spaces as well as different results from the same building simulations. For example, a single-zone model would mix heat gain from the south-side or west-side in a building because the DOE-2.1e program uses average temperature in thermal zones. Such a fact moderates daily indoor air temperature changes over time than the 5-zone model because the single-zone model cannot distinguish indoor air temperatures in different perimeter zones or different space types. Therefore, the sensitivity tests in this chapter quantified the impact in energy use between the single-zone model and the 5-zone model in Houston and Chicago.

Table 36. Maximum Energy Use Reduction on Building Total Loads by Thermal Zoning Models, Systems, and Climate Zones

(MMBtu)	1Z,Houston PSZ	5Z,Houston PSZ	1Z,Houston PVAV	5Z,Houston PVAV	1Z,Chicago PSZ	5Z,Chicago PSZ	1Z,Chicago PVAV	5Z,Chicago PVAV
Lights	27.6	27.6	27.6	27.6	27.6	27.6	27.6	27.6
Equipment	21.5	21.5	21.5	21.5	21.5	21.5	21.5	21.5
Space Heat	-1.4	-2.7	0.1	0.0	-8.0	-10.4	0.8	0.1
Space Cool	11.9	14.5	10.5	10.0	5.6	7.1	5.8	5.3
Pump & Misc	0.0	0.0	-0.1	-0.1	0.0	0.1	-0.1	-0.1
Vent Fans	5.0	5.2	3.6	3.4	4.4	4.6	3.0	2.8
Total	64.4	66.2	63.2	62.4	51.0	50.4	58.5	57.1

* Maximum energy reduction = differences between 100% OBC energy use – 0% OBC energy use

Table 37. Maximum Energy Use Reduction Percentages on Building Total Loads by Thermal Zoning Models, Systems, and Climate Zones

(%)	1Z,Houston PSZ	5Z,Houston PSZ	1Z,Houston PVAV	5Z,Houston PVAV	1Z,Chicago PSZ	5Z,Chicago PSZ	1Z,Chicago PVAV	5Z,Chicago PVAV
Lights	41.0%	38.6%	43.7%	44.2%	41.1%	38.8%	48.4%	48.4%
Equipment	31.9%	30.0%	34.0%	34.4%	32.0%	30.2%	37.7%	37.7%
Space Heat	-2.1%	-3.7%	0.1%	0.0%	-12.0%	-14.6%	1.4%	0.2%
Space Cool	17.6%	20.3%	16.7%	16.1%	8.3%	9.9%	10.2%	9.4%
Pump & Misc	0.0%	0.0%	-0.1%	-0.2%	0.0%	0.1%	-0.2%	-0.2%
Vent Fans	7.4%	7.3%	5.8%	5.5%	6.5%	6.4%	5.3%	4.9%

* Maximum energy reduction percentages = (100% OBC energy use – 0% OBC energy use)/ 100% OBC energy use

Table 36 and Table 37 compare maximum energy reduction and percentages from 100% OBC – 0% OBC between single-zone and 5-zone models. The maximum energy reduction from 100% OBC to 0% OBC in Houston were 64.4 MMBtu/yr in single-zone PSZ and 66.2 MMBtu/yr in 5-zone PSZ. For PVAV systems in Houston, single-zone mode saved 63.2 MMBtu/yr, and 5-zone model reduced 62.4 MMBtu/yr. In Chicago, single-zone PSZ less used 51.0 MMBtu/yr, and 5-zone PSZ was 50.4 MMBtu/yr. For PVAV systems, single-zone PVAV reduced 58.5 MMBtu/yr, and 5-zone PVAV eliminated 57.1 MMBtu/yr. In terms of load components, differences of 100% OBC to 0% OBC showed -3.7% to 44.2% changes in Houston and -14.6% to 48.4% changes in Chicago.

The findings of load component trends from the 100% OBC – 0% OBC sensitivity test are summarized below:

- No major difference were found in lighting and equipment energy reduction between single-zone and 5-zone models in Houston and Chicago: lighting and equipment are weather-independent load components and thus used based on the simulation schedules only
- In Houston and Chicago, single-zone PSZ systems underestimated heating loads more than 5-zone PSZ systems, while single-zone PVAV systems overestimated heating loads versus the 5-zone PVAV systems
- For cooling loads, single-zone PSZ and PVAV models in Houston and Chicago mostly underestimated reduction versus the 5-zone PSZ and PVAV models
- For ventilation fans, all cases in the single-zone PSZ and PVAV models underestimated energy use than 5-zone PSZ and PVAV models.
- Most comparison cases between single-zone models and 5-zone models showed underestimations in single-zone models. PVAV systems in Chicago showed similar result patterns between single-zone models and 5-zone models.

In conclusion, the single-zone model shows slightly different results in heating, cooling, and ventilation fan loads of occupancy-based control analysis. 5-zone model showed more sensitivity to the response of occupancy-related parameters and controls.

5.2. Impact of Different Occupancy-Based Controls

This chapter investigated the impact of occupancy-based controls in Houston and Chicago. The impact in building loads was interpreted in different load levels (i.e., total loads, load components) as well as different building design (i.e., reference, raised floor lightweight and heavyweight materials, WWR 10%-40%) and systems (i.e., PSZ, PVAV). Also, the impact of occupancy-based controls would be distinguished depending on thermal zones due to different orientations and space usage profiles. Therefore, the estimations were computed using simulation cases to predict energy reduction in U.S. commercial office buildings.

5.2.1. Sensitivity Analysis of Occupancy-Based Controls in Total Building

In buildings, there are complicated and heterogeneous interactions between energy variables, which determines total building energy use patterns. However, each energy variable has a different impact on energy usage. Therefore, this chapter performed a sensitivity analysis of occupancy-related schedule parameters (i.e., occupancy, lighting, and equipment) using the reference small office models. The amount of ventilation is connected to the occupancy density in offices because the outdoor air intake is determined based on OA-CFM/PER= 17 in DOE-2.1e. Table 38 represents the cases of sensitivity analysis in Houston (CZ 2A) and Chicago (CZ 5A). In simulations, only selected schedules were adjusted from 100% to 0% to estimate sensitivity in energy use of occupancy-based controls with 10% rate intervals, and other schedules were controlled at a 100% rate.

Table 38. Sensitivity Analysis Table for Small Office Buildings

Group	Location	Zoning Model	System Type	Schedule Type (Weekdays, 9AM-5PM)							Average WWR
				Occupancy	Light	Equip	Infiltration	Vent Fan	Set-temp	Set-back	
1	Houston	Five zones	PSZ	1.0-0.0	1.0	1.0	Off	1.0	H: 70ºF C: 75ºF	H: 60ºF C: 85ºF	21% (default)
2	Houston	Five zones	PSZ	1.0	1.0-0.0	1.0	Off	1.0	H: 70ºF C: 75ºF	H: 60ºF C: 85ºF	21% (default)
3	Houston	Five zones	PSZ	1.0	1.0	1.0-0.0	Off	1.0	H: 70ºF C: 75ºF	H: 60ºF C: 85ºF	21% (default)
4	Houston	Five zones	PVAV	1.0-0.0	1.0	1.0	Off	1.0	H: 70ºF C: 75ºF	H: 60ºF C: 85ºF	21% (default)
5	Houston	Five zones	PVAV	1.0	1.0-0.0	1.0	Off	1.0	H: 70ºF C: 75ºF	H: 60ºF C: 85ºF	21% (default)
6	Houston	Five zones	PVAV	1.0	1.0	1.0-0.0	Off	1.0	H: 70ºF C: 75ºF	H: 60ºF C: 85ºF	21% (default)
7	Chicago	Five zones	PSZ	1.0-0.0	1.0	1.0	Off	1.0	H: 70ºF C: 75ºF	H: 60ºF C: 85ºF	21% (default)
8	Chicago	Five zones	PSZ	1.0	1.0-0.0	1.0	Off	1.0	H: 70ºF C: 75ºF	H: 60ºF C: 85ºF	21% (default)
9	Chicago	Five zones	PSZ	1.0	1.0	1.0-0.0	Off	1.0	H: 70ºF C: 75ºF	H: 60ºF C: 85ºF	21% (default)
10	Chicago	Five zones	PVAV	1.0-0.0	1.0	1.0	Off	1.0	H: 70ºF C: 75ºF	H: 60ºF C: 85ºF	21% (default)
11	Chicago	Five zones	PVAV	1.0	1.0-0.0	1.0	Off	1.0	H: 70ºF C: 75ºF	H: 60ºF C: 85ºF	21% (default)
12	Chicago	Five zones	PVAV	1.0	1.0	1.0-0.0	Off	1.0	H: 70ºF C: 75ºF	H: 60ºF C: 85ºF	21% (default)

* 6PM-8AM in weekdays uses minimum operating conditions of simulation schedules and set-temperatures

** Weekend schedules set to minimum operating conditions of simulation schedules (e.g., occupancy=0.0, 0%; lighting=0.18, 18%; equipment=0.20, 20%;; infiltration=off; ventilation fan=0.0; set-point temperature: heating 60ºF, cooling 85ºF).

*** Window-to-wall (WWR) ratio in small office models is 21% on average. Window fraction is 24.4% for South and 19.8% for the other three orientations (e.g., east, west, north).

5.2.1.1. The sensitivity of Occupancy-Based Control Parameters in Houston

The hot and humid climate characteristics in Houston require more cooling and less heating than the Chicago region, which is weather-dependent loads in office buildings. Weather conditions do not influence on interior lighting and equipment loads. Those energy uses are determined by usage schedules if lighting systems do not use daylighting to reduce artificial lighting in office buildings. Figure 57 shows the sensitivity analysis in total building energy use from the BEPS report in DOE-2.1e due to the changes in occupancy-related schedule parameters. The result of the sensitivity test revealed that the lighting schedule has the largest impacts on energy consumption, with the equipment schedule followed after that. The occupancy schedule had the smallest impact of the three schedule types, which influenced the use of heating, cooling, and ventilation. Figure 58 represents the energy sensitivity in load components. The energy reduction of lighting and equipment schedules were primarily from the reduction of lighting and equipment loads. Also, the decrease of internal heat gains from lighting and equipment led to energy reduction in cooling and ventilation loads and increased heating energy loads. The changes (100%-0%) in the occupancy schedules did not affect lighting and equipment loads. It lowered cooling and ventilation loads and augmented heating loads due to reduced internal heat gains in winter. The energy consumption patterns of sensitivity analysis were identical regardless of the system types (i.e., PSZ, PVAV). Figure 59 depicts normalized potential energy use reduction (EUI) sensitivity due to the controls of simulation schedules. In both the PSZ and PVAV systems, energy use reduction rates from lighting and equipment schedules were about the same, which is not related to HVAC system types and weather conditions in energy use. In all cases of (c), space heating showed a negative effect.

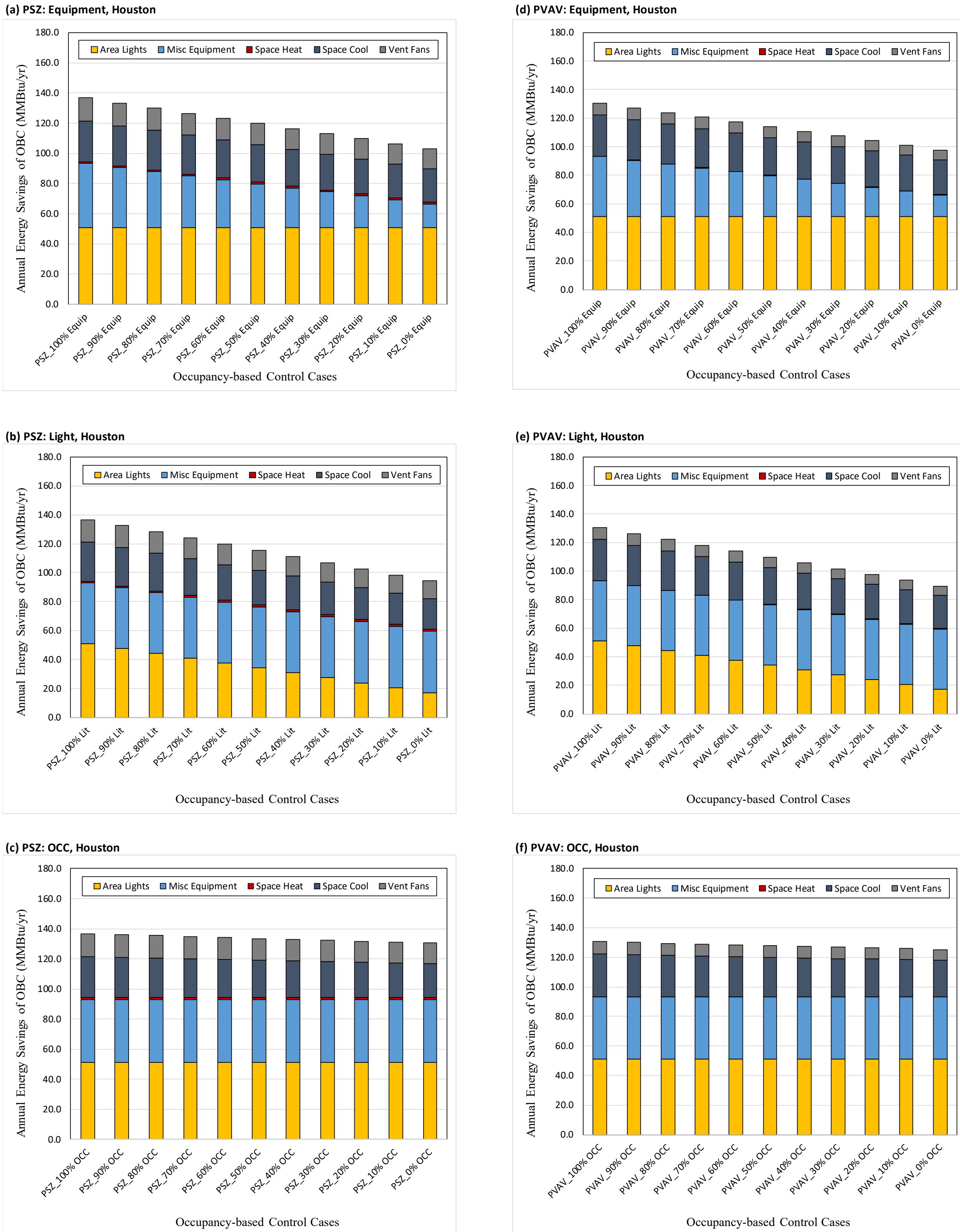


Figure 57. Houston: Sensitivity in Total Energy Use of OBC schedule controls

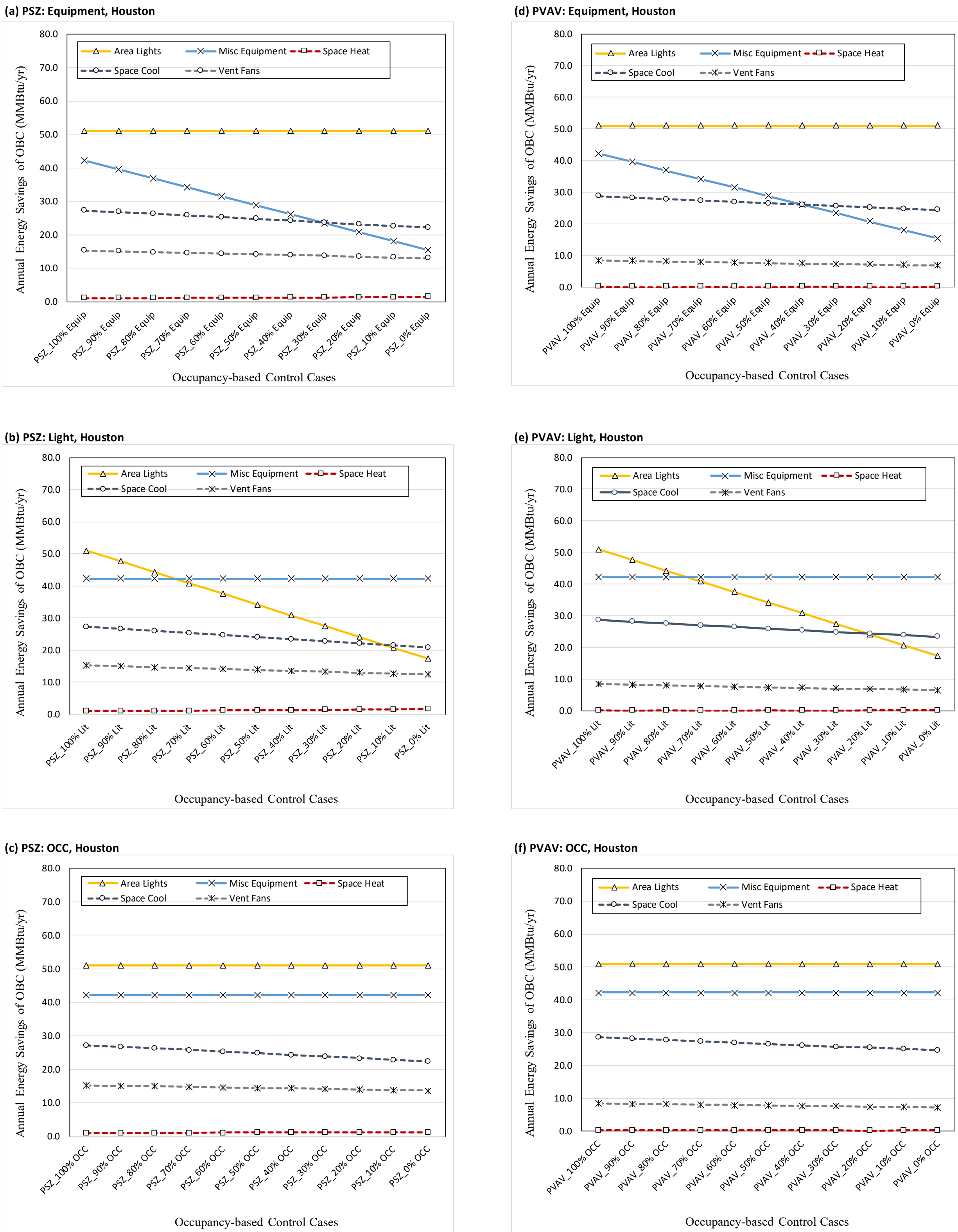


Figure 58. Houston: Sensitivity in Load Components of OBC schedule controls

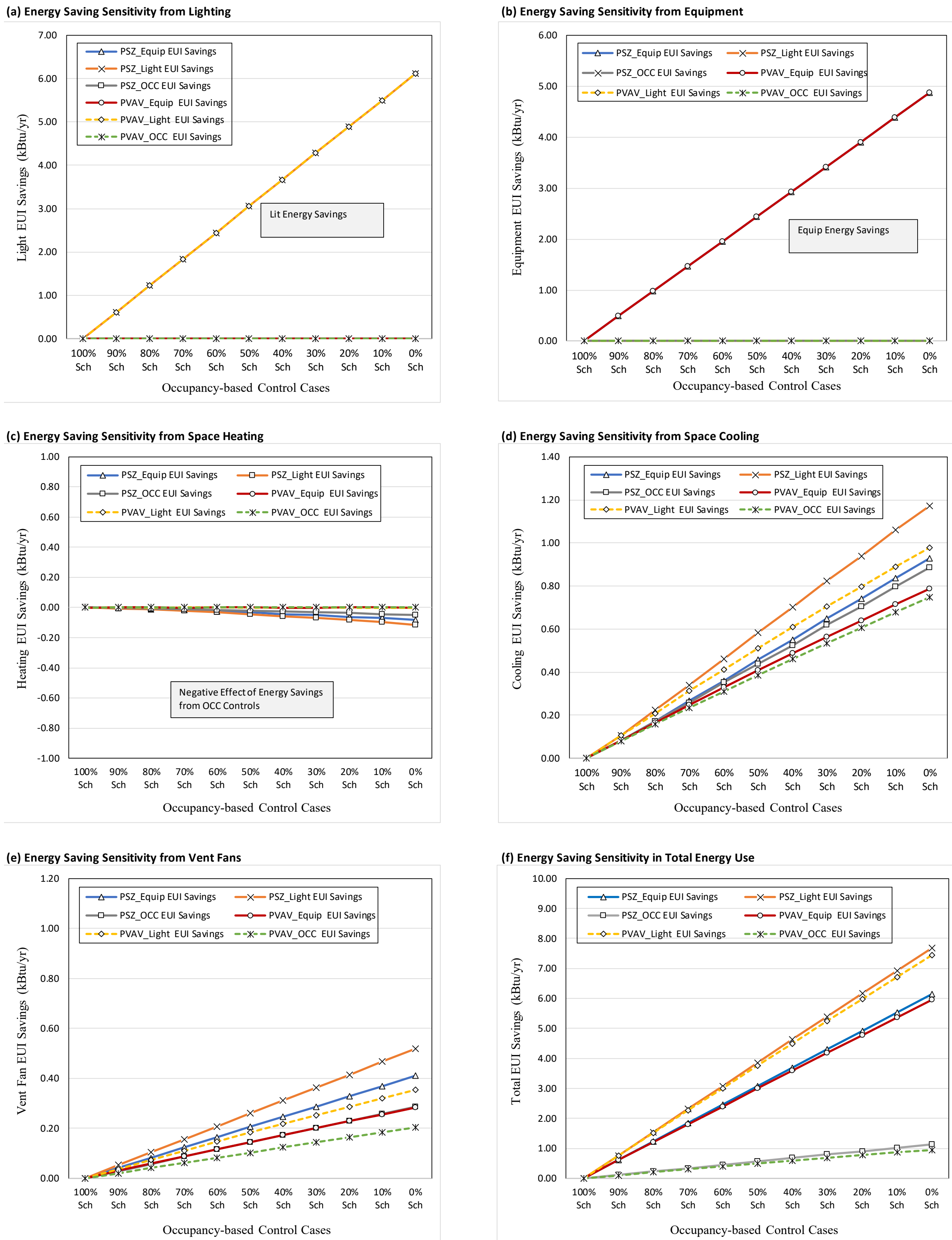


Figure 59. Houston: Sensitivity in EUI Energy Use Reduction of OBC schedule controls

In cooling loads, the lighting had the most significant potential in cooling energy reduction. Following this, equipment had the second most impact, and the occupancy rate showed the least impact on cooling energy use. The simple reduction of the cooling loads of occupancy-based controls is larger in PSZ systems than PVAV systems. Figure 59 (e) showed a proportional increase in energy use reduction impact due to occupancy-related schedule controls. The lighting and equipment also affected the ventilation fan operation because of the decrease in internal gains, which reduced cooling demands in building spaces. Lastly, Figure 59 (f) summarizes energy use reduction sensitivity in total building EUI. This result shows that the same schedules in different HVAC systems about produced the same energy use reduction patterns. The lighting schedule and the equipment schedule showed 6.9-7.8 times and 5.5-6.2 times more energy use reduction than the occupancy loads in PSZ and PVAV systems, respectively. Table 39 to Table 41 represents the result of the sensitivity analysis in Houston. In the sensitivity of individual simulation schedules related to OBC, the lighting schedule had a sensitivity of 31.0-31.4%, and the equipment schedule had a sensitivity of 24.7-25.1%, and the occupancy schedule showed a sensitivity of 4.0-4.5% in total EUI. The variability of total energy use would be interpreted as potential energy reduction from OBC in Houston.

Table 39. Houston: Sensitivity in Total Energy Use of OBC (unit: MMBtu/ft^2)

	100% Sch	90% Sch	80% Sch	70% Sch	60% Sch	50% Sch	40% Sch	30% Sch	20% Sch	10% Sch	0% Sch
PSZ_Equip	136.7	133.4	130.0	126.6	123.2	119.8	116.5	113.1	109.7	106.3	103.0
PSZ_Light	136.7	132.5	128.3	124.0	119.8	115.5	111.3	107.0	102.8	98.6	94.4
PSZ_OCC	136.7	136.1	135.5	134.9	134.2	133.6	133.0	132.4	131.8	131.2	130.5
PVAV_Equip	130.6	127.3	124.0	120.7	117.4	114.2	110.9	107.6	104.4	101.1	97.9
PVAV_Light	130.6	126.5	122.3	118.2	114.1	110.0	105.9	101.8	97.8	93.7	89.7
PVAV_OCC	130.6	130.1	129.5	129.0	128.5	127.9	127.4	126.9	126.4	125.9	125.4

Table 40. Houston: Sensitivity in Energy Use Intensity of OBC (unit: kBtu/ft^2)

	100% Sch	90% Sch	80% Sch	70% Sch	60% Sch	50% Sch	40% Sch	30% Sch	20% Sch	10% Sch	0% Sch
PSZ_Equip	24.8	24.2	23.6	23.0	22.4	21.8	21.2	20.5	19.9	19.3	18.7
PSZ_Light	24.8	24.1	23.3	22.5	21.8	21.0	20.2	19.4	18.7	17.9	17.1
PSZ_OCC	24.8	24.7	24.6	24.5	24.4	24.3	24.2	24.1	23.9	23.8	23.7
PVAV_Equip	23.7	23.1	22.5	21.9	21.3	20.7	20.2	19.6	19.0	18.4	17.8
PVAV_Light	23.7	23.0	22.2	21.5	20.7	20.0	19.2	18.5	17.8	17.0	16.3
PVAV_OCC	23.7	23.6	23.5	23.4	23.3	23.2	23.2	23.1	23.0	22.9	22.8

Table 41. Houston: Energy Reduction Potential in Energy Use Intensity of OBC

	100% Sch	90% Sch	80% Sch	70% Sch	60% Sch	50% Sch	40% Sch	30% Sch	20% Sch	10% Sch	0% Sch
PSZ_Equip	0.0%	2.4%	4.9%	7.4%	9.9%	12.4%	14.8%	17.3%	19.8%	22.2%	24.7%
PSZ_Light	0.0%	3.1%	6.2%	9.3%	12.4%	15.5%	18.6%	21.7%	24.8%	27.9%	31.0%
PSZ_OCC	0.0%	0.4%	0.9%	1.3%	1.8%	2.3%	2.7%	3.2%	3.6%	4.1%	4.5%
PVAV_Equip	0.0%	2.5%	5.1%	7.6%	10.1%	12.6%	15.1%	17.6%	20.1%	22.6%	25.1%
PVAV_Light	0.0%	3.2%	6.3%	9.5%	12.6%	15.8%	18.9%	22.0%	25.1%	28.2%	31.4%
PVAV_OCC	0.0%	0.4%	0.8%	1.2%	1.6%	2.1%	2.5%	2.8%	3.2%	3.6%	4.0%

5.2.1.2. The sensitivity of Occupancy-Based Control Parameters in Chicago

The cold and humid climate characteristics in Chicago need to have more heating and less cooling than the Houston region. In lighting and equipment loads, weather conditions do not make influential, which is determined by usage schedules if lighting systems do not introduce daylighting to reduce artificial lighting in office buildings. Figure 60 shows the result of sensitivity analysis in total building energy use from the BEPS report in DOE-2.1e due to the changes (100%-0%) in occupancy-related schedule parameters. The result of the sensitivity test found that the lighting schedule has the largest impact on energy consumption, and the equipment schedule followed after that. The occupancy schedule had the smallest impact of the three schedule types, which typically influenced the use of heating, cooling, and ventilation.

Figure 61 presents the energy sensitivity in load components. The energy reduction of lighting and equipment schedules came mainly from the reduction of lighting and equipment loads. Also, the decrease of internal heat gains from lighting and equipment produced energy reduction in cooling and ventilation loads, while it mostly caused the increase of heating energy loads except a case of PVAV-equipment. The changes (100%-0%) in the occupancy schedules were not influential in lighting and equipment loads. It lowered cooling and ventilation loads and augmented heating loads in PSZ systems due to reduced internal heat gains in winter. Figure 62 provides the sensitivity of normalized energy use reduction (EUI) potential due to the simulation schedule controls. In both PSZ and PVAV systems, energy use reduction rates from lighting and equipment schedules were the same, which is not related to HVAC system types and weather conditions in energy use. In all cases of (c), space heating showed a negative effect. Most of the increase in heating loads were seen in the PSZ systems while PVAV systems showed minor changes in heating loads due to occupancy-related schedules. In cooling loads of (d), the lighting had the largest potential in cooling energy reduction. Following this, equipment had a second place, and the occupancy rate showed the least impact on cooling energy use. Figure 62 (e) showed a proportional increment in ventilation energy use reduction due to occupancy-related schedule controls. The lighting and equipment also had an influence here because of the decrease in internal gains, which reduced cooling demand in building spaces. Lastly, Figure 62 (f) outlines energy use reduction sensitivity in total building EUI. The PVAV systems showed more energy use reduction potential than the PSZ in total energy use. Depending on schedule type, the lighting and equipment schedules resulted in much higher energy use reduction potential than the occupancy schedule.

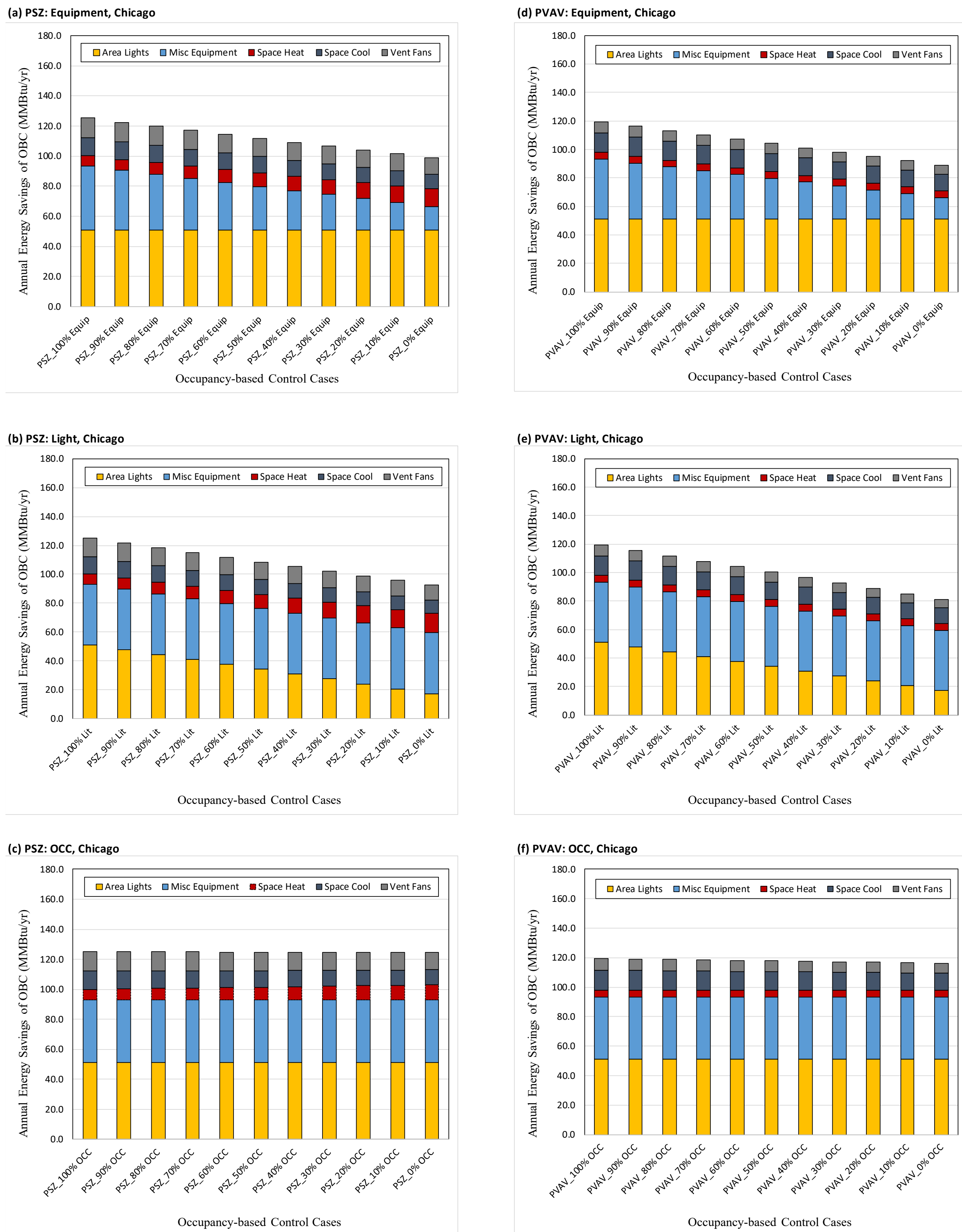


Figure 60. Chicago: Sensitivity in Total Energy Use of OBC schedule controls

Figure 61. Chicago: Sensitivity in Load Components of OBC schedule controls

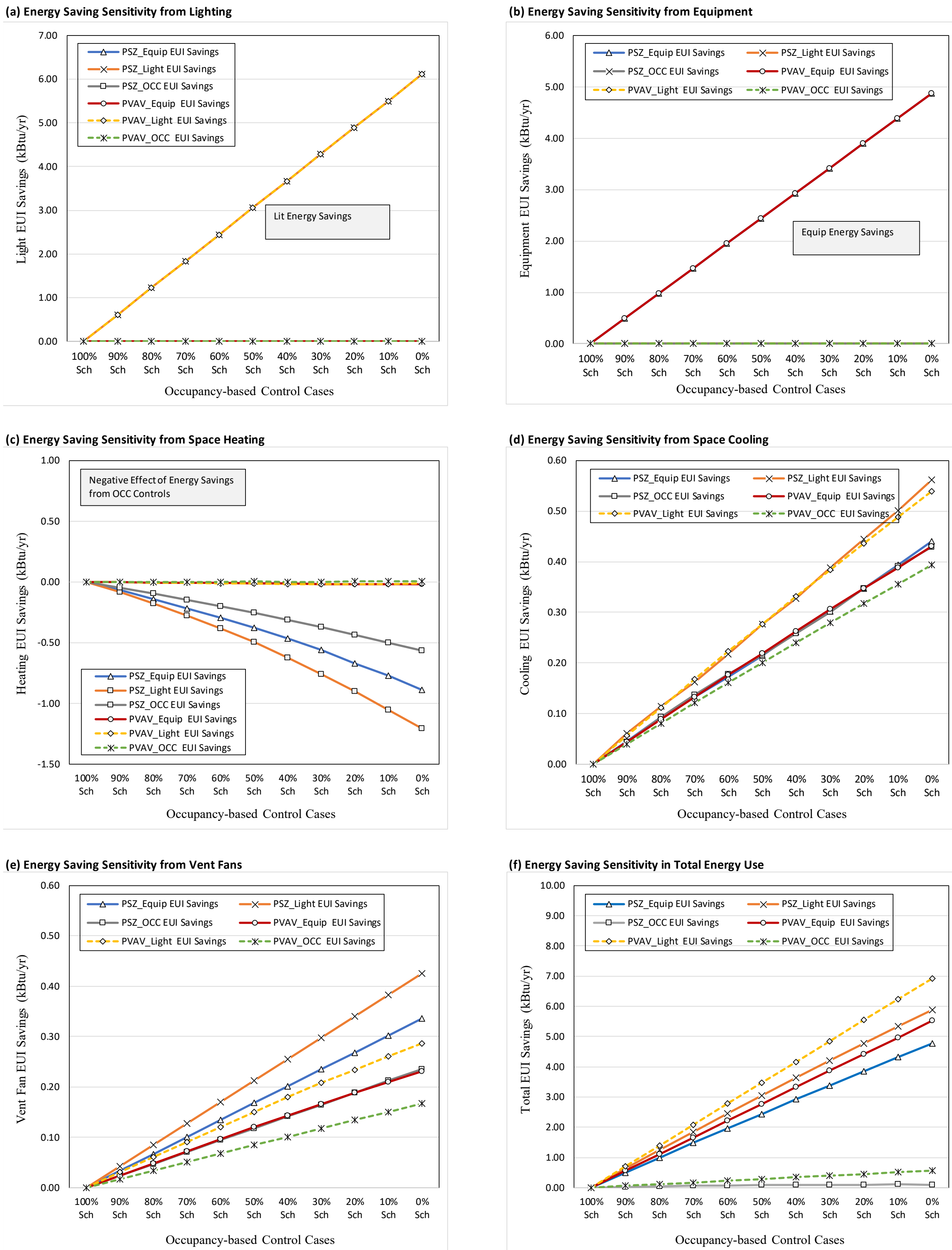


Figure 62. Chicago: Sensitivity in EUI Energy Use Reduction of OBC schedule controls

Table 42. Chicago: Sensitivity in Total Energy Use of OBC (unit: MMBtu/ft^2)

	100% Sch	90% Sch	80% Sch	70% Sch	60% Sch	50% Sch	40% Sch	30% Sch	20% Sch	10% Sch	0% Sch
PSZ_Equip	125.2	122.5	119.7	117.1	114.4	111.8	109.1	106.6	104.0	101.5	99.0
PSZ_Light	125.2	121.7	118.4	115.1	111.7	108.4	105.3	102.1	98.9	95.9	92.8
PSZ_OCC	125.2	125.1	124.9	124.9	124.8	124.8	124.7	124.7	124.6	124.6	124.7
PVAV_Equip	119.4	116.4	113.3	110.3	107.2	104.2	101.2	98.1	95.1	92.1	89.0
PVAV_Light	119.4	115.6	111.8	107.9	104.1	100.3	96.5	92.7	88.9	85.1	81.3
PVAV_OCC	119.4	119.1	118.8	118.5	118.2	117.8	117.5	117.2	116.9	116.6	116.3

Table 43. Chicago: Sensitivity in Energy Use Intensity of OBC (unit: kBtu/ft^2)

	100% Sch	90% Sch	80% Sch	70% Sch	60% Sch	50% Sch	40% Sch	30% Sch	20% Sch	10% Sch	0% Sch
PSZ_Equip	22.8	22.3	21.8	21.3	20.8	20.3	19.8	19.4	18.9	18.4	18.0
PSZ_Light	22.8	22.1	21.5	20.9	20.3	19.7	19.1	18.5	18.0	17.4	16.9
PSZ_OCC	22.8	22.7	22.7	22.7	22.7	22.7	22.7	22.7	22.7	22.6	22.7
PVAV_Equip	21.7	21.1	20.6	20.0	19.5	18.9	18.4	17.8	17.3	16.7	16.2
PVAV_Light	21.7	21.0	20.3	19.6	18.9	18.2	17.5	16.8	16.2	15.5	14.8
PVAV_OCC	21.7	21.6	21.6	21.5	21.5	21.4	21.4	21.3	21.2	21.2	21.1

Table 44. Chicago: Energy Use Reduction Potential in Energy Use Intensity of OBC

	100% Sch	90% Sch	80% Sch	70% Sch	60% Sch	50% Sch	40% Sch	30% Sch	20% Sch	10% Sch	0% Sch
PSZ_Equip	0.0%	2.2%	4.4%	6.5%	8.6%	10.7%	12.8%	14.9%	16.9%	19.0%	20.9%
PSZ_Light	0.0%	2.8%	5.5%	8.1%	10.8%	13.4%	15.9%	18.5%	21.0%	23.4%	25.9%
PSZ_OCC	0.0%	0.1%	0.2%	0.3%	0.3%	0.4%	0.4%	0.4%	0.4%	0.5%	0.4%
PVAV_Equip	0.0%	2.6%	5.1%	7.7%	10.2%	12.7%	15.3%	17.8%	20.4%	22.9%	25.4%
PVAV_Light	0.0%	3.2%	6.4%	9.6%	12.8%	16.0%	19.2%	22.4%	25.5%	28.7%	31.9%
PVAV_OCC	0.0%	0.3%	0.5%	0.8%	1.1%	1.3%	1.6%	1.8%	2.1%	2.3%	2.6%

Table 42 to Table 44 shows the result of the sensitivity analysis in Chicago. In the sensitivity from individual simulation schedules, the lighting schedule had a sensitivity of 25.4-25.9%, and the equipment schedule had a sensitivity of 20.9-25.4%, and the occupancy schedule showed a sensitivity of 0.4-2.6% in total EUI. In Chicago, the occupancy schedule showed less contribution to total energy reduction. The variability of total energy use would be analyzed as potential energy use reduction from OBC in Chicago.

5.2.2. Impact on Building Energy Use of Occupancy-Based Controls in Reference Building, Lightweight Building and Heavyweight Building

The selection of building envelope materials influences the heat transfer of the building surface layers. The thicker and high heat capacity materials can extend heat transfer to pass through the building envelope, which is called time lag on the thermal mass. Therefore, this study modeled the reference building and the heavyweight small office buildings to compare energy performance in different thermal characteristics of envelope materials from the PNNL small and large office prototype models for Standard 90.1-2016 (PNNL and U.S.DOE 2018). Also, a raised floor lightweight building was modeled to analyze the impact when excluding the ground-coupling in simulations. In the PNNL models, small office prototype models used a wooden structure with an attic roof and concrete slab-on-grade, while large office building models used a concrete structure with a built-up roof and concrete slab-on-grade. Thus, this study developed the lightweight building model from reference small office prototype models and only changed concrete slab-on-grade to the raised wooden floor, and heavyweight building materials were extracted from large office prototype models for climate zone 2A and 5A.

In reference and lightweight models, the exterior walls used stucco, gypsum board, and insulation, and ceiling construction used gypsum board and insulation. On the contrary heavyweight models used normal weight concrete, insulation, and gypsum board for exterior walls and worked up built-up roofing, insulation, and metal surface for the flat roof. For this study, heavyweight models used only exterior wall and slab materials from the PNNL models and maintained attic roof instead of built-up roofing to keep the same building design. The use of these materials in office buildings would bring about different energy use reduction impacts due to the time lag effect on the building surface. Between reference, raised floor lightweight, and heavyweight models, thermal properties (e.g., R-value, u-value, SHGC) are designed identically in DOE-2.1e. Therefore, in this chapter, the simulations tested energy use reduction impacts for whole buildings using the reference, raised floor lightweight, and heavyweight structures. The simulation schedules were changed from 100% to 0% to evaluate the impact of OBC. Table 45 represents simulation cases to analyze total building energy reduction in Houston and Chicago. Table 46 to Table 51 represent simulation envelope parameters for the reference, lightweight and heavyweight small office buildings in Houston (2A) and Chicago (5A). BEPS reports were exploited to compare total building energy performance in DOE-2.1e simulations.

Also, in terms of DOE-2 calculations, it uses weighting factors for the estimations of thermal loads and room air temperatures. It describes a compromise between simpler methods and more complex methods. For example, simple methods are a steady-state calculation that neglects the calculations of the building mass to store energy, while sophisticated methods refer to complete energy-balance calculations. Using weighting-factors, an hourly thermal-load calculation is computed according to physical information of the building and hourly adjacent weather conditions (e.g., temperature, solar radiation, wind velocity, etc.). The weighting-factor methods offer a simple, flexible, fast, and efficient calculation method about the significant parameters that influence building energy calculations (LBL and LANL 1982). There are two general premises of all weighting factor methods used in DOE-2. The first one is that the process modeled is able to be described by linear differential equations. This assumption is inevitable because DOE-2 calculates heat gains from different sources independently and later combines to obtain the aggregate result. Thus, nonlinear processes (i.e., natural convection, radiation) have to be approximated linearly. The second general premise is that the influence of system properties are constant in the weighting factor calculations. This indicates that system properties (e.g., film coefficients, incident radiation on surfaces) are used by average values over the time of interest (LBL and LANL 1982).

To develop weighting factors in DOE-2, two classes of weighting factors are available: custom weighting factors (CWFs) and ASHRAE weighting factors (AWFs). Basically, if DOE exploits FLOOR-WEIGHT = 0, the program estimates CWFs based on your inputs of the building description. CWFs provide more accurate results than AWFs because they are customized to the actual building models. Contrastively, AWFs are generic because they are precalculated weighting factors for the building models. They may have a similar heat capacity as the actual building but may be different compared to the actual building due to the difference in geometry and construction. Also, AWFs assume that all of the heat gains from a space consequently is contained in a load, unlike CWFs. This is a poor premise for highly conductive building design (e.g., poorly insulated spaces or high window-to-wall ratio spaces), for which the overestimate can be as high as 25-30% of the heat gains. Thus, AWFs typically overestimate both heating and cooling loads. Also, the AWF methods assume that all of the solar radiation into space remains in the space, but the CWF methods represent that solar gain is reflected back out the windows. The AWFs are precalculated weighting factors that are already calculated for typical building spaces. The DOE-2 will apply AWFs if FLOOR-WEIGHT is greater than zero. To calculate the FLOOR-WEIGHT for space, the weight of the materials in the space (e.g., walls, ceilings, floors, furnishings) should be divided by the floor area of the space in lb/ft^2 or kg/m^2. Only the weight of materials on the space side of the insulating layers should be calculated. For example, if concrete block walls are on the outside of the insulation layers, they are not counted as the weight of the blocks; but if the insulation is on the outside of the blocks, they can be counted for the weight of the blocks (LBNL and JJA 2015).

Therefore, to prevent over-estimations of weighting factors, the CWFs were used in all calculations of occupancy-based building controls to develop more accurate models of heating and cooling loads in DOE-2.1e simulations.

Table 45. Sensitivity Analysis Table for Reference, Raised Floor Lightweight and Heavyweight Buildings

Group	Location	Zoning Model	Envelope Material	System Type	OBC Schedule Type (Weekdays, 9AM-5PM)							Average WWR
					Occupancy	Light	Equip	Infiltration	Vent Fan	Set-temp	Set-back	
1B	Houston	Five zones	Baseline	PSZ	1.0-0.0	1.0-0.0	1.0-0.0	Off	1.0	H: 70ºF C: 75ºF	H: 60ºF C: 85ºF	21% (default)
1L	Houston	Five zones	Lightweight w/raised floor	PSZ	1.0-0.0	1.0-0.0	1.0-0.0	Off	1.0	H: 70ºF C: 75ºF	H: 60ºF C: 85ºF	21% (default)
1H	Houston	Five zones	Heavyweight	PSZ	1.0-0.0	1.0-0.0	1.0-0.0	Off	1.0	H: 70ºF C: 75ºF	H: 60ºF C: 85ºF	21% (default)
2B	Houston	Five zones	Baseline	PVAV	1.0-0.0	1.0-0.0	1.0-0.0	Off	1.0	H: 70ºF C: 75ºF	H: 60ºF C: 85ºF	21% (default)
2L	Houston	Five zones	Lightweight w/raised floor	PVAV	1.0-0.0	1.0-0.0	1.0-0.0	Off	1.0	H: 70ºF C: 75ºF	H: 60ºF C: 85ºF	21% (default)
2H	Houston	Five zones	Heavyweight	PVAV	1.0-0.0	1.0-0.0	1.0-0.0	Off	1.0	H: 70ºF C: 75ºF	H: 60ºF C: 85ºF	21% (default)
3B	Chicago	Five zones	Baseline	PSZ	1.0-0.0	1.0-0.0	1.0-0.0	Off	1.0	H: 70ºF C: 75ºF	H: 60ºF C: 85ºF	21% (default)
3L	Chicago	Five zones	Lightweight w/raised floor	PSZ	1.0-0.0	1.0-0.0	1.0-0.0	Off	1.0	H: 70ºF C: 75ºF	H: 60ºF C: 85ºF	21% (default)
3H	Chicago	Five zones	Heavyweight	PSZ	1.0-0.0	1.0-0.0	1.0-0.0	Off	1.0	H: 70ºF C: 75ºF	H: 60ºF C: 85ºF	21% (default)
4B	Chicago	Five zones	Baseline	PVAV	1.0-0.0	1.0-0.0	1.0-0.0	Off	1.0	H: 70ºF C: 75ºF	H: 60ºF C: 85ºF	21% (default)
4L	Chicago	Five zones	Lightweight w/raised floor	PVAV	1.0-0.0	1.0-0.0	1.0-0.0	Off	1.0	H: 70ºF C: 75ºF	H: 60ºF C: 85ºF	21% (default)
4H	Chicago	Five zones	Heavyweight	PVAV	1.0-0.0	1.0-0.0	1.0-0.0	Off	1.0	H: 70ºF C: 75ºF	H: 60ºF C: 85ºF	21% (default)

* Lightweight envelope materials refer to envelope properties used in PNNL small office buildings for Standard 90.1-2016, but floor material was replaced from concrete floor to wood floor. Heavyweight envelope materials are based on building constructions used in PNNL large office buildings for Standard 90.1-2016. Thermal properties (e.g., u-value) for envelope are identical between lightweight and heavyweight.

** Weekend schedules set to minimum operating conditions of simulation schedules (e.g., occupancy=0.0, 0%; lighting=0.18, 18%; equipment=0.20, 20%;; infiltration=off; ventilation fan=0.0; set-point temperature: heating 60ºF, cooling 85ºF).

*** Window-to-wall (WWR) ratio in small office models is 21% on average. Window fraction is 24.4% for South and 19.8% for the other three orientations (e.g., east, west, north).

Table 46. Simulation Parameters for Reference Building in Houston, TX

#	Type	Layer	Unit	Value
1	Attic roof	Asphalt shingles, 16mm plywood	U-value (hr-ft^2-F/Btu)	0.83
2	Ceiling	R-35.4 Insulation, 16mm gypsum board	U-value (hr-ft^2-F/Btu)	0.03
3	External wall	25mm stucco, 16mm gypsum board, R-9 insulation, 16mm gypsum board	U-value (hr-ft^2-F/Btu)	0.10
4	Internal wall	13mm gypsum board, 13mm gypsum board	U-value (hr-ft^2-F/Btu)	1.11
5	Attic soffit	16mm plywood	U-value (hr-ft^2-F/Btu)	1.33
6	Swinging door	Opaque door panel	U-value (hr-ft^2-F/Btu)	0.37
7	Slab-on-grade floor	200mm normal weight concrete floor, carpet pad	U-value (hr-ft^2-F/Btu)	0.58
8	Window	Glass_1576_LayerAvg, 52mm air, Glass_102_LayerAvg	Window to Wall ration (%)	21.2
			U-value (hr-ft^2-F/Btu)	0.58
			SHGC (Fraction)	0.227

* U-value calculations did not include air films on material surfaces due to internal calculations of air films in simulation programs.
** Slab-on-grade models used average monthly ground temperatures for calculations from the PNNL prototype models.
*** Reference building envelope materials used envelope properties from PNNL small office buildings in Tampa, FL and Buffalo, NY for Standard 90.1-2016. Tampa and Buffalo are representative cities of climate zone 2A and 5A for Standard 90.1-2016 prototype models.

Table 47. Simulation Parameters for Reference Building in Chicago, IL

#	Type	Layer	Unit	Value
1	Attic roof	Asphalt shingles, 16mm plywood	U-value (hr-ft^2-F/Btu)	0.83
2	Ceiling	R-46 Insulation, 16mm gypsum board	U-value (hr-ft^2-F/Btu)	0.02
3	External wall	25mm stucco, 16mm gypsum board, R-17.4 insulation, 16mm gypsum board	U-value (hr-ft^2-F/Btu)	0.05
4	Internal wall	13mm gypsum board, 13mm gypsum board	U-value (hr-ft^2-F/Btu)	1.11
5	Attic soffit	16mm plywood	U-value (hr-ft^2-F/Btu)	1.33
6	Swinging door	Opaque door panel	U-value (hr-ft^2-F/Btu)	0.37
7	Slab-on-grade floor	200mm normal weight concrete floor, carpet pad	U-value (hr-ft^2-F/Btu)	0.58
8	Window	Glass_8652_LayerAvg, 12.7mm air, Glass_102_LayerAvg	Window to Wall ration (%)	21.2
			U-value (hr-ft^2-F/Btu)	0.40
			SHGC (Fraction)	0.365

* U-value calculations did not include air films on material surfaces due to internal calculations of air films in simulation programs.
** Slab-on-grade models used average monthly ground temperatures for calculations from the PNNL prototype models.
*** Reference building materials used envelope properties from PNNL small office buildings in Tampa, FL and Buffalo, NY for Standard 90.1-2016. Tampa and Buffalo are representative cities of climate zone 2A and 5A for Standard 90.1-2016 prototype models.

Table 48. Simulation Parameters for Raised Floor, Lightweight Building in Houston, TX

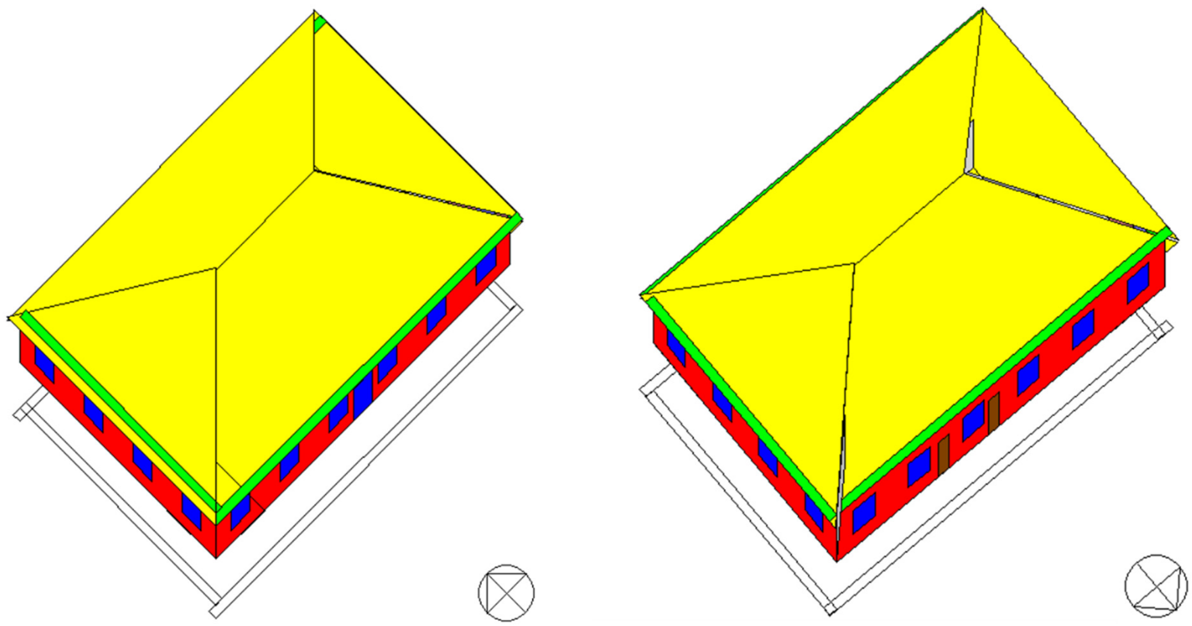
#	Type	Layer	Unit	Value
1	Attic roof	Asphalt shingles, 16mm plywood	U-value (hr-ft^2-F/Btu)	0.83
2	Ceiling	R-35.4 Insulation, 16mm gypsum board	U-value (hr-ft^2-F/Btu)	0.03
3	External wall	25mm stucco, 16mm gypsum board, R-9 insulation, 16mm gypsum board	U-value (hr-ft^2-F/Btu)	0.10
4	Internal wall	13mm gypsum board, 13mm gypsum board	U-value (hr-ft^2-F/Btu)	1.11
5	Attic soffit	16mm plywood	U-value (hr-ft^2-F/Btu)	1.33
6	Swinging door	Opaque door panel	U-value (hr-ft^2-F/Btu)	0.37
7	Raised floor	13mm gypsum board, R-30 Insulation, 16mm gypsum board, carpet pad	U-value (hr-ft^2-F/Btu)	0.30
8	Window	Glass_1576_LayerAvg, 52mm air, Glass_102_LayerAvg	Window to Wall ration (%)	21.2
			U-value (hr-ft^2-F/Btu)	0.58
			SHGC (Fraction)	0.227

* U-value calculations did not include air films on material surfaces due to internal calculations of air films in simulation programs.
** Lightweight envelope materials used envelope properties from PNNL small office buildings in Tampa, FL and Buffalo, NY for Standard 90.1-2016 except wooden floor. Tampa and Buffalo are representative cities of climate zone 2A and 5A for Standard 90.1-2016 prototype models.

Table 49. Simulation Parameters for Raised Floor, Lightweight Building in Chicago, IL

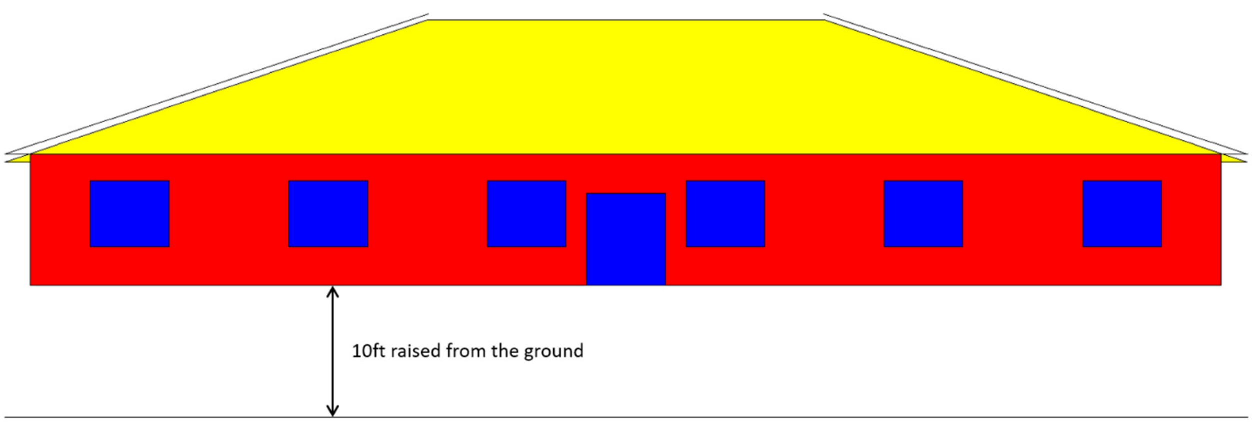
#	Type	Layer	Unit	Value
1	Attic roof	Asphalt shingles, 16mm plywood	U-value (hr-ft^2-F/Btu)	0.83
2	Ceiling	R-46 Insulation, 16mm gypsum board	U-value (hr-ft^2-F/Btu)	0.02
3	External wall	25mm stucco, 16mm gypsum board, R-17.4 insulation, 16mm gypsum board	U-value (hr-ft^2-F/Btu)	0.05
4	Internal wall	13mm gypsum board, 13mm gypsum board	U-value (hr-ft^2-F/Btu)	1.11
5	Attic soffit	16mm plywood	U-value (hr-ft^2-F/Btu)	1.33
6	Swinging door	Opaque door panel	U-value (hr-ft^2-F/Btu)	0.37
7	Raised floor	13mm gypsum board, R-30 Insulation, 16mm gypsum board, carpet pad	U-value (hr-ft^2-F/Btu)	0.30
8	Window	Glass_8652_LayerAvg, 12.7mm air, Glass_102_LayerAvg	Window to Wall ration (%)	21.2
			U-value (hr-ft^2-F/Btu)	0.40
			SHGC (Fraction)	0.365

* U-value calculations did not include air films on material surfaces due to internal calculations of air films in simulation programs.
** Lightweight envelope materials used envelope properties from PNNL small office buildings in Tampa, FL and Buffalo, NY for Standard 90.1-2016 except wooden floor. Tampa and Buffalo are representative cities of climate zone 2A and 5A for Standard 90.1-2016 prototype models.



(a) Southeast View

(b) Northeast View



(c) Front View

Figure 63. Raised Floor, Lightweight Models

Table 50. Simulation Parameters for Heavyweight Building in Houston, TX

#	Type	Layer	Unit	Value
1	Attic roof	Asphalt shingles, 16mm plywood	U-value (hr-ft^2-F/Btu)	0.83
2	Ceiling	R-35.4 insulation, 16mm gypsum board	U-value (hr-ft^2-F/Btu)	0.03
3	External wall	200mm normal weight concrete wall, R-9 insulation, 13mm gypsum board	U-value (hr-ft^2-F/Btu)	0.10
4	Internal wall	13mm gypsum board, 13mm gypsum board	U-value (hr-ft^2-F/Btu)	1.11
5	Attic soffit	16mm plywood	U-value (hr-ft^2-F/Btu)	1.33
6	Swinging door	Opaque door panel	U-value (hr-ft^2-F/Btu)	0.37
7	Slab-on-grade floor	200mm normal weight concrete floor, carpet pad	U-value (hr-ft^2-F/Btu)	0.58
8	Window	Glass_1576_LayerAvg, 52mm air, Glass_102_LayerAvg	Window to Wall ration (%)	21.2
			U-value (hr-ft^2-F/Btu)	0.58
			SHGC (Fraction)	0.227

* U-value calculations did not include films on material surfaces due to internal calculations of films in simulation programs.
** Slab-on-grade models used average monthly ground temperatures for calculations from the PNNL prototype models.
*** Heavyweight envelope materials used envelope properties from PNNL large office buildings in Tampa, FL and Buffalo, NY for Standard 90.1-2016. Tampa and Buffalo are representative cities of climate zone 2A and 5A for Standard 90.1-2016 prototype models.

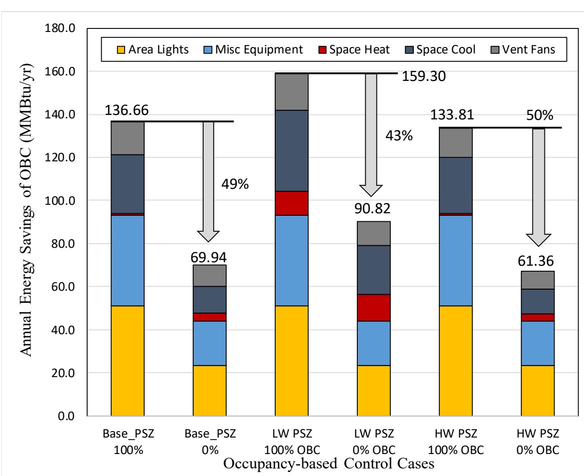
Table 51. Simulation Parameters for Heavyweight Building in Chicago, IL

#	Type	Layer	Unit	Value
1	Attic roof	Asphalt shingles, 16mm plywood	U-value (hr-ft^2-F/Btu)	0.83
2	Ceiling	R-46 insulation, 16mm gypsum board	U-value (hr-ft^2-F/Btu)	0.02
3	External wall	200mm normal weight concrete wall, R-17.4 insulation, 13mm gypsum board	U-value (hr-ft^2-F/Btu)	0.05
4	Internal wall	13mm gypsum board, 13mm gypsum board	U-value (hr-ft^2-F/Btu)	1.11
5	Attic soffit	16mm plywood	U-value (hr-ft^2-F/Btu)	1.33
6	Swinging door	Opaque door panel	U-value (hr-ft^2-F/Btu)	0.37
7	Slab-on-grade floor	200mm normal weight concrete floor, carpet pad	U-value (hr-ft^2-F/Btu)	0.58
8	Window	Glass_8652_LayerAvg, 12.7mm air, Glass_102_LayerAvg	Window to Wall ration (%)	21.2
			U-value (hr-ft^2-F/Btu)	0.40
			SHGC (Fraction)	0.365

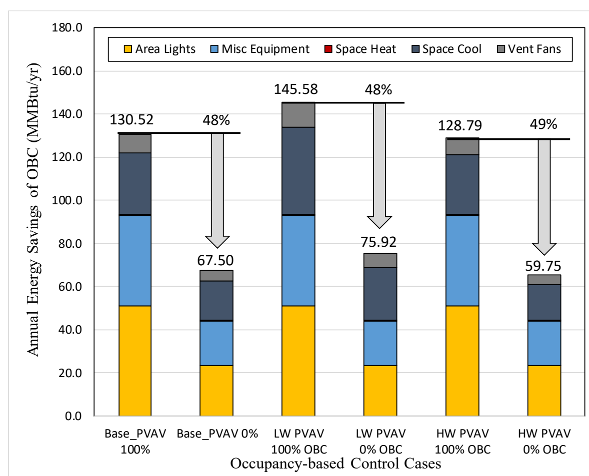
* U-value calculations did not include films on material surfaces due to internal calculations of films in simulation programs.
** Slab-on-grade models used average monthly ground temperatures for calculations from the PNNL prototype models.
*** Heavyweight envelope materials used envelope properties from PNNL large office buildings in Tampa, FL and Buffalo, NY for Standard 90.1-2016. Tampa and Buffalo are representative cities of climate zone 2A and 5A for Standard 90.1-2016 prototype models.

5.2.2.1. Building Energy Use in Houston

This chapter addressed the impact of 100%-0% occupancy-based controls (i.e., occupancy, lighting, and equipment schedules) in the reference, lightweight and heavyweight small office models in Houston. The ventilation rate was controlled by occupant density using OA-CFM/PER command in DOE-2.1e models. Figure 64 shows the maximum energy use reduction of occupancy-based controls in the reference, raised floor lightweight and heavyweight small office models using PSZ and PVAV systems. PSZ system is a default system for small office models in the PNNL models. However, since medium and large office buildings typically use VAV systems, PVAV system models were also evaluated to quantify energy use reduction effect. The maximum energy use reduction from occupancy-based controls in PSZ were 49% of reference, 43% of raised floor lightweight and 50% of heavyweight. PVAV systems represented reduction potential up to 48% of reference, 48% of raised floor lightweight and 49% of heavyweight. Although the reduction rates of PVAV were slightly higher than PSZ systems, the amounts of total energy use reduction in PSZ were larger than PVAV systems.

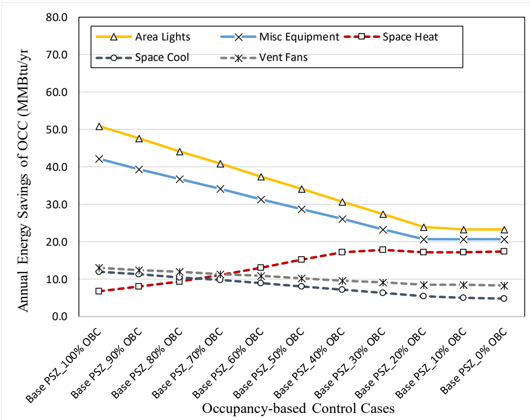


a. PSZ system

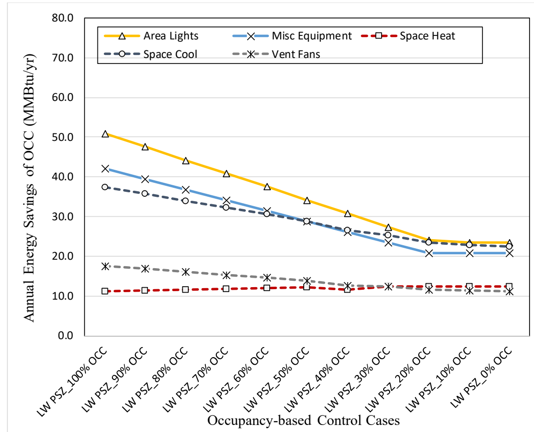


b. PVAV system

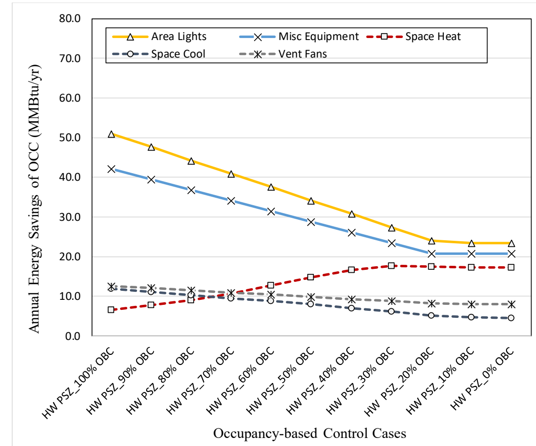
Figure 64. Houston: Reference, Lightweight and Heavyweight Building Total Loads



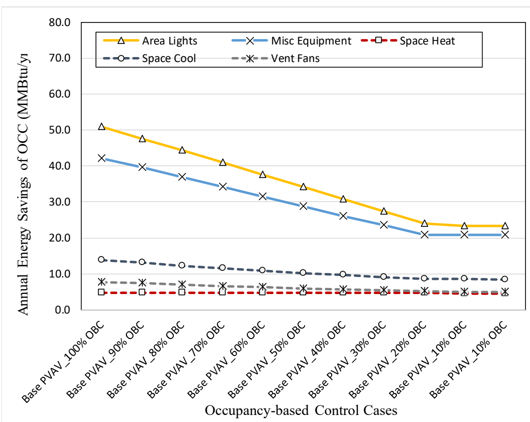
a. Reference, PSZ



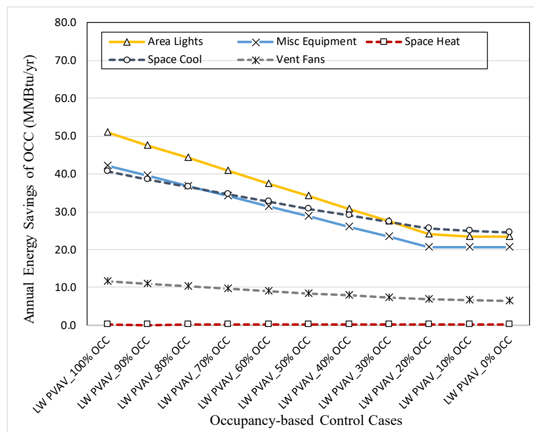
b. Lightweight, PSZ



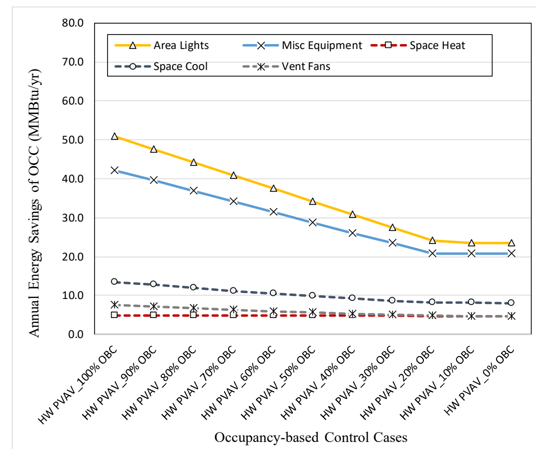
c. Heavyweight, PSZ



d. Reference, PVAV



e. Lightweight, PVAV



f. Heavyweight, PVAV

Figure 65. Houston: Reference, Lightweight and Heavyweight Building Load Components

The differences in total loads between the reference, lightweight and heavyweight were significant, especially in the raised floor lightweight models due to wooden materials and exposed floor environment. In energy use analysis in Houston, when considering with the high-intensity schedules for Standard 90.1-2016 that is average 0.89 of occupancy schedule from 9 AM to 5 PM on weekdays, office buildings have substantial potential to reduce energy waste depending on usage profiles (e.g., medium and low-intensity usage). Figure 65 depicts the trends of component load energy reduction in diverse OBC in the reference, lightweight and heavyweight buildings. The trends represent that the energy use reductions are expected proportionally due to OBC except heating loads. Heating loads showed the negative effect of OBC, especially in PSZ systems. This is because occupancy-based building control leads to less internal heat gains from occupants, lights, and equipment, which creates more heating demand in internal spaces. Most of the energy use reduction came from lighting and equipment, and the reduction rate of cooling energy was relatively low. Table 52 to Table 57 provides normalized total building energy use in the reference, lightweight and heavyweight buildings. Weather-dependent energy use includes heating, cooling, and ventilation loads, while weather-independent energy use contains lighting and equipment loads. The loads from weather-independent components were identical throughout the year between PSZ and PVAV and between the reference, lightweight and heavyweight. Monthly load differences in lighting and equipment are due to differences in the number of HVAC operating days per month. Weather-dependent energy use shows the seasonal impact of OBC, which would be maximized in summer. Cooling and ventilation dominated the seasonal load changes. The result indicates that, for Houston areas, occupancy-based building control is significant from May to September to operate HVAC systems efficiently.

Table 52. Total Building Energy Use Intensity of PSZ Systems in Reference Building (Unit: kBtu/yr-ft^2)

	Base PSZ_100% OBC	Base PSZ_90% OBC	Base PSZ_80% OBC	Base PSZ_70% OBC	Base PSZ_60% OBC	Base PSZ_50% OBC	Base PSZ_40% OBC	Base PSZ_30% OBC	Base PSZ_20% OBC	Base PSZ_10% OBC	Base PSZ_0% OBC
Area Lights	9.26	8.65	8.04	7.43	6.82	6.21	5.60	4.98	4.37	4.25	4.25
Misc Equipment	7.67	7.18	6.69	6.20	5.72	5.23	4.74	4.25	3.77	3.77	3.77
Space Heat	0.19	0.20	0.23	0.26	0.29	0.33	0.40	0.51	0.62	0.64	0.65
Space Cool	4.95	4.66	4.36	4.05	3.76	3.45	3.15	2.82	2.50	2.39	2.31
Vent Fans	2.77	2.65	2.53	2.41	2.29	2.16	2.04	1.92	1.80	1.76	1.73
Total	24.84	23.34	21.85	20.35	18.87	17.38	15.93	14.49	13.06	12.81	12.71

* Total building EUI of different building systems and materials in Houston. Occupancy-based controls of simulation applied 100% to 0% in occupancy and 100% to minimum values in light and equipment schedules. Ventilation calculation is linked to the occupancy rate in simulation models.

** For EUI calculations, system end-use energy is used from the BEPS report in DOE-2.1e.

Table 53. Total Building Energy Use Intensity of PVAV Systems in Reference Building (Unit: kBtu/yr-ft^2)

	Base PVAV_100 % OBC	Base PVAV_90% OBC	Base PVAV_80% OBC	Base PVAV_70% OBC	Base PVAV_60% OBC	Base PVAV_50% OBC	Base PVAV_40% OBC	Base PVAV_30% OBC	Base PVAV_20% OBC	Base PVAV_10% OBC	Base PVAV_0% OBC
Area Lights	9.26	8.65	8.04	7.43	6.82	6.21	5.60	4.98	4.37	4.25	4.25
Misc Equipment	7.67	7.18	6.69	6.20	5.72	5.23	4.74	4.25	3.77	3.77	3.77
Space Heat	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
Space Cool	5.22	4.96	4.70	4.46	4.23	4.02	3.81	3.62	3.44	3.37	3.33
Vent Fans	1.53	1.44	1.36	1.28	1.20	1.12	1.05	0.98	0.92	0.90	0.88
Total	23.72	22.27	20.83	19.41	18.00	16.61	15.24	13.88	12.53	12.33	12.27

* Total building EUI of different building systems and materials in Houston. Occupancy-based controls of simulation applied 100% to 0% in occupancy and 100% to minimum values in light and equipment schedules. Ventilation calculation is linked to the occupancy rate in simulation models.

** For EUI calculations, system end-use energy is used from the BEPS report in DOE-2.1e.

Table 54. Total Building Energy Use Intensity of PSZ Systems in Raised Floor Lightweight Building (Unit: kBtu/yr-ft^2)

	LT PSZ_100% OBC	LT PSZ_90% OBC	LT PSZ_80% OBC	LT PSZ_70% OBC	LT PSZ_60% OBC	LT PSZ_50% OBC	LT PSZ_40% OBC	LT PSZ_30% OBC	LT PSZ_20% OBC	LT PSZ_10% OBC	LT PSZ_0% OBC
Area Lights	9.26	8.65	8.04	7.43	6.82	6.21	5.60	4.98	4.37	4.25	4.25
Misc Equipment	7.67	7.18	6.69	6.20	5.72	5.23	4.74	4.25	3.77	3.77	3.77
Space Heat	2.02	2.07	2.11	2.15	2.20	2.22	2.10	2.25	2.26	2.26	2.27
Space Cool	6.80	6.48	6.18	5.87	5.55	5.24	4.82	4.61	4.28	4.16	4.07
Vent Fans	3.20	3.06	2.93	2.79	2.65	2.52	2.30	2.24	2.10	2.06	2.03
Total	28.95	27.45	25.95	24.45	22.94	21.41	19.55	18.34	16.79	16.50	16.38

* Total building EUI of different building systems and materials in Houston. Occupancy-based controls of simulation applied 100% to 0% in occupancy and 100% to minimum values in light and equipment schedules. Ventilation calculation is linked to the occupancy rate in simulation models.

** For EUI calculations, system end-use energy is used from the BEPS report in DOE-2.1e.

Table 55. Total Building Energy Use Intensity of PVAV Systems in Raised Floor Lightweight Building (Unit: kBtu/yr-ft^2)

	LT PVAV_100 % OBC	LT PVAV_90% OBC	LT PVAV_80% OBC	LT PVAV_70% OBC	LT PVAV_60% OBC	LT PVAV_50% OBC	LT PVAV_40% OBC	LT PVAV_30% OBC	LT PVAV_20% OBC	LT PVAV_10% OBC	LT PVAV_0% OBC
Area Lights	9.26	8.65	8.04	7.43	6.82	6.21	5.60	4.98	4.37	4.25	4.25
Misc Equipment	7.67	7.18	6.69	6.20	5.72	5.23	4.74	4.25	3.77	3.77	3.77
Space Heat	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
Space Cool	7.37	7.01	6.66	6.30	5.95	5.60	5.27	4.95	4.64	4.54	4.46
Vent Fans	2.12	2.00	1.88	1.76	1.65	1.54	1.43	1.33	1.24	1.21	1.19
Total	26.46	24.87	23.30	21.73	20.16	18.61	17.07	15.55	14.05	13.80	13.70

* Total building EUI of different building systems and materials in Houston. Occupancy-based controls of simulation applied 100% to 0% in occupancy and 100% to minimum values in light and equipment schedules. Ventilation calculation is linked to the occupancy rate in simulation models.

** For EUI calculations, system end-use energy is used from the BEPS report in DOE-2.1e.

Table 56. Total Building Energy Use Intensity of PSZ Systems in Heavyweight Building (Unit: kBtu/yr-ft^2)

	HW PSZ_100% OBC	HW PSZ_90% OBC	HW PSZ_80% OBC	HW PSZ_70% OBC	HW PSZ_60% OBC	HW PSZ_50% OBC	HW PSZ_40% OBC	HW PSZ_30% OBC	HW PSZ_20% OBC	HW PSZ_10% OBC	HW PSZ_0% OBC
Area Lights	9.26	8.65	8.04	7.43	6.82	6.21	5.60	4.98	4.37	4.25	4.25
Misc Equipment	7.67	7.18	6.69	6.20	5.72	5.23	4.74	4.25	3.77	3.77	3.77
Space Heat	0.13	0.15	0.18	0.22	0.26	0.30	0.37	0.47	0.58	0.61	0.63
Space Cool	4.72	4.43	4.13	3.83	3.53	3.23	2.92	2.60	2.28	2.18	2.10
Vent Fans	2.53	2.41	2.29	2.17	2.05	1.92	1.80	1.68	1.56	1.52	1.50
Total	24.32	22.83	21.34	19.85	18.37	16.89	15.43	13.99	12.56	12.33	12.25

* Total building EUI of different building systems and materials in Houston. Occupancy-based controls of simulation applied 100% to 0% in occupancy and 100% to minimum values in light and equipment schedules. Ventilation calculation is linked to the occupancy rate in simulation models.

** For EUI calculations, system end-use energy is used from the BEPS report in DOE-2.1e.

Table 57. Total Building Energy Use Intensity of PVAV Systems in Heavyweight Building (Unit: kBtu/yr-ft^2)

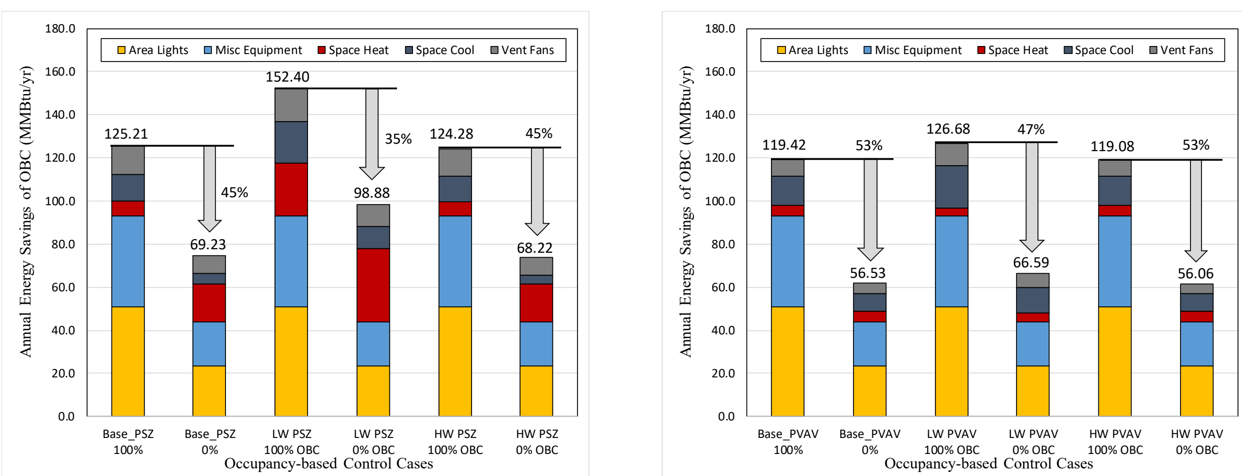
	HW PVAV_100 % OBC	HW PVAV_90% OBC	HW PVAV_80% OBC	HW PVAV_70% OBC	HW PVAV_60% OBC	HW PVAV_50% OBC	HW PVAV_40% OBC	HW PVAV_30% OBC	HW PVAV_20% OBC	HW PVAV_10% OBC	HW PVAV_0% OBC
Area Lights	9.26	8.65	8.04	7.43	6.82	6.21	5.60	4.98	4.37	4.25	4.25
Misc Equipment	7.67	7.18	6.69	6.20	5.72	5.23	4.74	4.25	3.77	3.77	3.77
Space Heat	0.08	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.06	0.06	0.06
Space Cool	4.98	4.71	4.45	4.19	3.96	3.73	3.52	3.32	3.13	3.07	3.03
Vent Fans	1.42	1.33	1.24	1.16	1.08	1.00	0.93	0.86	0.79	0.77	0.76
Total	23.41	21.95	20.50	19.06	17.64	16.24	14.85	13.48	12.13	11.93	11.87

* Total building EUI of different building systems and materials in Houston. Occupancy-based controls of simulation applied 100% to 0% in occupancy and 100% to minimum values in light and equipment schedules. Ventilation calculation is linked to the occupancy rate in simulation models.

** For EUI calculations, system end-use energy is used from the BEPS report in DOE-2.1e.

5.2.2.2. Building Energy Use in Chicago

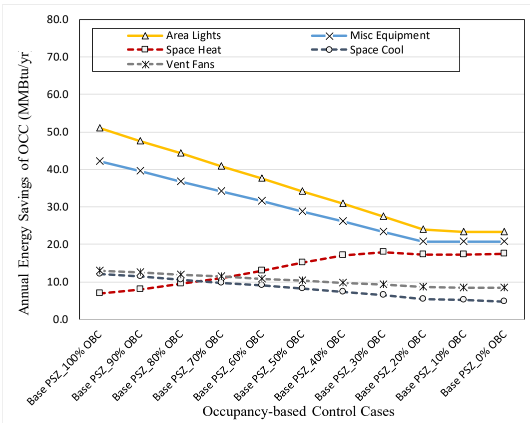
This chapter calculated the energy use reduction effect of 100%-0% OBC (i.e., occupancy, lighting, and equipment schedules) in the reference, lightweight and heavyweight small office models in Chicago. The ventilation rate that is also related to OBC was controlled by occupant density using OA-CFM/PER command in DOE-2.1e models. Figure 66 shows the potential energy use reduction of OBC using PSZ and PVAV systems in Chicago. The maximum energy use reduction from OBC in PSZ was expected up to 45% of reference, 35% of raised floor lightweight and 45% of heavyweight. The energy use reduction potential of PVAV systems were 53% of reference, 47% of raised floor lightweight and 53% of heavyweight. All PSZ used more energy than PVAV buildings from weather-dependent load components. The differences in total loads between the reference and heavyweight were almost zero, but raised lightweight models showed substantial differences in total energy use and reduction. The energy use reduction rates and amounts in Chicago models were lower compared to the results of lightweight and heavyweight buildings in Houston.



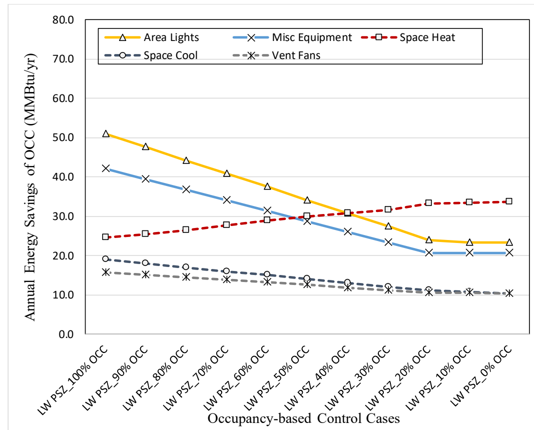
a. PSZ CAV system

b. PVAV system

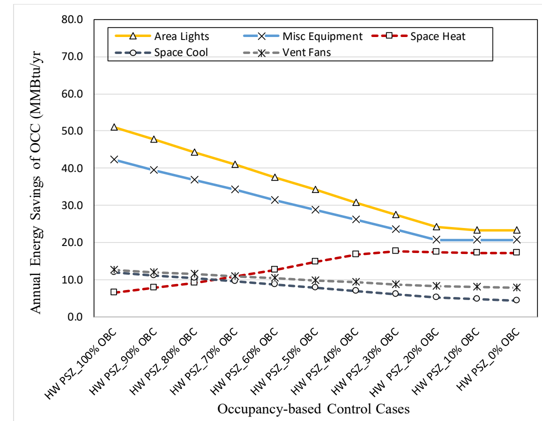
Figure 66. Chicago: Reference, Lightweight and Heavyweight Building Total Loads



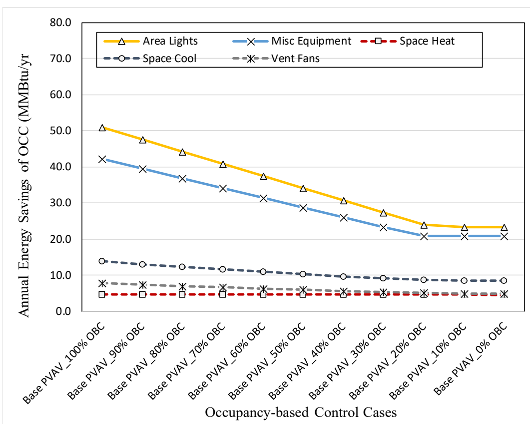
a. Reference, PSZ



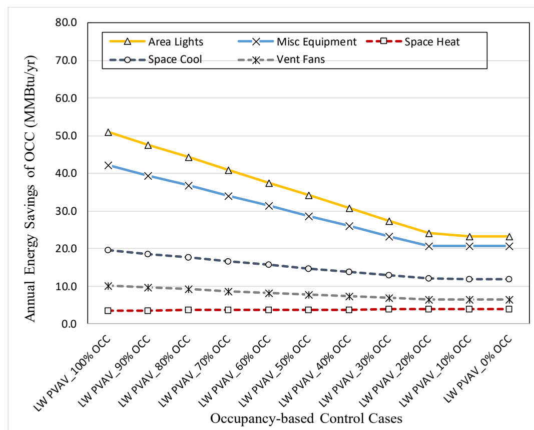
b. Lightweight, PSZ



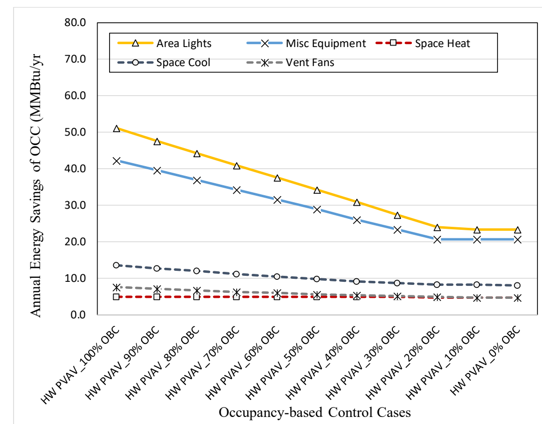
c. Heavyweight, PSZ



d. Reference, PVAV



e. Lightweight, PVAV



f. Heavyweight, PVAV

Figure 67. Chicago: Reference, Lightweight and Heavyweight Building Load Components

In comparison with Standard 90.1-2016, the result showed that office buildings have enormous potential to reduce energy consumption depending on usage levels (e.g., medium and low-intensity usage). Figure 67 presents the trends of component load energy reduction potential in different OBC from the reference, raised floor lightweight and heavyweight buildings. The trends represent that the energy use reduction are proportionally working due to OBC except heating loads. Heating loads described the negative effect of OBC, especially in PSZ systems. This is because OBC causes less internal heat gains from occupants, lights, and equipment, which requires more heating demand in internal spaces. However, the increasing trend in heating loads is slowing by around 40% of OBC in both lightweight and heavyweight.

The result of simulations informs that lighting and equipment are the most significant contributors to OBC energy use reduction. The energy use reduction impact of cooling energy in total energy use was relatively low because Chicago has more heating demand then Houston. Table 58 to Table 63 offers normalized total building energy use in the reference, lightweight and heavyweight buildings. Weather-dependent energy use contains heating, cooling, and ventilation loads, whereas weather-independent energy use includes lighting and equipment loads. The loads from weather-independent components were identical throughout the year between PSZ and PVAV and between reference, lightweight and heavyweight. Weather-dependent energy use describes the seasonal impact and potential reduction of occupancy-based building controls, which would be maximized in the summer of PVAV systems and winter of PSZ systems. Cooling and ventilation loads dominated the seasonal load changes of PVAV systems and heating loads led in PSZ systems. The result indicates that, for Chicago areas, OBC is important to operate HVAC systems efficiently, but the contributing load components would vary depending on the system type.

Table 58. Total Building Energy Use Intensity of PSZ Systems in Reference Building (Unit: kBtu/yr-ft^2)

	Base PSZ_100% OBC	Base PSZ_90% OBC	Base PSZ_80% OBC	Base PSZ_70% OBC	Base PSZ_60% OBC	Base PSZ_50% OBC	Base PSZ_40% OBC	Base PSZ_30% OBC	Base PSZ_20% OBC	Base PSZ_10% OBC	Base PSZ_0% OBC
Area Lights	9.26	8.65	8.04	7.43	6.82	6.21	5.60	4.98	4.37	4.25	4.25
Misc Equipment	7.67	7.18	6.69	6.20	5.72	5.23	4.74	4.25	3.77	3.77	3.77
Space Heat	1.25	1.47	1.71	2.02	2.36	2.76	3.11	3.24	3.15	3.13	3.16
Space Cool	2.20	2.06	1.92	1.78	1.63	1.48	1.33	1.17	1.00	0.92	0.87
Vent Fans	2.37	2.27	2.17	2.07	1.97	1.87	1.77	1.67	1.57	1.54	1.52
Total	22.75	21.63	20.54	19.50	18.50	17.55	16.55	15.33	13.85	13.61	13.58

* Total building EUI of different building systems and materials in Chicago. Occupancy-based controls of simulation applied 100% to 0% in occupancy and 100% to minimum values in light and equipment schedules. Ventilation calculation is linked to the occupancy rate in simulation models.
** For EUI calculations, system end-use energy is used from the BEPS report in DOE-2.1e.

Table 59. Total Building Energy Use Intensity of PVAV Systems in Reference Building (Unit: kBtu/yr-ft^2)

	Base PVAV_100 % OBC	Base PVAV_90% OBC	Base PVAV_80% OBC	Base PVAV_70% OBC	Base PVAV_60% OBC	Base PVAV_50% OBC	Base PVAV_40% OBC	Base PVAV_30% OBC	Base PVAV_20% OBC	Base PVAV_10% OBC	Base PVAV_0% OBC
Area Lights	9.26	8.65	8.04	7.43	6.82	6.21	5.60	4.98	4.37	4.25	4.25
Misc Equipment	7.67	7.18	6.69	6.20	5.72	5.23	4.74	4.25	3.77	3.77	3.77
Space Heat	0.85	0.86	0.86	0.87	0.86	0.86	0.85	0.84	0.84	0.84	0.83
Space Cool	2.51	2.37	2.23	2.10	1.97	1.85	1.74	1.65	1.57	1.54	1.52
Vent Fans	1.41	1.34	1.27	1.20	1.14	1.08	1.02	0.97	0.92	0.90	0.90
Total	21.70	20.40	19.09	17.80	16.51	15.22	13.95	12.70	11.47	11.30	11.27

* Total building EUI of different building systems and materials in Chicago. Occupancy-based controls of simulation applied 100% to 0% in occupancy and 100% to minimum values in light and equipment schedules. Ventilation calculation is linked to the occupancy rate in simulation models.
** For EUI calculations, system end-use energy is used from the BEPS report in DOE-2.1e.

Table 60. Total Building Energy Use Intensity of PSZ Systems in Raised Floor Lightweight Building (Unit: kBtu/yr-ft^2)

	LT PSZ_100% OBC	LT PSZ_90% OBC	LT PSZ_80% OBC	LT PSZ_70% OBC	LT PSZ_60% OBC	LT PSZ_50% OBC	LT PSZ_40% OBC	LT PSZ_30% OBC	LT PSZ_20% OBC	LT PSZ_10% OBC	LT PSZ_0% OBC
Area Lights	9.26	8.65	8.04	7.43	6.82	6.21	5.60	4.98	4.37	4.25	4.25
Misc Equipment	7.67	7.18	6.69	6.20	5.72	5.23	4.74	4.25	3.77	3.77	3.77
Space Heat	4.46	4.62	4.82	5.03	5.25	5.44	5.60	5.75	6.06	6.10	6.11
Space Cool	3.45	3.27	3.08	2.91	2.75	2.57	2.38	2.20	2.03	1.95	1.88
Vent Fans	2.86	2.74	2.63	2.51	2.40	2.28	2.16	2.05	1.93	1.91	1.89
Total	27.70	26.46	25.26	24.09	22.93	21.73	20.48	19.24	18.16	17.97	17.90

* Total building EUI of different building systems and materials in Chicago. Occupancy-based controls of simulation applied 100% to 0% in occupancy and 100% to minimum values in light and equipment schedules. Ventilation calculation is linked to the occupancy rate in simulation models.
** For EUI calculations, system end-use energy is used from the BEPS report in DOE-2.1e.

Table 61. Total Building Energy Use Intensity of PVAV Systems in Raised Floor Lightweight Building (Unit: kBtu/yr-ft^2)

	LT PVAV_100 % OBC	LT PVAV_90% OBC	LT PVAV_80% OBC	LT PVAV_70% OBC	LT PVAV_60% OBC	LT PVAV_50% OBC	LT PVAV_40% OBC	LT PVAV_30% OBC	LT PVAV_20% OBC	LT PVAV_10% OBC	LT PVAV_0% OBC
Area Lights	9.26	8.65	8.04	7.43	6.82	6.21	5.60	4.98	4.37	4.25	4.25
Misc Equipment	7.67	7.18	6.69	6.20	5.72	5.23	4.74	4.25	3.77	3.77	3.77
Space Heat	0.63	0.66	0.66	0.67	0.69	0.69	0.70	0.71	0.72	0.72	0.72
Space Cool	3.59	3.39	3.21	3.03	2.86	2.69	2.52	2.36	2.21	2.17	2.15
Vent Fans	1.87	1.78	1.69	1.60	1.51	1.43	1.35	1.27	1.21	1.19	1.18
Total	23.02	21.66	20.30	18.94	17.59	16.24	14.91	13.58	12.27	12.10	12.07

* Total building EUI of different building systems and materials in Chicago. Occupancy-based controls of simulation applied 100% to 0% in occupancy and 100% to minimum values in light and equipment schedules. Ventilation calculation is linked to the occupancy rate in simulation models.
** For EUI calculations, system end-use energy is used from the BEPS report in DOE-2.1e.

Table 62. Total Building Energy Use Intensity of PSZ Systems in Heavyweight Building (Unit: kBtu/yr-ft^2)

	HW PSZ_100% OBC	HW PSZ_90% OBC	HW PSZ_80% OBC	HW PSZ_70% OBC	HW PSZ_60% OBC	HW PSZ_50% OBC	HW PSZ_40% OBC	HW PSZ_30% OBC	HW PSZ_20% OBC	HW PSZ_10% OBC	HW PSZ_0% OBC
Area Lights	9.26	8.65	8.04	7.43	6.82	6.21	5.60	4.98	4.37	4.25	4.25
Misc Equipment	7.67	7.18	6.69	6.20	5.72	5.23	4.74	4.25	3.77	3.77	3.77
Space Heat	1.20	1.41	1.66	1.96	2.31	2.68	3.03	3.21	3.17	3.13	3.13
Space Cool	2.17	2.02	1.88	1.74	1.59	1.44	1.28	1.12	0.94	0.86	0.80
Vent Fans	2.29	2.19	2.09	1.99	1.89	1.79	1.69	1.59	1.49	1.46	1.44
Total	22.59	21.46	20.36	19.32	18.32	17.35	16.33	15.16	13.74	13.46	13.40

* Total building EUI of different building systems and materials in Chicago. Occupancy-based controls of simulation applied 100% to 0% in occupancy and 100% to minimum values in light and equipment schedules. Ventilation calculation is linked to the occupancy rate in simulation models.
* For EUI calculations, system end-use energy is used from the BEPS report in DOE-2.1e.

Table 63. Total Building Energy Use Intensity of PVAV Systems in Heavyweight Building (Unit: kBtu/yr-ft^2)

	HW PVAV_100 % OBC	HW PVAV_90% OBC	HW PVAV_80% OBC	HW PVAV_70% OBC	HW PVAV_60% OBC	HW PVAV_50% OBC	HW PVAV_40% OBC	HW PVAV_30% OBC	HW PVAV_20% OBC	HW PVAV_10% OBC	HW PVAV_0% OBC
Area Lights	9.26	8.65	8.04	7.43	6.82	6.21	5.60	4.98	4.37	4.25	4.25
Misc Equipment	7.67	7.18	6.69	6.20	5.72	5.23	4.74	4.25	3.77	3.77	3.77
Space Heat	0.90	0.89	0.89	0.89	0.90	0.89	0.89	0.88	0.86	0.85	0.85
Space Cool	2.45	2.31	2.17	2.03	1.90	1.78	1.68	1.59	1.51	1.48	1.46
Vent Fans	1.36	1.29	1.22	1.15	1.09	1.03	0.98	0.92	0.88	0.86	0.85
Total	21.64	20.32	19.01	17.71	16.43	15.15	13.88	12.63	11.39	11.22	11.19

* Total building EUI of different building systems and materials in Chicago. Occupancy-based controls of simulation applied 100% to 0% in occupancy and 100% to minimum values in light and equipment schedules. Ventilation calculation is linked to the occupancy rate in simulation models.
* For EUI calculations, system end-use energy is used from the BEPS report in DOE-2.1e.

5.2.2.3. Comparison of the Impact of Occupancy-Based Controls in Reference, Lightweight and Heavyweight buildings

Among load components, although lighting and equipment loads provide internal heat gains into buildings, their load amounts are not determined by building envelope materials. Thermal characteristics of building surfaces affect heating, cooling, and ventilation loads in office buildings, which are weather-dependent load components. Therefore, this chapter compared the energy use impact of occupancy-based controls between the reference, raised floor lightweight and heavyweight models to identify the impact of occupancy-based controls in building loads. Figure 68 and Figure 69 outlines total annual heating, cooling, and ventilation loads of occupancy-based controls in the reference, raised floor lightweight and heavyweight models in Houston and Chicago.

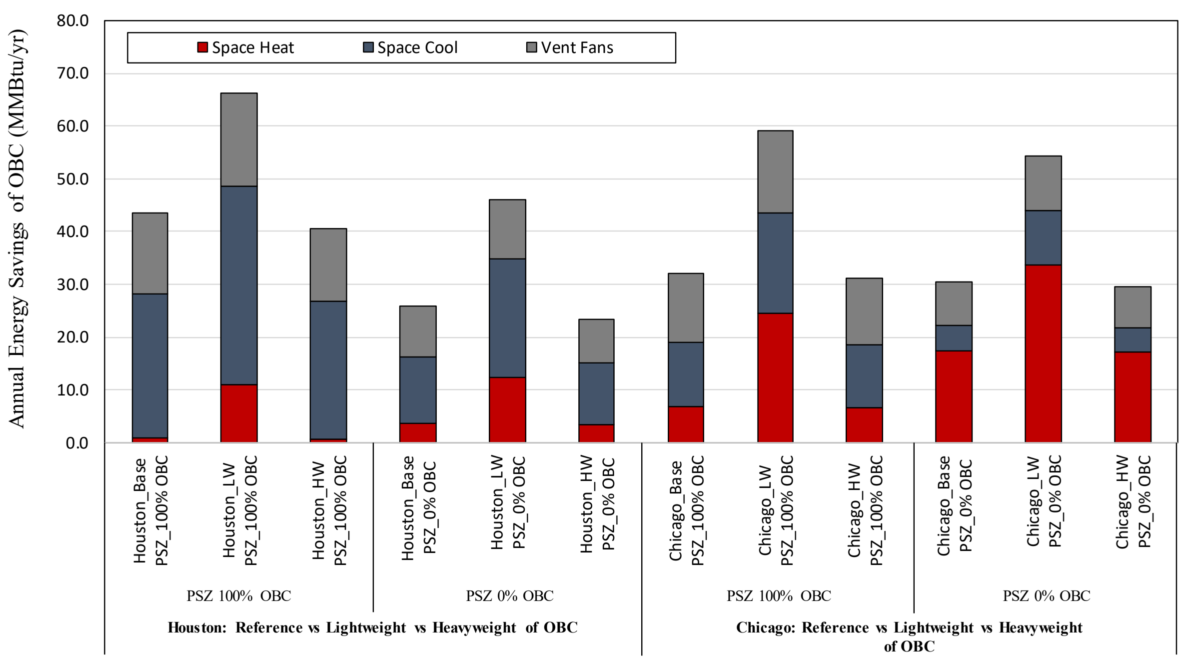


Figure 68. Total Loads of OBC in Reference, Lightweight and Heavyweight PSZ Models

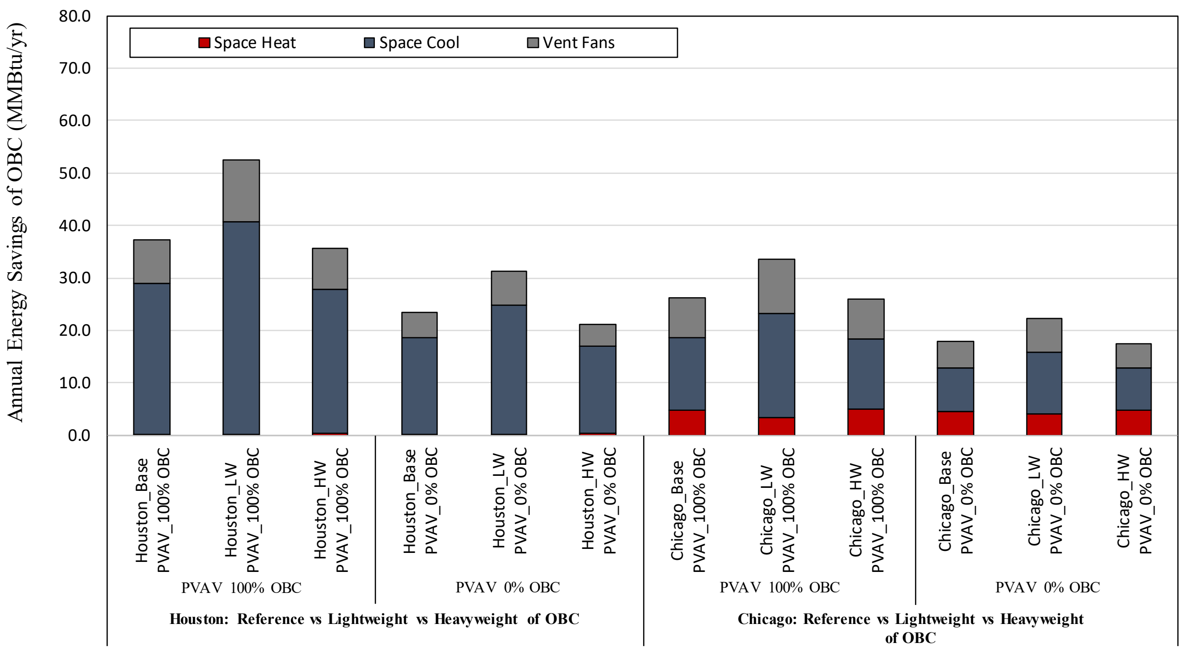


Figure 69. Total Loads of OBC in Reference, Lightweight and Heavyweight PVAV Models

In terms of PSZ systems, Table 64 and Table 65 revealed that PSZ raised floor lightweight models consumed 52.0-78.2% more energy and PSZ heavyweight models used 6.5-9.9% less energy than the reference models in Houston. The result showed 77.7-84.8% more energy use of PSZ raised floor lightweight models and 2.9-3.2% less energy use of PSZ heavyweight models in Chicago. All loads (i.e., heating, cooling, ventilation) in Houston decreased in heavyweight models compared to the reference and lightweight models.

In terms of PVAV systems, Table 66 and Table 67 represents the impact of occupancy-based controls in the reference, lightweight and heavyweight models using PVAV systems in Houston and Chicago. The results showed that PVAV raised floor lightweight models used more energy up to 40.3% and PVAV heavyweight models used less energy up to 9.3% than the reference models in Houston. Also, PVAV raised floor lightweight models used more energy up to 27.7% and PSZ heavyweight models used more energy up to -3.8% than the reference models in Chicago. The differences in PVAV systems were lower than PSZ CAV systems. The impact of the energy use changes from OBC 100% to OBC 0% was slightly different depending on building material types.

Table 64. Impact of OBC in the Reference, Lightweight and Heavyweight Models using PSZ Systems in Houston

Load Type	Category	Base PSZ_100% OBC	LW PSZ_100% OBC	HW PSZ_100% OBC	Base PSZ_0% OBC	LW PSZ_0% OBC	HW PSZ_0% OBC
Space Heat	Energy Use (MMBtu/yr)	1.0	11.1	0.7	3.6	12.5	3.5
	Difference (MMBtu/yr)	-	-10.1	0.3	-	-8.9	0.1
Space Cool	Energy Use (MMBtu/yr)	27.2	37.4	26.0	12.7	22.4	11.5
	Difference (MMBtu/yr)	-	-10.2	1.2	-	-9.7	1.1
Vent Fans	Energy Use (MMBtu/yr)	15.3	17.6	13.9	9.5	11.2	8.2
	Difference (MMBtu/yr)	-	-2.4	1.3	-	-1.6	1.3
Total	Energy Use (MMBtu/yr)	43.5	66.1	40.7	25.8	46.0	23.3
	Difference (MMBtu/yr)	-	-22.6	2.8	-	-20.2	2.6
	Difference (%)	-	-52.0%	6.5%	-	-78.2%	9.9%

Table 65. Impact of OBC in the Reference, Lightweight and Heavyweight Models using PSZ Systems in Chicago

Load Type	Category	Base PSZ_100% OBC	LW PSZ_100% OBC	HW PSZ_100% OBC	Base PSZ_0% OBC	LW PSZ_0% OBC	HW PSZ_0% OBC
Space Heat	Energy Use (MMBtu/yr)	6.9	24.5	6.6	17.4	33.6	17.2
	Difference (MMBtu/yr)	-	-17.6	0.3	-	-16.2	0.2
Space Cool	Energy Use (MMBtu/yr)	12.1	19.0	11.9	4.8	10.3	4.4
	Difference (MMBtu/yr)	-	-6.8	0.2	-	-5.5	0.4
Vent Fans	Energy Use (MMBtu/yr)	13.0	15.7	12.6	8.4	10.4	7.9
	Difference (MMBtu/yr)	-	-2.7	0.4	-	-2.0	0.5
Total	Energy Use (MMBtu/yr)	32.1	59.2	31.1	30.6	54.4	29.6
	Difference (MMBtu/yr)	-	-27.2	0.9	-	-23.8	1.0
	Difference (%)	-	-84.8%	2.9%	-	-77.8%	3.2%

Table 66. Impact of OBC in the Reference, Lightweight and Heavyweight Models using PVAV Systems in Houston

Load Type	Category	Base PVAV 100% OBC	LW PVAV 100% OBC	HW PVAV 100% OBC	Base PVAV 0% OBC	LW PVAV 0% OBC	HW PVAV 0% OBC
Space Heat	Energy Use (MMBtu/yr)	0.2	0.2	0.4	0.2	0.2	0.4
	Difference (MMBtu/yr)	-	0.1	-0.2	-	0.0	-0.1
Space Cool	Energy Use (MMBtu/yr)	28.7	40.6	27.4	18.3	24.6	16.7
	Difference (MMBtu/yr)	-	-11.9	1.3	-	-6.2	1.6
Vent Fans	Energy Use (MMBtu/yr)	8.4	11.7	7.8	4.9	6.5	4.2
	Difference (MMBtu/yr)	-	-3.3	0.6	-	-1.7	0.7
Total	Energy Use (MMBtu/yr)	37.4	52.4	35.6	23.4	31.3	21.2
	Difference (MMBtu/yr)	-	-15.1	1.7	-	-7.9	2.2
	Difference (%)	-	-40.3%	4.6%	-	-33.7%	9.3%

Table 67. Impact of OBC in the Reference, Lightweight and Heavyweight Models using PVAV Systems in Chicago

Load Type	Category	Base PVAV 100% OBC	LW PVAV 100% OBC	HW PVAV 100% OBC	Base PVAV 0% OBC	LW PVAV 0% OBC	HW PVAV 0% OBC
Space Heat	Energy Use (MMBtu/yr)	4.7	3.5	4.9	4.6	4.0	4.7
	Difference (MMBtu/yr)	-	1.2	-0.2	-	0.6	-0.1
Space Cool	Energy Use (MMBtu/yr)	13.8	19.8	13.5	8.4	11.8	8.1
	Difference (MMBtu/yr)	-	-5.9	0.3	-	-3.4	0.3
Vent Fans	Energy Use (MMBtu/yr)	7.7	10.3	7.5	4.9	6.5	4.7
	Difference (MMBtu/yr)	-	-2.6	0.3	-	-1.6	0.2
Total	Energy Use (MMBtu/yr)	26.3	33.5	25.9	17.9	22.3	17.4
	Difference (MMBtu/yr)	-	-7.3	0.3	-	-4.4	0.5
	Difference (%)	-	-27.7%	1.3%	-	-24.6%	2.6%

5.2.3. Impact on Building Energy Use of Occupancy-Based Controls in 10-40% Window-to-Wall Ratio Models

In this chapter, the impact of OBC controls in different window-to-wall (WWR) office models was investigated in Houston and Chicago. For this study, twelve groups of simulations were developed in the considerations of two climate zones (i.e., Houston, TX, Chicago, IL), two envelope materials (i.e., reference, raised floor lightweight and heavyweight), and two HVAC systems (i.e., PSZ, PVAV). To evaluate the energy performance in the small office buildings, five-zone models were used in OBC schedules of 100%-0% to quantify the energy use reduction potential in WWR models. Heating, cooling, and ventilation loads for cases were calculated and compared.

Table 68 represents a test set of WWR models (i.e., 10%, 21%, 30%, 40%). The analysis cases only considered the WWR range of the prescriptive requirement in Standard 90.1-2016, which specified that vertical fenestration should be 0% to 40% of walls in Section 6 (ASHRAE 2016a). The WWR 20% is not developed in this analysis because baseline models based on PNNL prototype buildings originally have 21% WWR.

Typically, a high WWR ratio deteriorates thermal properties on the building envelopes due to increased overall U-value and solar heat gain. The energy use in different WWR models was verified by previous research, such as Phillips et al. (2020) and Troup et al. (2019).

Phillips et al. (2020) studied the environmental, economic, and social effects of various WWR levels (i.e., 20%, 40%, 60%) in Boston, Miami, and San Francisco. For testing U.S. DOE’s large office (12 stories) prototype building was modeled using Autodesk Revit, and then the TallyRevit application and EnergyPlus were used to calculated life cycle assessment (LCA) and energy cost. The results revealed that in all locations, electricity use was decreased with a lower WWR and increased with a higher WWR. The changes of energy use were mostly affected by the additional cooling and ventilation fans/pumps due to more solar heat gain from large window area. Also, high WWR models required more gas consumption for heating. In another study, Troup et al. (2019) evaluated the effect of WWR in U.S. office building using the 2012 CBECS data and regression model. This study found that average total EUI increases with high WWR, and had statistical significance on cooling, lighting, and ventilation energy use. The cooling loads represented the largest increase among disaggregated load components.

Table 68. Window-to-Wall Ratio Analysis of Occupancy-Based Controls in Houston and Chicago

Group	Location	Zoning Model	Envelope Material	System Type	Average WWR	OBC Schedule Type (Weekdays, 9AM-5PM)						
						Occupancy	Light	Equip	Infiltration	Vent Fan	Set-temp	Set-back
1B	Houston	Five zones	Reference	PSZ	10-40%	1.0-0.0	1.0-0.0	1.0-0.0	Off	1.0	H: 70ºF C: 75ºF	H: 60ºF C: 85ºF
1L	Houston	Five zones	Raised Floor Lightweight	PSZ	10-40%	1.0-0.0	1.0-0.0	1.0-0.0	Off	1.0	H: 70ºF C: 75ºF	H: 60ºF C: 85ºF
1H	Houston	Five zones	Heavyweight	PSZ	10-40%	1.0-0.0	1.0-0.0	1.0-0.0	Off	1.0	H: 70ºF C: 75ºF	H: 60ºF C: 85ºF
2B	Houston	Five zones	Reference	PVAV	10-40%	1.0-0.0	1.0-0.0	1.0-0.0	Off	1.0	H: 70ºF C: 75ºF	H: 60ºF C: 85ºF
2L	Houston	Five zones	Raised Floor Lightweight	PVAV	10-40%	1.0-0.0	1.0-0.0	1.0-0.0	Off	1.0	H: 70ºF C: 75ºF	H: 60ºF C: 85ºF
2H	Houston	Five zones	Heavyweight	PVAV	10-40%	1.0-0.0	1.0-0.0	1.0-0.0	Off	1.0	H: 70ºF C: 75ºF	H: 60ºF C: 85ºF
3B	Chicago	Five zones	Reference	PSZ	10-40%	1.0-0.0	1.0-0.0	1.0-0.0	Off	1.0	H: 70ºF C: 75ºF	H: 60ºF C: 85ºF
3L	Chicago	Five zones	Raised Floor Lightweight	PSZ	10-40%	1.0-0.0	1.0-0.0	1.0-0.0	Off	1.0	H: 70ºF C: 75ºF	H: 60ºF C: 85ºF
3H	Chicago	Five zones	Heavyweight	PSZ	10-40%	1.0-0.0	1.0-0.0	1.0-0.0	Off	1.0	H: 70ºF C: 75ºF	H: 60ºF C: 85ºF
4B	Chicago	Five zones	Reference	PVAV	10-40%	1.0-0.0	1.0-0.0	1.0-0.0	Off	1.0	H: 70ºF C: 75ºF	H: 60ºF C: 85ºF
4L	Chicago	Five zones	Raised Floor Lightweight	PVAV	10-40%	1.0-0.0	1.0-0.0	1.0-0.0	Off	1.0	H: 70ºF C: 75ºF	H: 60ºF C: 85ºF
4H	Chicago	Five zones	Heavyweight	PVAV	10-40%	1.0-0.0	1.0-0.0	1.0-0.0	Off	1.0	H: 70ºF C: 75ºF	H: 60ºF C: 85ºF

* Reference and lightweight envelope materials refer to envelope properties used in PNNL small office buildings for Standard 90.1-2016. Raised floor complied with Standard 90.1-2016. Heavyweight envelope materials are based on building.
constructions used in PNNL large office buildings for Standard 90.1-2016. Thermal properties (e.g., u-value) for envelope are identical between lightweight and heavyweight.

** Weekend schedules set to minimum operating conditions of simulation schedules (e.g., occupancy=0.0, 0%; lighting=0.18, 18%; equipment=0.20, 20%;; infiltration=off; ventilation fan=0.0; set-point temperature: heating 60ºF, cooling 85ºF).

*** Default window-to-wall (WWR) ratio in small office models is 21% on average. Window fraction is 24.4% for South and 19.8% for the other three orientations (e.g., east, west, north).

Table 69. Designed Window Areas by Thermal Zone

Zone	Area [ft²]	Conditioned [Y/N]	Volume [ft³]	Multipliers	External Wall Area [ft²]	10% Window Glass Area [ft²]	Baseline (21%) Window Glass Area [ft²]	30% Window Glass Area [ft²]	40% Window Glass Area [ft²]
Space5-1 (Core)	1,611	Yes	16,122	1	0	0	0	0	0
Space1-1 (South)	1,221	Yes	12,221	1	908	91	222	273	364
Space2-1 (East)	724	Yes	7,250	1	605	61	120	182	243
Space3-1 (North)	1,221	Yes	12,221	1	908	91	180	273	364
Space4-1 (West)	724	Yes	7,250	1	605	61	120	182	243
Attic	6,114	No	25,437	1	0	0	0	0	0
Window to Wall Ratio (WWR)					3,026	10%	21%	30%	40%

* Baseline Case Window Fraction (Window-to-Wall Ratio) is 24.4% for South and 19.8% for the other three orientations
* Window Locations are evenly distributed along four façades (Baseline Case Window Dimensions: 6.0 ft x 5.0 ft punch windows for all façades)
* Top of the window is fixed at 8 ft high with different high glasses in test cases

Table 70. Designed Window Dimensions of 10-40% Window-to-Wall Ratios

Zone	Numbers of Windows	10% Window Glass Height [ft]	Baseline (21.2%) Window Glass Height [ft]	30% Window Glass Height [ft]	40% Window Glass Height [ft]	10% Window Glass Width [ft]	Baseline (21%) Window Glass Width [ft]	30% Window Glass Width [ft]	40% Window Glass Width [ft]
Space5-1 (Core)	0	0	0	0	0	0	0	0	0
Space1-1 (South)	6	2.04	5	4.82	5.97	4	6	8	9
Space2-1 (East)	4	3.79	5	5.69	6.74	4	6	8	9
Space3-1 (North)	6	3.79	5	5.68	6.74	4	6	8	9
Space4-1 (West)	4	3.79	5	5.69	6.74	4	6	8	9
Attic	0	0	0	0	0	0	0	0	0
Total	20					16	24	32	36

* Baseline Case Window Fraction (Window-to-Wall Ratio) is 24.4% for South and 19.8% for the other three orientations
* Window Locations are evenly distributed along four façades (Baseline Case Window Dimensions: 6.0 ft x 5.0 ft punch windows for all façades)
* Glassdoor is included for Space1-1 window fraction in the baseline case
* Top of the window is fixed at 8 ft high with different high glasses in test cases

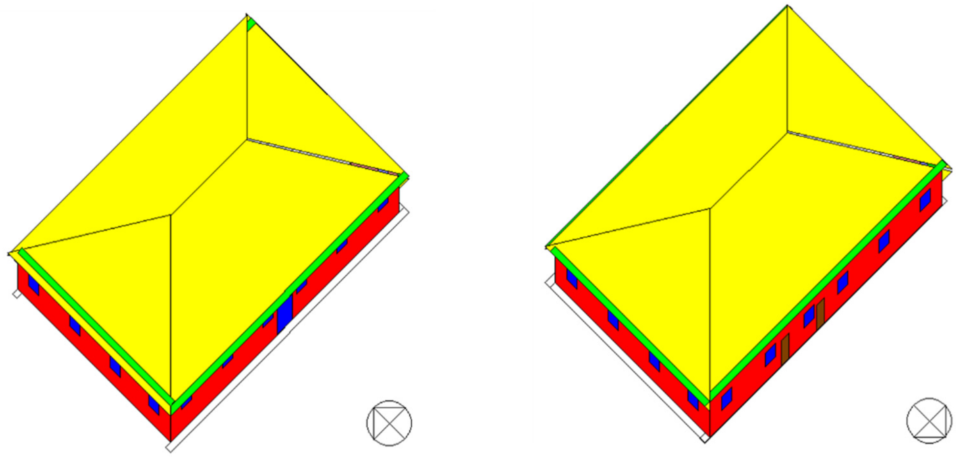
However, the previous researcher did not fully include varying impact of occupancy modeling in their study scope due to building design and system conditions, and locations. For example, Ouf et al. (2019) developed a method to generate and integrate design-sensitive occupant-related lighting schedules for building energy simulations. Using a decision tree model based on a different orientation, window to wall (WWR) ratio, optical characteristics of windows and blinds, and indoor surface reflectances, light schedules were determined and evaluated. The results of this study represented the strongest effect of WWR and building orientation on light use schedules. However, this study only focused on producing design-sensitive light schedules for single offices, even though other simulation schedules for other building types and systems (i.e., windows, equipment, or thermostats) can be developed using a similar workflow. Therefore, this study of OBC can contribute to the identification of the impact of occupancy schedules, considering different designs, systems, and climates on building energy use. For this, three more models are designed at 10%, 30%, and 40% WWR for simulations. The material properties for the reference, raised floor lightweight and heavyweight models were identical with the models in previous chapter 5.2.2. Table 69 and Table 70 are designed window areas and dimensions by the thermal zone.

Table 71. Window-to-Wall Ratios in Four Orientations for Simulations

Orientation	10% Window-to-Wall	Baseline (21.2%) Window-to-Wall	30% Window-to-Wall	40% Window-to-Wall
South	10%	24%	30%	40%
East	10%	20%	30%	40%
North	10%	20%	30%	40%
West	10%	20%	30%	40%
Average WWR	10%	21%	30%	40%

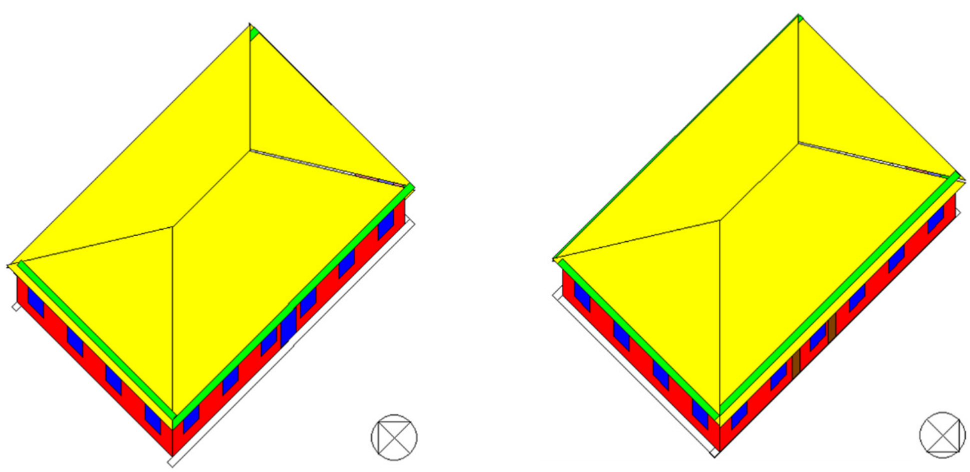
* Baseline (original) models contained glassdoor in the south (space 1-1). South WWR was adjusted in other 10-40% models to evenly distributed for different building orientations. The adjusted south WWR still included glassdoor on the envelope.
* WWR 0% to 40% is the prescriptive requirement of vertical walls in Standard 90.1-2016.

WWR on the facade is evenly distributed on four orientations (i.e., North, East, South, West) in Table 71. The building direction faces the south in all cases. Figure 70 to Figure 73 are exterior views of the simulation models used in this study.



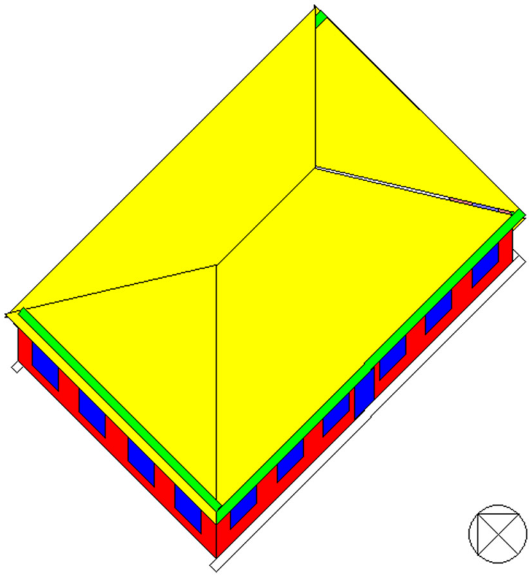
(a) Southeast View (b) Northeast View

Figure 70. Window-to-Wall Ratio 10% Model

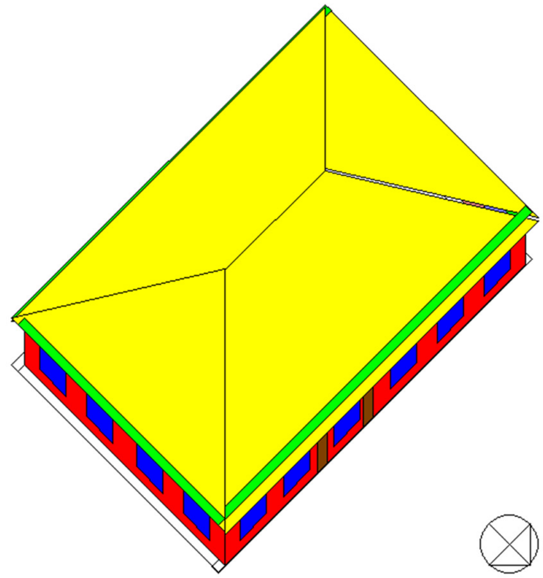


(a) Southeast View (b) Northeast View

Figure 71. Window-to-Wall Ratio 21% Model (default model)

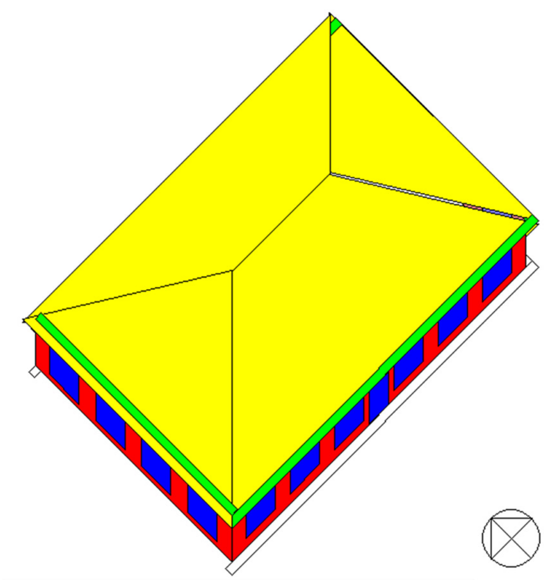


(a) Southeast View

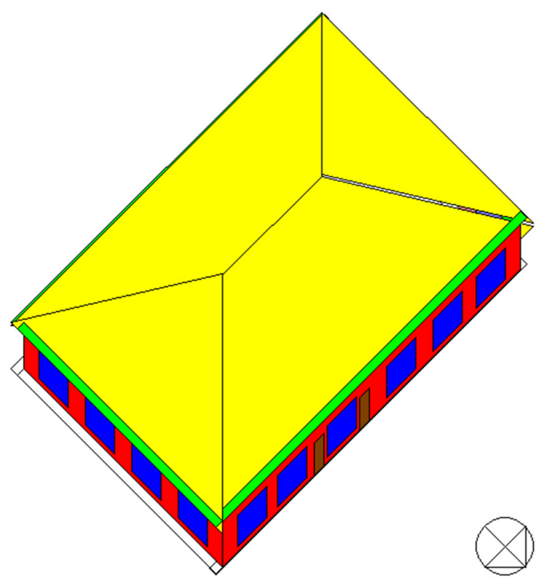


(b) Northeast View

Figure 72. Window-to-Wall Ratio 30% Model



(a) Southeast View



(b) Northeast View

Figure 73. Window-to-Wall Ratio 40% Model

5.2.3.1. Impact of Occupancy-Based Controls in Related Component Loads

In Figure 74 to Figure 79, this study identified the impact of occupancy-based controls in heating, cooling, and ventilation loads. These loads are primarily influenced in energy use by the changes of WWR. The results showed the calculated loads at 100% OBC and 0% OBC of WWR 10-40% models to represent the trends of WWR changes and the maximum energy use reduction potential of OBC. The changes in total energy use with component loads revealed the load sensitivity of OBC in 10-40% WWR models.

In Houston models, PSZ models had higher sensitivity than PVAV systems. According to OBC changes (i.e., 100-0%), cooling and ventilation loads are remarkably reduced, whereas heating loads were expanded, especially in PSZ systems.

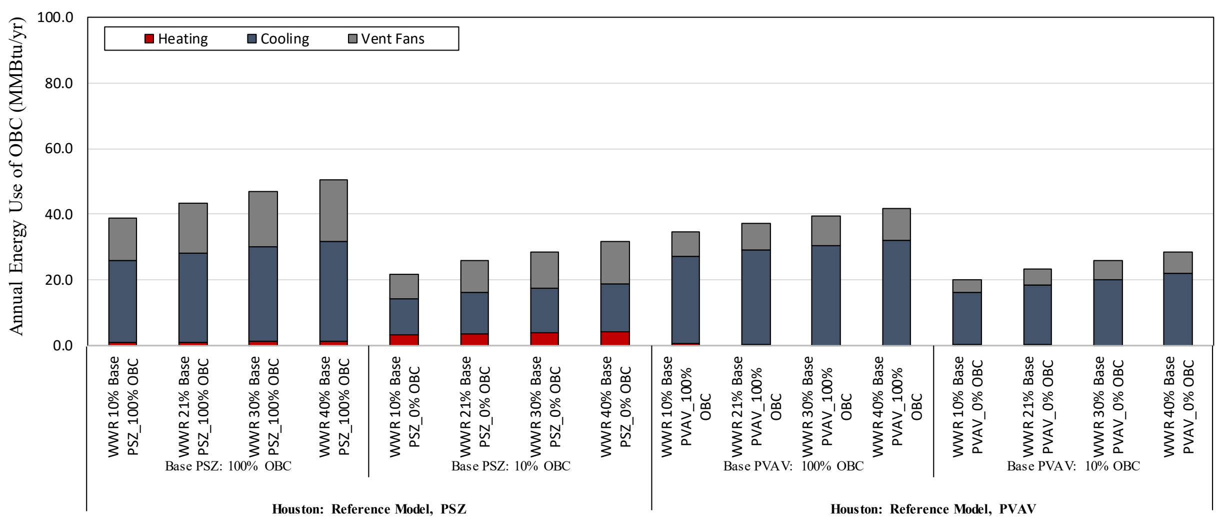


Figure 74. Energy Use of OBC-related Component Loads in Reference Models in Houston

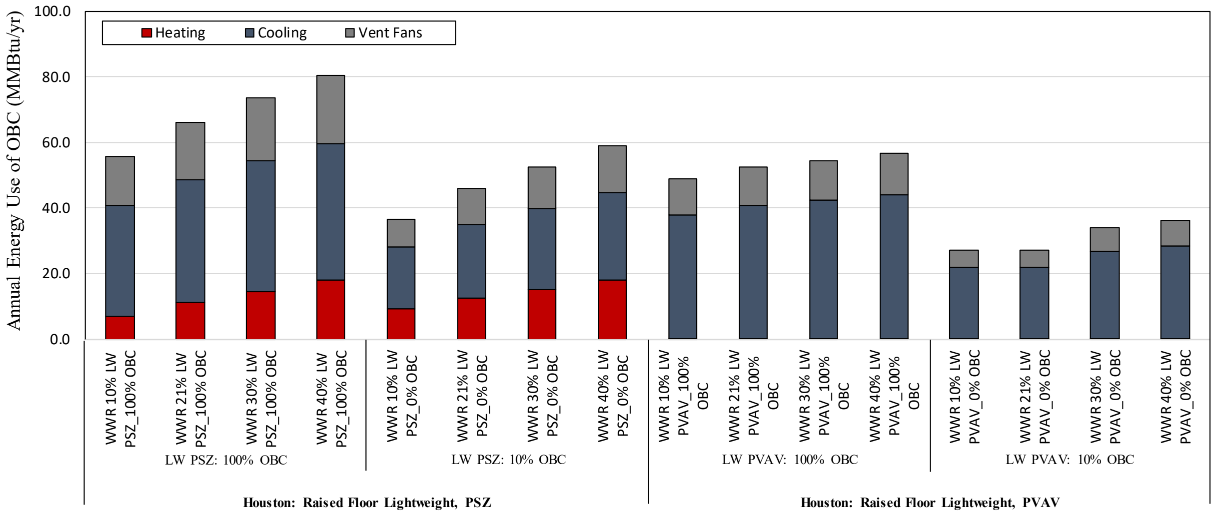


Figure 75. Energy Use of OBC-related Component Loads in Raised Floor Lightweight Models in Houston

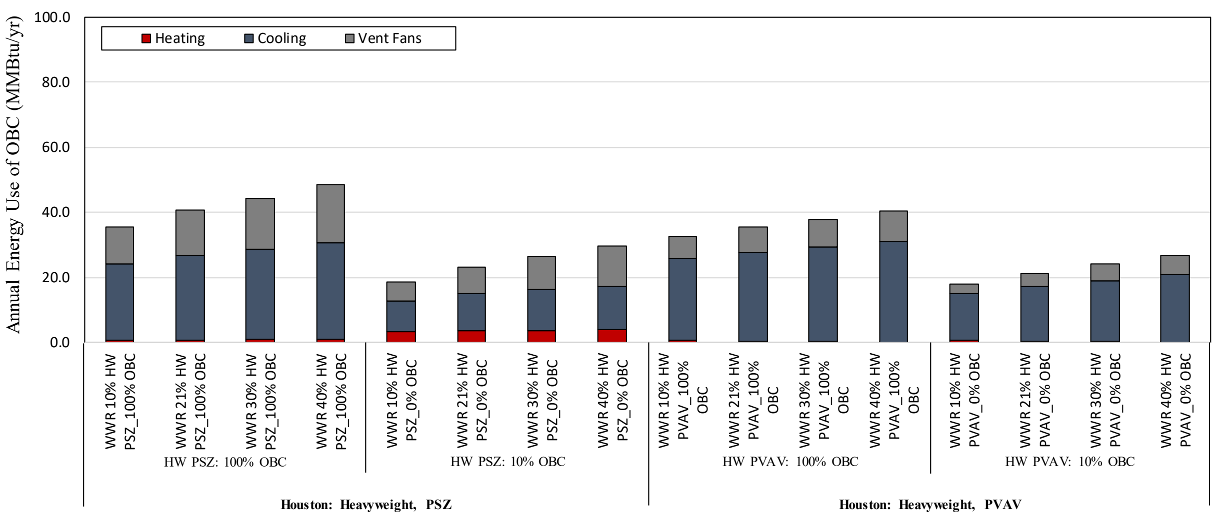


Figure 76. Energy Use of OBC-related Component Loads in Heavyweight Models in Houston

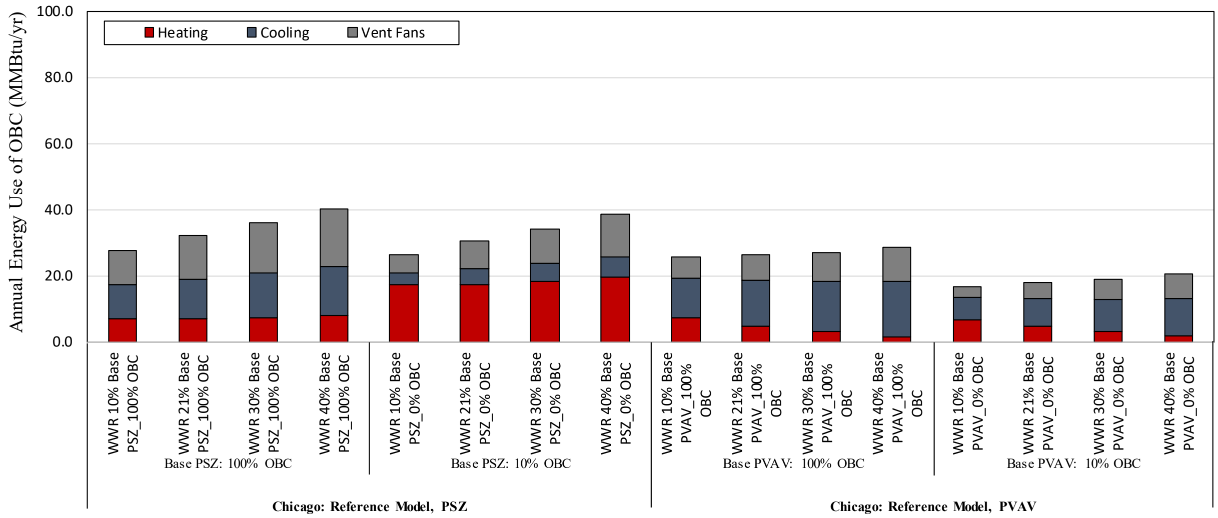


Figure 77. Energy Use of OBC-related Component Loads in Reference Models in Chicago

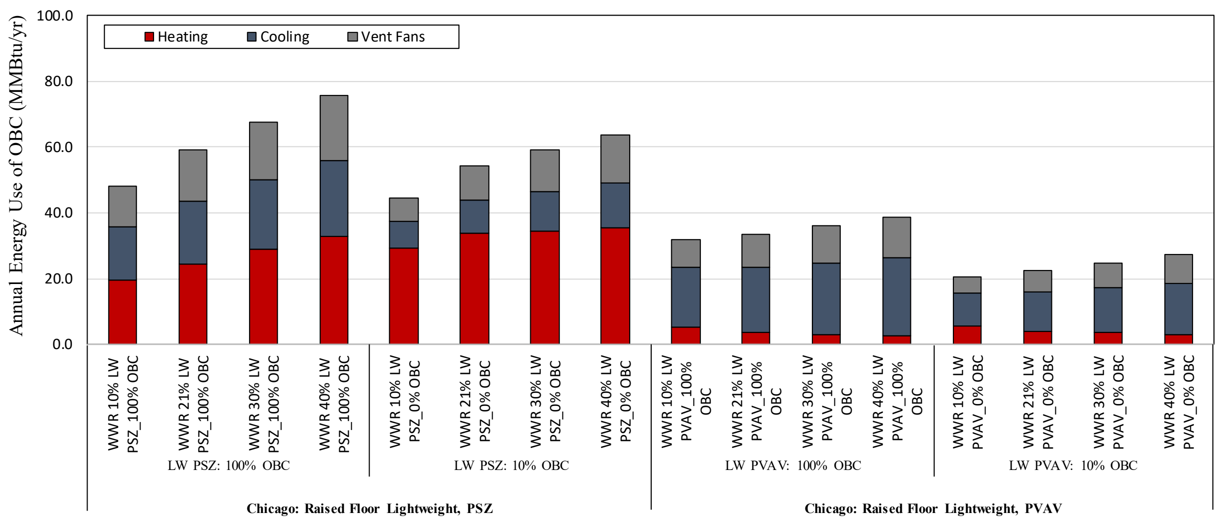


Figure 78. Energy Use of OBC-related Component Loads in Raised Floor Lightweight Models in Chicago

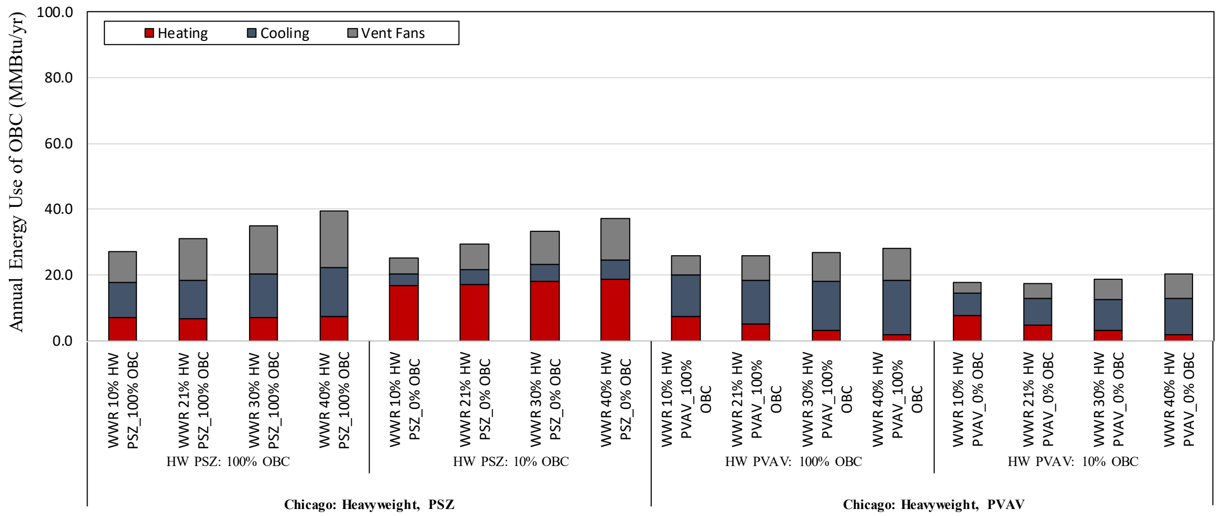
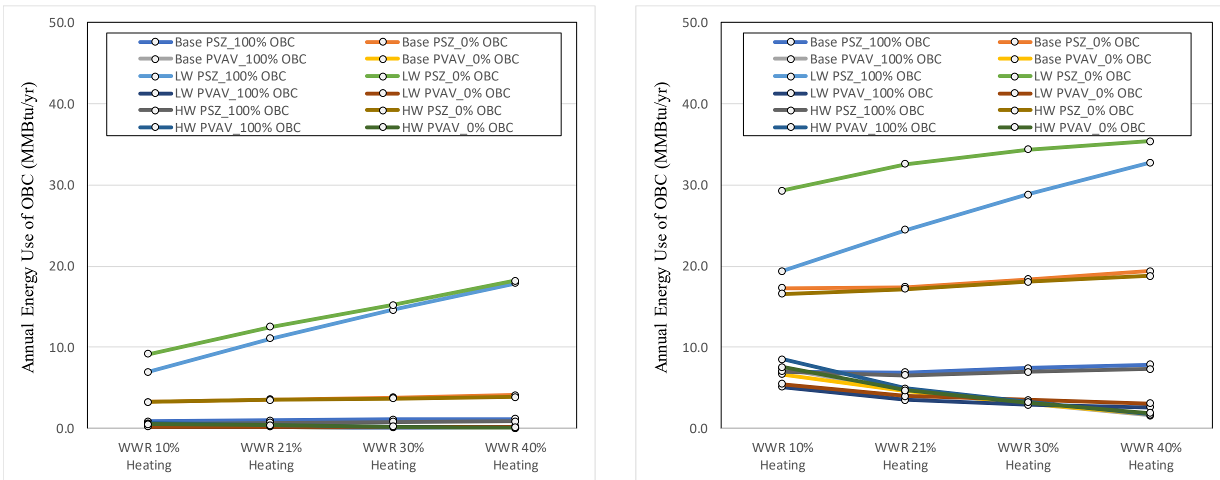


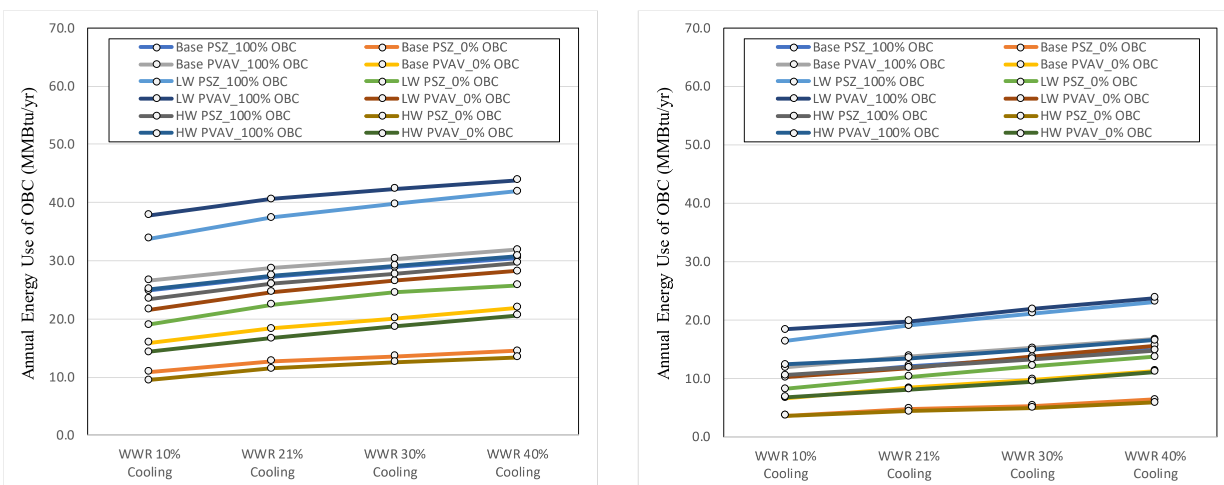
Figure 79. Energy Use of OBC-related Component Loads in Heavyweight Models in Chicago

In Chicago, the increase of heating loads partly offsets a portion of cooling and ventilation loads reduction because the cold-humid climate of Chicago requires more heating energy than Houston. The total energy use of 100% OBC and 0% OBC in Chicago models were mostly less than Houston models except PSZ 0% OBC models. As for total energy use, cooling loads in Houston and heating loads in Chicago had a decisive effect on total load reduction. Also, in all cases, heavyweight models used slightly less energy than the reference models in all climate zones. In WWR 10-40% models of OBC control from 100% to 0%, the trends of heating loads varied depending on the HVAC system type. PSZ systems showed a negative effect of occupancy-based controls, which required more heating energy in both Houston and Chicago as the OBC rate decreased gradually. On the contrary, heating energy in PVAV systems was steadily reduced when WWR was changed from 10% to 40%. Chicago used more heating energy due to higher heating demand under the cold-humid climate in Illinois. Figure 80 showed the simulation result of heating loads of OBC in different WWR designs. As for cooling and ventilation loads, cooling and ventilation load types were consistently grown when window areas were expanded on the building envelope.



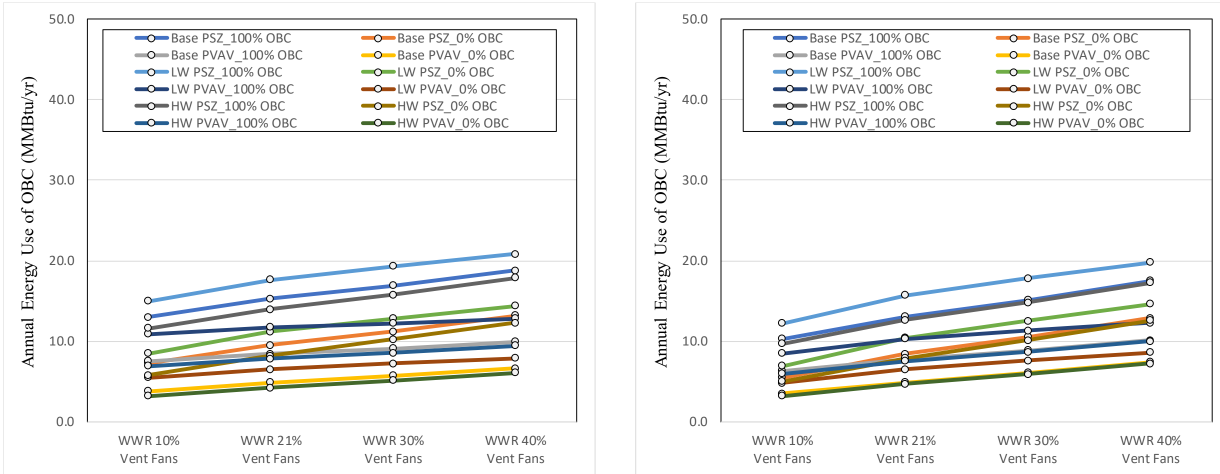
(a) Houston (b) Chicago

Figure 80. Heating Energy Use of OBC in WWR 10-40% Models



(a) Houston (b) Chicago

Figure 81. Cooling Energy Use of OBC in WWR 10-40% Models



(a) Houston (b) Chicago

Figure 82. Ventilation Energy Use of OBC in WWR 10-40% Models

Figure 81 and Figure 82 represent the trends of annual cooling and ventilation energy use in different WWR conditions. The results describe that the increase of WWR led to more energy use in all design cases (i.e., lightweight and heavyweight, PSZ and PVAV system) in Houston and Chicago. The increased range and slope were slightly different, based on OBC rates and HVAC system types. Also, between OBC 100% and OBC 10% models, there were significant gaps. This refers to the large energy use reduction potential of OBC in Houston and Chicago.

5.2.3.2. Impact on Building Energy Use of OBC in Heating, Cooling, Ventilation Loads

Following the calculated OBC-related loads, this chapter addressed the potential energy use reduction of weather-dependent factors using 100%-10% OBC (i.e., occupancy, lighting, and equipment schedules) in WWR 10-40% models. Figure 83 provides the impact on total energy use in the percentage of OBC-related component loads (i.e., heating, cooling, ventilation) in WWR 10-40% designs. In Houston, the potential energy use reduction ratios of PSZ and PVAV systems were similar, but PSZ systems were marginally higher. Contrastively, Chicago models showed significant differences between PSZ and PVAV systems. PSZ systems represented smaller energy use reduction effects due to the large increase in heating energy consumption than PVAV systems in Chicago. The maximum energy use reduction of OBC in Houston were 47.1-50.2% of reference PSZ, 40.5-45.7% of raised floor LW PSZ, 47.9-51.2% of HW PSZ, 46.0-49.6% of reference PVAV, 46.2-49.6% of raised floor LW PVAV, and 46.8-50.5% of HW PVAV. In Chicago, the maximum energy use reduction of OBC were 37.8-41.5% of reference PSZ, 37.2-40.1% of raised floor LW PSZ, 38.4-42.4% of HW PSZ, 46.5-48.4% of reference PVAV, 45.4-47.8% of raised floor LW PVAV, and 46.6-48.3% of HW PVAV. The maximum energy use reduction percentage of OBC occurred in all cases of WWR 10% models, and the minimum energy use reduction percentage of OBC was produced in all cases of WWR 40%.

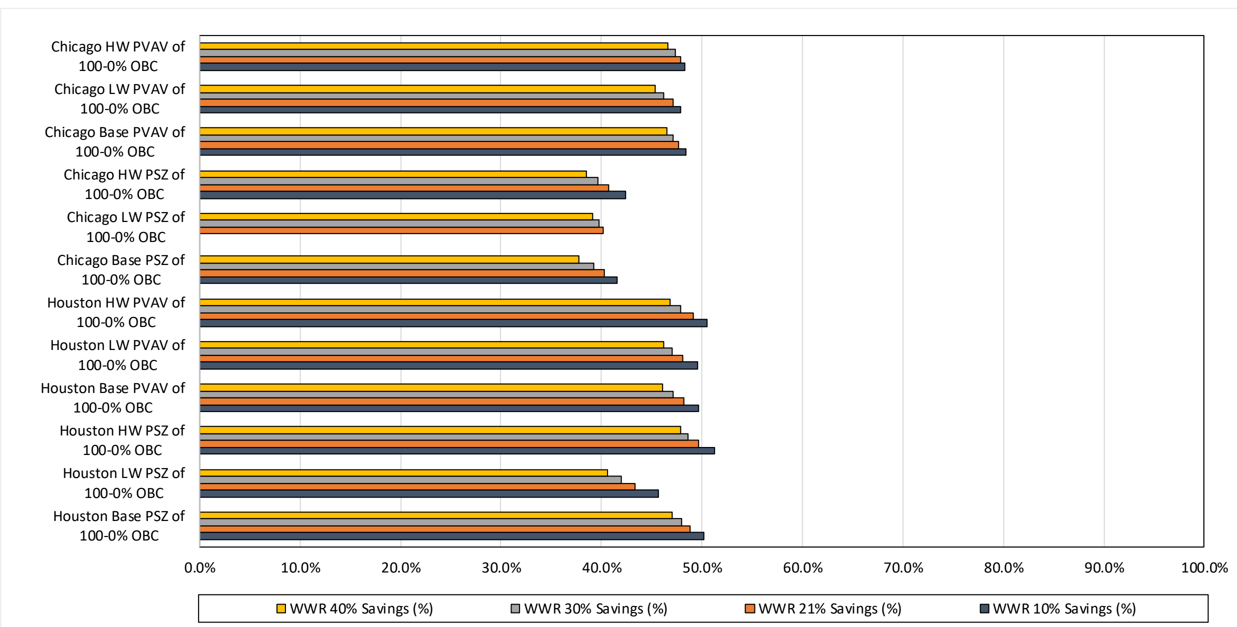


Figure 83. Impact on Total Energy Use Reduction of OBC Component Loads in WWR 10-40%

The result of WWR ratio showed that the effect of occupancy-based controls would vary depending on building design, such as different window-to-wall ratio in office buildings. However, typically high WWR ratio buildings represented more energy use reduction in weather-dependent factors (i.e., heating, cooling, ventilation) in Houston and Chicago.

5.2.4. Impact on Building Energy Use of Individual Zone Occupancy-Based Controls

This chapter evaluated potential energy use reduction of partial OBC applications in thermal zones. In reality, each space of the buildings has a different usage schedule depending on space type, user type, and activity type. This fact indicates that each space holds its schedules and thermal demands for HVAC operations. Therefore, this study calculated possible energy use reduction from individual OBC applications in five-zone models using different usage scenarios.

Table 72. Office Building Usage Intensity of OBC in simulations

OBC Intensity Type	OBC Schedule level	Description
Maximum Usage	OBC 100%	Maximum building usage in 24-hour operations
Standard Usage	OBC 90%	Standard OBC usage based on average occupancy rate (i.e., 90%) in Standard 90.1-2016 schedules during 9 AM-5 PM on weekdays
Medium Usage	OBC 50%	Medium building usage during 9 AM-5 PM in weekdays
Minimum Usage	OBC 0%	Unoccupied condition, Weekend and set-back schedules used

* Weekend schedules of OBC are identical with Standard 90.1-2016 small office schedules. OBC operations applied only on weekdays.
* The details of OBC schedules are described in Chapter 4.3.

An individual zone was selected for occupancy-based controls and the remaining four zones used Standard 90.1-2016 schedules (i.e., occupancy, lighting, equipment, set-temperature, set-back schedule, ventilation fan schedule). Among 100% OBC to 0% OBC, a selected thermal zone used four types of OBC schedules (i.e., max, standard, medium, min) to represent different space usage levels in practice. OBC schedules in this chapter are identical to previously used schedules for weekdays. Table 72 describes four types of OBC usage intensities for simulation evaluations in this chapter. Maximum usage represents 100% building occupancy and operation for 24 hours. Also, standard usage (i.e., OBC 90%) is a Standard 90.1-2016 schedule-based OBC schedule. In Standard 90.1-2016 schedules, the average occupancy from 9 AM-5 PM on weekdays is around 90%. The medium level reflects the recent changes in the working environment, such as new information technology development (e.g., conference call, homeworking) and business culture shift. Minimum usage is an unoccupied condition during the daytime on weekdays.

To estimate the impact of OBC applications in the selected zone when the buildings applied different types of simulation schedules in thermal zones, a total of 960 analysis cases were simulated as Table 73. Simulation cases included several independent variables of building designs, such as different orientations, WWR, building material (i.e., reference, raised floor lightweight, heavyweight), system type (i.e., PSZ, PVAV), climate zone (i.e., CZ 2A, CZ 5A). The results of various cases would show energy use reduction in different building operation environments and design conditions.

Table 73. Individual Zone Energy Performance Analysis of 100-0% OBC in Houston and Chicago

Group	Location	Simulation Cases			Independent Variables				Controlled Variables		Other Schedules			
		System Type	Envelope Material	Average WWR	Thermal Zone	OBC Schedule Type** (Weekdays, 9 AM-5 PM)			Thermal Zone	Schedule Type				
						Occup	Light	Equip			Infilt	Vent	Set-temp	Set-back
1	Houston	PSZ, PVAV	Ref/ LW/HW	10-40%	South (S1-1)	Max-Min	Max-Min	Max-Min	Rest Zones	Std 90.1-2016	Off	1.0	H: 70°F C: 75°F	H: 60°F C: 85°F
2	Houston	PSZ, PVAV	Ref/ LW/HW	10-40%	East (S2-1)	Max-Min	Max-Min	Max-Min	Rest Zones	Std 90.1-2016	Off	1.0	H: 70°F C: 75°F	H: 60°F C: 85°F
3	Houston	PSZ, PVAV	Ref/ LW/HW	10-40%	North (S3-1)	Max-Min	Max-Min	Max-Min	Rest Zones	Std 90.1-2016	Off	1.0	H: 70°F C: 75°F	H: 60°F C: 85°F
4	Houston	PSZ, PVAV	Ref/ LW/HW	10-40%	West (S4-1)	Max-Min	Max-Min	Max-Min	Rest Zones	Std 90.1-2016	Off	1.0	H: 70°F C: 75°F	H: 60°F C: 85°F
5	Houston	PSZ, PVAV	Ref/ LW/HW	10-40%	Core (S5-1)	Max-Min	Max-Min	Max-Min	Rest Zones	Std 90.1-2016	Off	1.0	H: 70°F C: 75°F	H: 60°F C: 85°F
6	Chicago	PSZ, PVAV	Ref/ LW/HW	10-40%	South (S1-1)	Max-Min	Max-Min	Max-Min	Rest Zones	Std 90.1-2016	Off	1.0	H: 70°F C: 75°F	H: 60°F C: 85°F
7	Chicago	PSZ, PVAV	Ref/ LW/HW	10-40%	East (S2-1)	Max-Min	Max-Min	Max-Min	Rest Zones	Std 90.1-2016	Off	1.0	H: 70°F C: 75°F	H: 60°F C: 85°F
8	Chicago	PSZ, PVAV	Ref/ LW/HW	10-40%	North (S3-1)	Max-Min	Max-Min	Max-Min	Rest Zones	Std 90.1-2016	Off	1.0	H: 70°F C: 75°F	H: 60°F C: 85°F
9	Chicago	PSZ, PVAV	Ref/ LW/HW	10-40%	West (S4-1)	Max-Min	Max-Min	Max-Min	Rest Zones	Std 90.1-2016	Off	1.0	H: 70°F C: 75°F	H: 60°F C: 85°F
10	Chicago	PSZ, PVAV	Ref/ LW/HW	10-40%	Core (S5-1)	Max-Min	Max-Min	Max-Min	Rest Zones	Std 90.1-2016	Off	1.0	H: 70°F C: 75°F	H: 60°F C: 85°F

* In individual zone analysis, OBC applied only in a selected thermal zone, and the rest four zones were controlled and used the Standard 90.1-2016 schedules for occupancy, lighting, equipment schedules. The other schedule types (i.e., infiltration, ventilation fan, set-temperature, set-back temperature) are identical between all models.

* Lightweight envelope materials refer to envelope properties used in PNNL small office buildings for Standard 90.1-2016 except floor. The floor u-value complied with Standard 90.1-2016. Heavyweight envelope materials are based on building
constructions used in PNNL large office buildings for Standard 90.1-2016. Thermal properties (e.g., u-value) for envelope are identical between lightweight and heavyweight.

* Weekend schedules set to minimum operating conditions of simulation schedules (e.g., occupancy=0.0, 0%; lighting=0.18, 18%; equipment=0.20, 20%;; infiltration=off; ventilation fan=0.0; set-point temperature: heating 60°F, cooling 85°F).

* Default window-to-wall (WWR) ratio in small office models is 21% on average. Window fraction is 24.4% for South and 19.8% for the other three orientations (e.g., east, west, north).

** OBC schedule types are OBC 100%, OBC 90%, OBC 50%, and OBC 0%, which are maximum to minimum OBC usage intensities for office models.

5.2.4.1. Impact of Individual Occupancy-Based Controls in Houston

The occupancy-based control impact in the selected zone applications was analyzed by orientation in five zone models. Briefly, the results showed that total loads gradually increased as WWR increased while their patterns decreased as the OBC rate decreases. In architectural design, WWR significantly affected heating, cooling, and ventilation loads. Higher WWR led to more heating loads in PSZ systems due to reduced internal heat gains and required more cooling and ventilation loads due to increased solar gains. Occupancy-based controls had a bigger impact on energy use reduction when WWR are smaller. In this chapter, all results of simulations were extracted from the BEPS reports in DOE-2.1e. Table 74 outlines the impact of partial occupancy-based control applications in a particular zone in total load calculations. The energy use reduction ranges of WWR changes were lowered in high WWR office buildings in both PSZ and PVAV systems. Maximum occupancy control reduction rates were found in Space5-1 (core), whereas min OBC energy use reduction rate happened in Space2-1 (East). In terms of orientation effect in occupancy-based building control energy reductions, the west zone (Space4-1) represented more energy use reduction potential compared to the east zone (Space2-1). Also, the south zone (Space1-1) showed higher energy use reduction ratios than the north zone (Space3-1).

Table 74. Normalized Energy Use Reduction on Total Loads in Individual Zone OBC

Type	PSZ System				PVAV System			
	WWR 10%	WWR 21%	WWR 30%	WWR 40%	WWR 10%	WWR 21%	WWR 30%	WWR 40%
Ref: OBC South zone	-43%	-41%	-40%	-39%	-44%	-43%	-42%	-41%
Ref: OBC East zone	-41%	-40%	-39%	-38%	-43%	-42%	-40%	-39%
Ref: OBC North zone	-42%	-40%	-39%	-38%	-41%	-40%	-39%	-39%
Ref: OBC West zone	-42%	-40%	-39%	-38%	-45%	-44%	-43%	-42%
Ref: OBC Core zone	-44%	-42%	-41%	-40%	-44%	-43%	-41%	-40%
LW: OBC South zone	-39%	-38%	-36%	-35%	-43%	-41%	-40%	-39%
LW: OBC East zone	-37%	-35%	-33%	-32%	-44%	-42%	-41%	-40%
LW: OBC North zone	-39%	-36%	-34%	-32%	-41%	-40%	-39%	-42%
LW: OBC West zone	-39%	-36%	-34%	-33%	-45%	-44%	-43%	-41%
LW: OBC Core zone	-43%	-42%	-41%	-40%	-44%	-43%	-41%	-40%
HW: OBC South zone	-44%	-42%	-41%	-40%	-43%	-41%	-40%	-39%
HW: OBC East zone	-43%	-41%	-39%	-38%	-44%	-42%	-41%	-40%
HW: OBC North zone	-44%	-42%	-40%	-39%	-42%	-41%	-39%	-39%
HW: OBC West zone	-43%	-41%	-40%	-38%	-44%	-42%	-41%	-40%
HW: OBC Core zone	-45%	-43%	-42%	-40%	-44%	-43%	-42%	-41%
Reduction range of WWR	-37 to -45%	35 to -43%	-33 to -42%	-32 to -40%	-41 to -45%	-40 to -44%	-39 to -43%	-39 to -42%

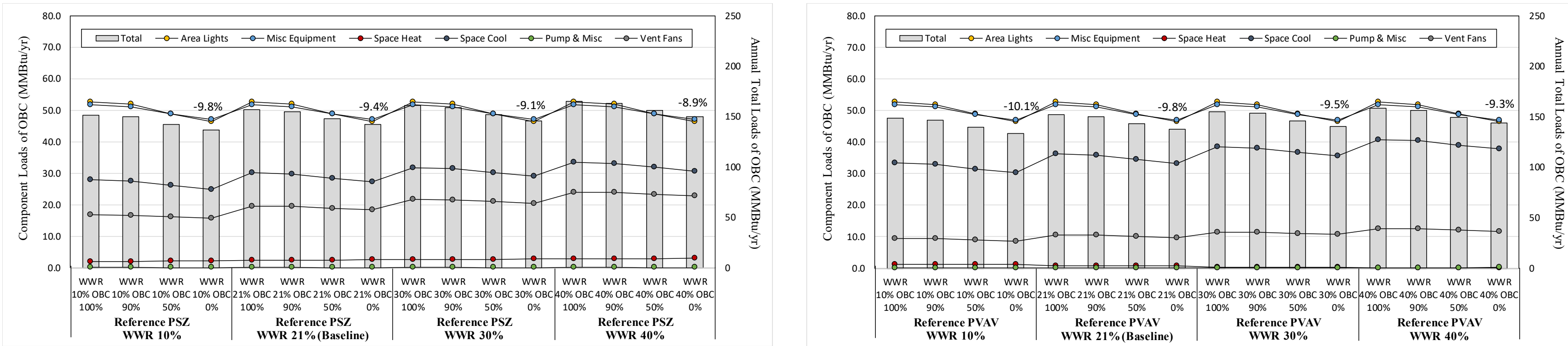
* Total loads energy reduction rates were calculated as the differences between OBC 100% (max usage) and OBC 0% (min usage, unoccupied)
* Occupant density for simulations is 180 ft^2/people based ASHRAE Standard 62.1-2013

Table 75. Normalized Energy Use Reduction on Total Loads in Individual Zone OBC

Type (Unit: kBtu/ft^2)	PSZ System				PVAV System			
	WWR 10%	WWR 21%	WWR 30%	WWR 40%	WWR 10%	WWR 21%	WWR 30%	WWR 40%
Ref: OBC South zone	11.8	11.7	11.7	11.7	12.0	11.8	11.8	11.7
Ref: OBC East zone	11.5	11.5	11.5	11.4	11.8	11.6	11.5	11.4
Ref: OBC North zone	11.6	11.5	11.5	11.4	11.6	11.5	11.3	11.2
Ref: OBC West zone	11.6	11.5	11.5	11.5	11.8	11.7	11.6	11.4
Ref: OBC Core zone	11.9	11.9	11.9	11.8	11.7	11.7	11.6	11.5
LW: OBC South zone	12.2	12.3	12.3	12.3	13.1	12.8	12.7	12.6
LW: OBC East zone	11.8	11.9	11.9	11.9	12.4	12.4	12.3	12.3
LW: OBC North zone	12.0	12.0	12.0	12.0	12.3	12.1	12.0	13.2
LW: OBC West zone	12.0	12.1	12.1	12.1	12.6	12.5	12.4	12.3
LW: OBC Core zone	12.6	12.7	12.7	12.7	13.3	13.3	13.3	13.3
HW: OBC South zone	11.8	11.7	11.7	11.7	11.9	12.0	11.9	11.7
HW: OBC East zone	11.6	11.5	11.5	11.4	11.8	11.7	11.6	11.4
HW: OBC North zone	11.7	11.6	11.5	11.4	11.8	11.7	11.5	11.3
HW: OBC West zone	11.7	11.6	11.5	11.5	11.8	11.8	11.6	11.5
HW: OBC Core zone	11.9	11.9	11.9	11.9	11.7	11.7	11.7	11.6
Reduction range of WWR	11.5 to 12.6	11.5 to 12.7	11.5 to 12.7	11.4 to 12.7	11.6 to 13.3	11.5 to 13.3	11.3 to 13.3	11.2 to 13.3

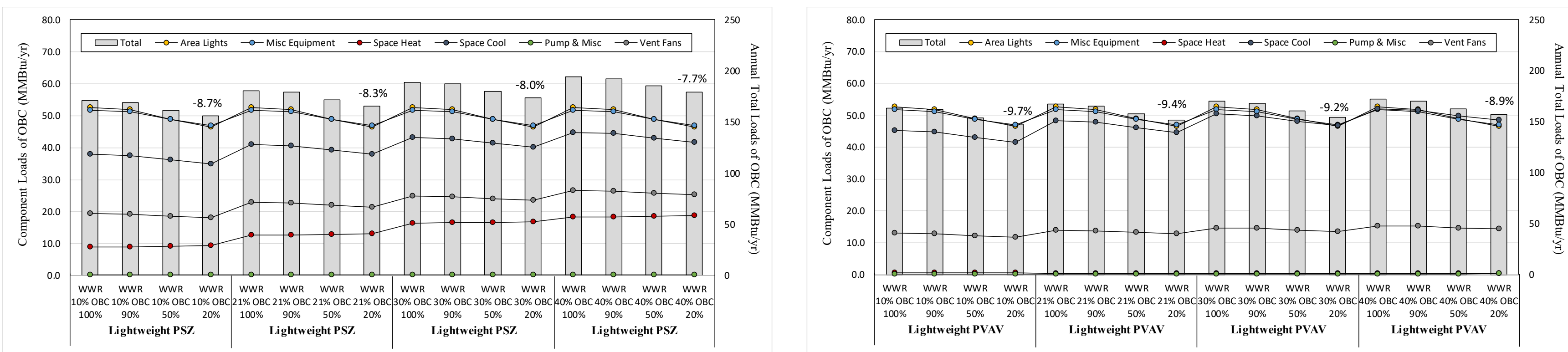
* Total loads energy reduction rates were calculated as the differences between OBC 100% (max usage) and OBC 0% (min usage, unoccupied)
* Occupant density for simulations is 180 ft^2/people based ASHRAE Standard 62.1-2013

In detail, Figure 84 to Figure 86 illustrate examples of the overall building loads and component loads when occupancy-based control is applied only to Space1-1 (south) in Houston. In this model, the rest four zones applied Standard 90.1-2016 schedules for HVAC operations. In the interpretation of the result, there were several significant findings of occupancy-based controls. The result showed that occupancy-based controls could contribute to load reduction more when WWR was smaller (e.g., WWR 10%). Between the reference, raised floor lightweight (LW) and heavyweight (HW) in PSZ models, heavyweight models showed higher energy use reduction ratios than reference and raised floor lightweight models. Between the PSZ system and PVAV systems, PVAV systems represented higher energy use reduction percentages than the PSZ system models, including both LW and HW cases. Occupancy-based controls applied in Space1-1 (south) showed that WWR 10% OBC 0% of the reference PSZ used 9.8% less energy in total loads than WWR 10% OBC 100% of the reference PSZ. WWR 40% OBC 0% of the reference PSZ used 8.9% less energy in total loads than WWR 40% OBC 100% of the reference PSZ. Also, as for envelope materials (i.e., reference, LW, HW), the reference PSZ of WWR 40% OBC 100% use 1.5% more energy than heavyweight PSZ of WWR 40% OBC 100% in total loads. The primary contributors to OBC energy use reduction were lighting, equipment, cooling, and ventilation loads. These load patterns of occupancy-based controls were similar in the other simulation groups (i.e., PVAV, heavyweight), but energy use reduction ratios varied depending on architectural design and system design. Also, similar energy use reduction trends are mostly shown across all individual zone OBC analyses.



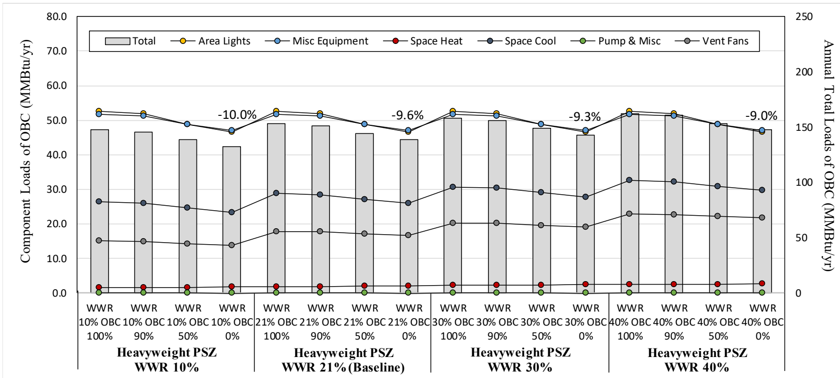
(a) Reference, PSZ (b) Reference, PVAV

Figure 84. Reference Model: Impact of Occupancy-Based Controls of Space1-1 (South) in Houston

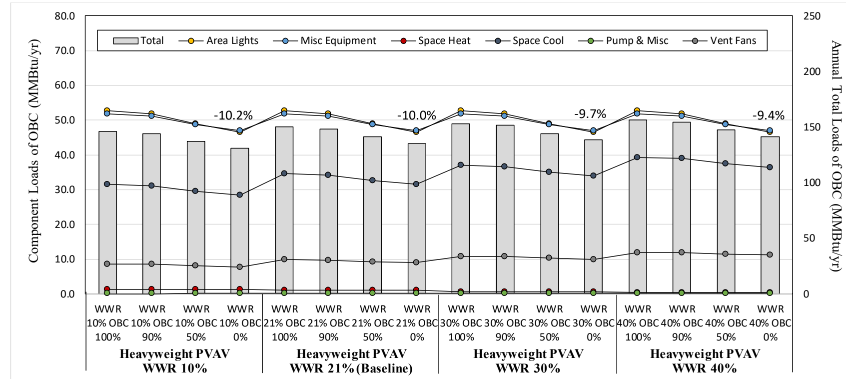


(a) Lightweight, PSZ (b) Lightweight, PVAV

Figure 85. Lightweight Model: Impact of Occupancy-Based Controls of Space1-1 (South) in Houston



(a) Heavyweight, PSZ



(b) Heavyweight, PVAV

Figure 86. Heavyweight Model: Impact of Occupancy-Based Controls of Space1-1 (South) in Houston

5.2.4.2. Impact of Individual Occupancy-Based Controls in Chicago

In this chapter, the impact of occupancy-based control application in a specific zone was calculated by orientation in Chicago. In conclusion, the total loads of occupancy-based controls steadily expanded as WWR increased while their patterns were declined as the OBC rate decreases. In building design, WWR on building envelope significantly affected heating, cooling, and ventilation loads. Higher WWR led to more heating loads in PSZ systems and less heating in PVAV systems. In contrast, cooling and ventilation loads were raised in high WWR. Occupancy-based controls had a more significant impact in Chicago when WWR are smaller.

Table 76. Normalized Energy Use Reduction on Total Loads in Individual Zone OBC

Type	PSZ System				PVAV System			
	WWR 10%	WWR 21%	WWR 30%	WWR 40%	WWR 10%	WWR 21%	WWR 30%	WWR 40%
Ref: OBC South zone	-37%	-36%	-35%	-34%	-42%	-42%	-42%	-41%
Ref: OBC East zone	-36%	-34%	-33%	-32%	-42%	-41%	-41%	-40%
Ref: OBC North zone	-34%	-33%	-33%	-32%	-40%	-40%	-39%	-38%
Ref: OBC West zone	-36%	-35%	-34%	-33%	-43%	-41%	-40%	-39%
Ref: OBC Core zone	-34%	-33%	-32%	-30%	-40%	-40%	-39%	-38%
LW: OBC South zone	-31%	-31%	-30%	-29%	-41%	-41%	-40%	-39%
LW: OBC East zone	-30%	-28%	-27%	-26%	-42%	-41%	-40%	-39%
LW: OBC North zone	-30%	-25%	-24%	-23%	-39%	-39%	-38%	-37%
LW: OBC West zone	-31%	-29%	-27%	-26%	-42%	-42%	-42%	-41%
LW: OBC Core zone	-32%	-28%	-27%	-27%	-41%	-42%	-41%	-40%
HW: OBC South zone	-37%	-37%	-36%	-34%	-40%	-40%	-40%	-38%
HW: OBC East zone	-37%	-35%	-34%	-32%	-42%	-42%	-41%	-41%
HW: OBC North zone	-38%	-33%	-33%	-33%	-41%	-41%	-40%	-39%
HW: OBC West zone	-38%	-35%	-34%	-33%	-41%	-41%	-40%	-39%
HW: OBC Core zone	-35%	-33%	-32%	-31%	-42%	-41%	-41%	-39%
Reduction range of WWR	-30 to -38%	-25 to -37%	-24 to -36%	-23 to -34%	-39 to -43%	-39 to -42%	-38 to -42%	-37 to -42%

* Total loads reduction rates were calculated as the differences between OBC 100% (max usage) and OBC 0% (min usage, unoccupied)
* Occupant density for simulations is 180 ft^2/people based ASHRAE Standard 62.1-2013

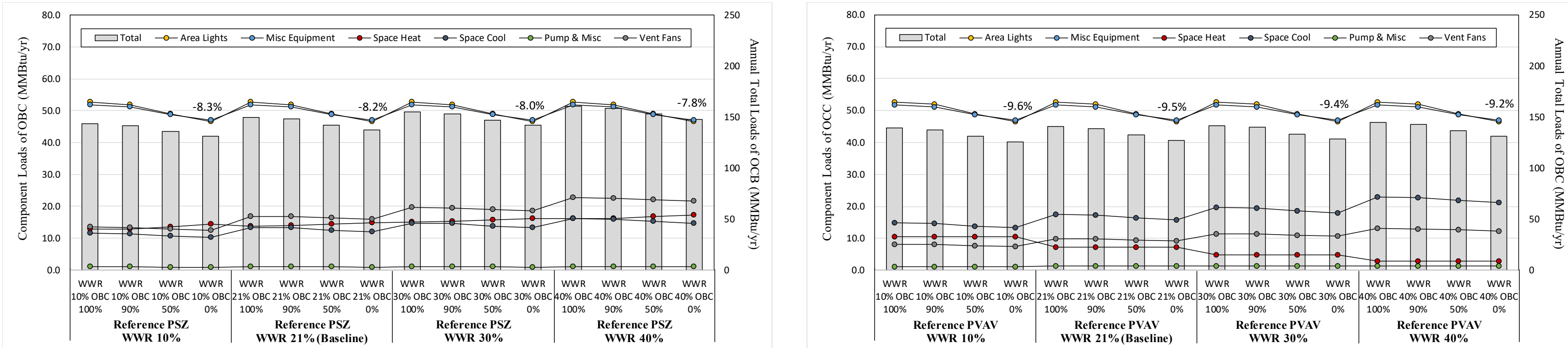
Table 76 summarizes the impact of OBC applications in a particular zone in total load estimations. The energy use reduction ranges of WWR became small in high WWR office buildings in both PSZ and PVAV systems. Like the results in Houston, max OBC energy use reduction rates were represented in Space5-1 (core), while min OBC energy use reduction rate found in Space2-1 (East). When it comes to the orientation effect in occupancy control energy reduction, the west zone (Space4-1) showed more energy use reduction potential compared to the east zone (Space2-1). Also, the south zone (Space1-1) showed higher energy use reduction ratios than the north zone (Space3-1).

Table 77. Normalized Energy Use Reduction on Total Loads in Individual Zone OBC

Type (Unit: kBtu/ft^2)	PSZ System				PVAV System			
	WWR 10%	**WWR 21%**	**WWR 30%**	**WWR 40%**	**WWR 10%**	**WWR 21%**	**WWR 30%**	**WWR 40%**
Ref: OBC South zone	9.6	9.9	9.9	10.0	10.7	10.7	10.7	10.7
Ref: OBC East zone	9.5	9.5	9.5	9.4	10.6	10.5	10.4	10.4
Ref: OBC North zone	8.6	9.0	9.2	9.3	10.3	10.2	10.4	10.1
Ref: OBC West zone	9.6	9.7	9.7	9.7	10.7	10.7	10.6	10.6
Ref: OBC Core zone	8.7	8.8	8.8	8.8	10.5	10.5	10.4	10.4
LW: OBC South zone	9.4	9.9	10.0	10.2	11.2	11.2	11.2	11.2
LW: OBC East zone	9.1	9.3	9.4	9.5	10.8	10.8	10.8	10.8
LW: OBC North zone	8.8	8.3	8.4	8.5	10.4	10.4	10.4	10.4
LW: OBC West zone	9.4	9.4	9.5	9.6	11.1	11.1	11.1	11.1
LW: OBC Core zone	9.0	8.3	8.3	8.3	11.2	10.9	10.9	10.9
HW: OBC South zone	9.6	9.9	9.9	10.0	10.8	10.7	10.7	10.7
HW: OBC East zone	9.3	9.6	9.5	9.4	10.6	10.6	10.5	10.5
HW: OBC North zone	9.4	8.9	9.2	9.4	10.4	10.2	10.2	10.1
HW: OBC West zone	9.4	9.7	9.7	9.6	10.8	10.7	10.6	10.6
HW: OBC Core zone	8.6	8.8	8.8	8.8	10.6	10.5	10.5	10.4
Reduction range of WWR	8.6 to 9.6	8.3 to 9.9	8.3 to 10.0	8.3 to 10.2	10.3 to 11.2	10.2 to 11.2	10.2 to 11.2	10.1 to 11.2

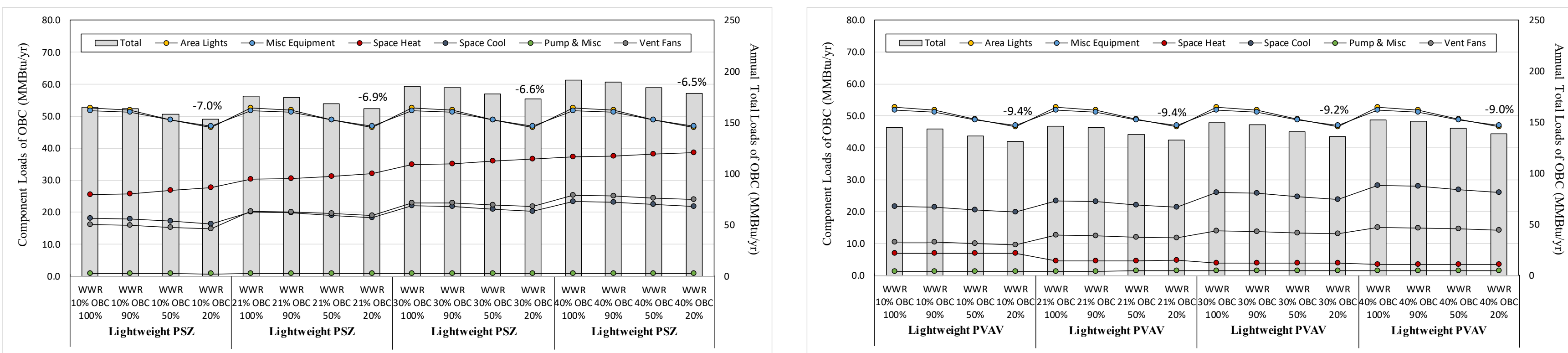
* Total loads reduction rates were calculated as the differences between OBC 100% (max usage) and OBC 0% (min usage, unoccupied)
* Occupant density for simulations is 180 ft^2/people based ASHRAE Standard 62.1-2013

Figure 87 to Figure 89 describes the example simulation results of the total building loads and the component loads in cases of Space1-1 (south) OBC in Chicago. In this model, the remaining four zones used Standard 90.1-2016 schedules for building system operations. From the results, several findings of occupancy-based controls were revealed. The result found that occupancy-based controls could provide more energy use reductions when WWR was smaller (e.g., WWR 10%). Between the reference, raised floor lightweight (LW) and heavyweight (HW) in PSZ models, heavyweight models showed higher energy energy use reduction ratios than the reference, raised floor lightweight models in Chicago. Between the PSZ system and PVAV systems, PVAV systems had higher energy use reduction percentages than the PSZ system models, including both LW and HW cases. The primary contributors to occupancy-based control reductions were lighting, equipment, cooling, and ventilation loads. Heating loads added more building loads in PSZ system simulations. Such trends of building loads in occupancy-based controls were similar in the other simulation groups (i.e., PVAV, heavyweight), but energy use reduction ratios varied depending on architectural design and system design. Also, similar energy use reduction trends are mostly shown across all individual zone OBC analyses.



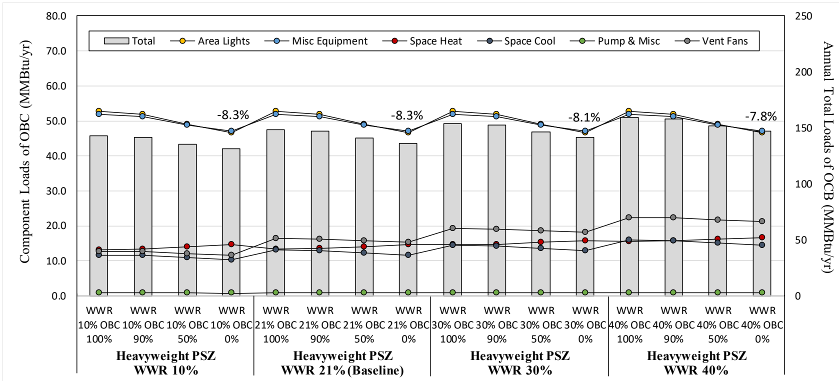
(a) Reference, PSZ (b) Reference, PVAV

Figure 87. Reference Model: Impact of Occupancy-Based Controls of Space1-1 (South) in Chicago

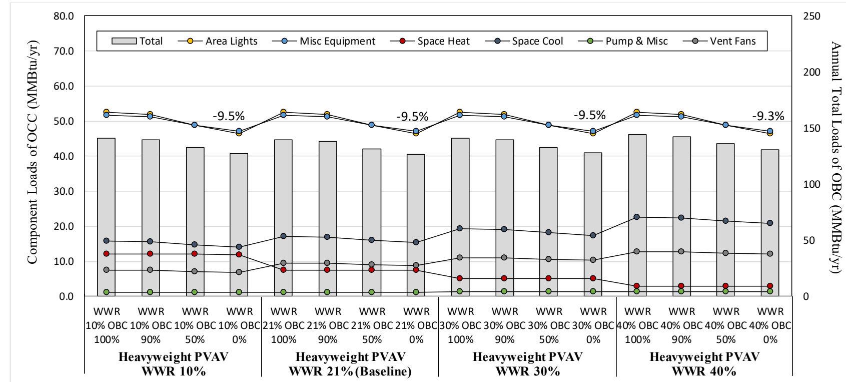


(a) Lightweight, PSZ (b) Lightweight, PVAV

Figure 88. Lightweight Model: Impact of Occupancy-Based Controls of Space1-1 (South) in Chicago



(a) Heavyweight, PSZ



(b) Heavyweight, PVAV

Figure 89. Heavyweight Model: Impact of Occupancy-Based Controls of Space1-1 (South) in Chicago

In terms of the impact in load components, lighting and equipment loads were influenced by only OBC intensity from 100% to 0%. Lighting and equipment loads are determined based on lighting power density (W/ft^2), equipment power density (W/ft^2), and their operating schedules. Therefore, if optimized occupancy-based controls can be applied in energy simulations, it would have a substantial impact on building energy performance calculations. The occupancy-based control effect in heating loads was different depending on HVAC system types. PSZ systems showed a negative effect on building energy use, while PVAV systems represented diverse effects depending on OBC intensity and WWR level. In Chicago, since heating loads were considerable, heating loads lowered energy use reduction potential in occupancy-based control models compared to Houston models. Cooling loads were still the most significant weather-dependent contributor to OBC energy use reduction in Chicago. Energy use reduction potential gradually increased when the office building's usage level was lower in WWR 10-40% models. In terms of system type, PVAV systems in Chicago displayed more energy use reduction potential than PSZ systems, especially in cooling loads. Also, although PVAV systems used less energy in ventilation fans than PSZ systems, energy use reduction potential was lower than PSZ systems except WWR 10% HW PSZ models. HW of WWR 10% PSZ models consumed more energy than LW of WWR 10% PSZ models. From WWR 20%, HW PSZ models used less energy compared to LW PSZ models. The result of energy use reduction in a particular zone OBC revealed that occupancy-based control of this study has the significance of updating code-compliant models using OBC credits.

5.2.4.3. Impact of Occupancy-Based Controls in Whole Buildings

The energy use reduction of occupancy-based controls can be maximized when OBC is applied to the whole building. This chapter calculated the energy use reduction impact in cases of 5 zones controlled by OBC. In this chapter, OBC energy use reduction represents a reduction of "OBC 100% (max usage) – OBC 0% (min usage)". The simulation results of OBC described that OBC energy use reduction has a low relationship with architectural design elements such as building materials and window-to-wall ratio. The climate zone and HVAC system had a significant influence on OBC energy use reduction. This is because OBC energy variables (e.g., lighting, equipment, occupant density, outdoor air intake) are independent of weather conditions and building design elements. Total cooling, heating, and ventilation demands of OBC were changed depending on architectural designs, but simulation schedules based on OBC almost fixed the load changes of heating, cooling, and ventilation. Figure 90 showed normalized energy use reduction of whole building OBC in Houston and Chicago by building design type.

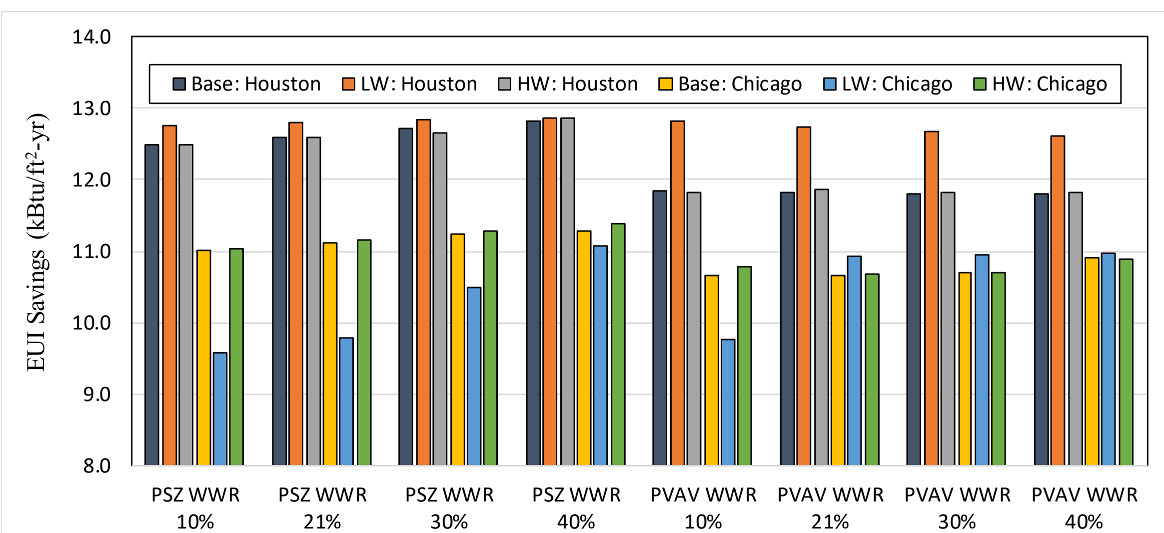


Figure 90. Normalized Energy Use Reduction of 5 Zone OBC on Total Building Loads

Table 78. Normalized Energy Use Reduction Ratios of OBC in Whole Buildings

Type	PSZ System				PVAV System			
	WWR 10%	**WWR 21%**	**WWR 30%**	**WWR 40%**	**WWR 10%**	**WWR 21%**	**WWR 30%**	**WWR 40%**
Houston Base	-50%	-49%	-48%	-47%	-50%	-49%	-48%	-47%
Houston LW	-46%	-43%	-42%	-41%	-50%	-48%	-47%	-46%
Houston HW	-51%	-50%	-49%	-48%	-51%	-50%	-49%	-48%
Chicago Base	-42%	-40%	-39%	-38%	-49%	-48%	-48%	-48%
Chicago LW	-37%	-35%	-36%	-36%	-42%	-47%	-46%	-45%
Chicago HW	-42%	-41%	-40%	-38%	-49%	-48%	-48%	-48%
Reduction range of WWR	-37 to -51%	-35 to -50%	-36 to -49%	-36 to -48%	-42 to -51%	-47 to -50%	-46 to -49%	-45 to -48%

* Total loads reduction rates were calculated as the differences between OBC 100% (max usage) and OBC 0% (min usage, unoccupied)
* Occupant density for simulations is 180 ft^2/people based ASHRAE Standard 62.1-2013

Table 79. Normalized Energy Use Reduction of Occupancy-Based Controls in Whole Buildings

Type (Unit: kBtu/ft^2)	PSZ System				PVAV System			
	WWR 10%	**WWR 21%**	**WWR 30%**	**WWR 40%**	**WWR 10%**	**WWR 21%**	**WWR 30%**	**WWR 40%**
Houston Base	12.5	12.6	12.7	12.8	11.9	11.8	11.8	11.8
Houston LW	12.8	12.8	12.8	12.9	12.8	12.7	12.7	12.6
Houston HW	12.5	12.6	12.7	12.9	11.8	11.9	11.8	11.8
Chicago Base	11.0	11.1	11.2	11.3	10.7	10.7	10.7	10.9
Chicago LW	9.6	9.8	10.5	11.1	9.8	10.9	11.0	11.0
Chicago HW	11.0	11.2	11.3	11.4	10.8	10.7	10.7	10.9
Reduction range of WWR	9.6 to 12.8	9.8 to 12.8	10.5 to 12.8	11.1 to 12.9	9.8 to 12.8	10.7 to 12.7	10.7 to 12.7	12.6 to 12.6

* Total loads reduction rates were calculated as the differences between OBC 100% (max usage) and OBC 0% (min usage, unoccupied)
* Occupant density for simulations is 180 ft^2/people based ASHRAE Standard 62.1-2013

When applying OBC to 5 zones (i.e., whole building), the OBC energy use reduction rates in total loads are computed in Table 78. Although architectural design (i.e., envelope material, WWR) had a quantitatively limited effect in OBC energy use reduction, architectural design influenced considerable impact in total loads. Thus, the OBC energy use reduction rates varied. Low WWR design had higher energy use reduction potential by percentage, and PVAV systems had higher energy use reduction potential in percentage than PSZ systems due to lower total loads. HW buildings had more energy use reduction potential than LW buildings, but the differences were not well distinguished.

5.2.4.4. Summary

In simulations of occupancy-based controls in a specific zone, this study explored building energy use reduction in different building designs and HVAC systems in hot and cold climates. The results show significant energy use reduction in both climates for reference, lightweight and heavyweight buildings. The results of this study in Houston and Chicago are summarized as below:

- Occupancy-based controls of whole buildings represented 41-51% of total load reduction potential in Houston and 35-49% of total load reduction potential in Chicago
- A specific zone OCC from Space1-1 to Space5-1 showed 32% to 45% energy reduction potential of selected zone EUIs in Houston and resulted in 24% to 43% energy reduction potential of selected zone EUIs in Chicago
- Total load reduction of occupancy-based building controls were larger in PSZ/PVAV and LW/HW models as this order: WWR 10% > WWR 21% > WWR 30% > WWR 40%
- Total load reduction ratios of PVAV systems were higher than PSZ systems
- Heavyweight models had higher reduction potential ratios compared to the reference and raised floor, lightweight models. Also, raised floor lightweight models mostly showed low energy reduction potential than the reference and heavyweight models
- The occupancy control reduction of component loads increased in lighting, equipment, cooling, and ventilation loads, while OBC reduction varied in heating loads depending on system type and OBC intensity

- Total load reduction ratio of specific zone OBC showed that west zone (Space4-1) models larger than the east zone (Space2-1) models, as well as south zone (Space1-1), models bigger than the north zone (Space3-1) models
- Max energy reduction ratios were found in the core zone (Space5-1) OBC in Houston and Chicago
- Min energy reduction ratios were represented in the east zone (Space2-1) OBC in Houston and Chicago
- The occupancy modeling's energy use reduction mostly came from internal load controls and heat gains (e.g., weather independent variables) in energy simulations. The impact of weather and design elements was limited in OBC energy use reduction. Weather and design elements mainly affected the total amount of building loads.

6. RESULTS: OCCUPANCY CREDITS FOR CODE-COMPLIANT MODELING

6.1. Overview of Simulation Results

This study analyzed the impact of Occupancy-Based Controls (OBC) in office buildings. The study calculated two types of control operation modes: 1) total building (5 zones) occupancy-based controls and 2) individual zone OBC controls. Total building application refers to the whole-building controlled by OBC. The particular zone OBC means that only the selected zones applied OBC and the remaining zones used Standard 90.1-2016 schedules for simulations. To evaluate the energy performance, baseline small office buildings were developed in DOE-2.1e based on the U.S.DOE sponsored PNNL prototype models for Standard 90.1-2016. The small office models were simulated in Houston, TX and Chicago, IL. Two cities represent the hot-humid climate zone (2A) and cold-humid climate zone (5A) in the U.S.

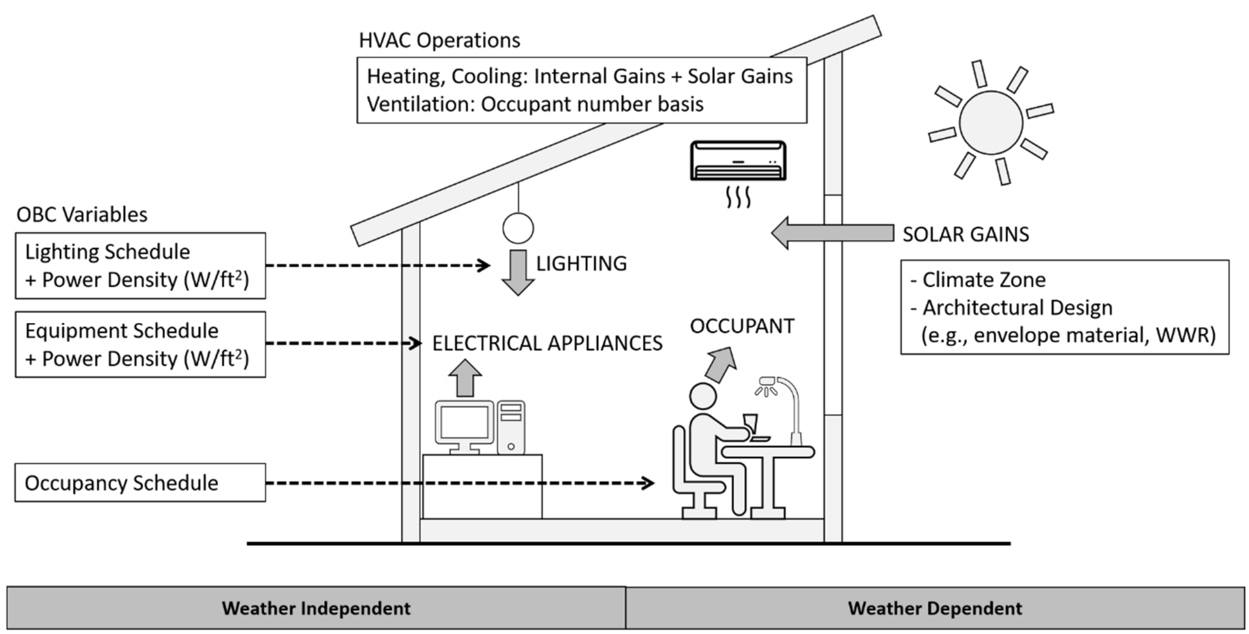
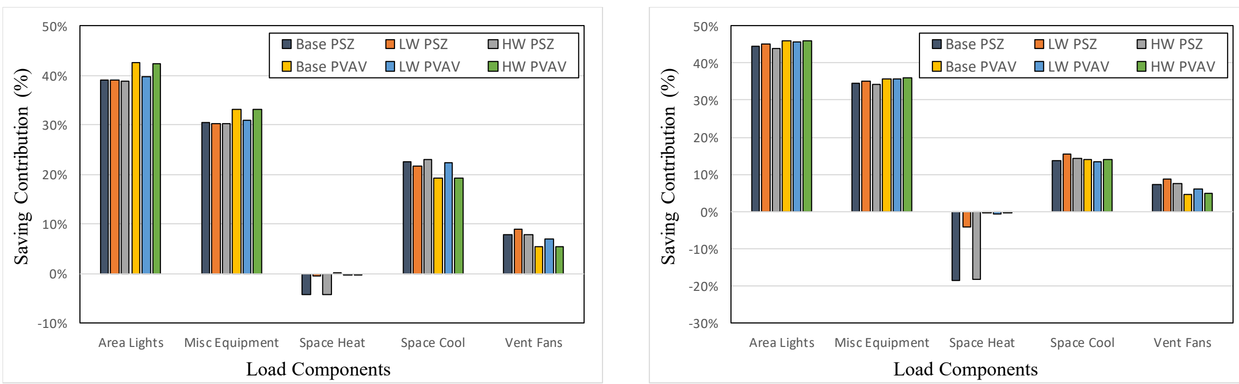


Figure 91. Relationship between Occupancy-Based Controls and Building Simulation

Figure 91 shows the relationship between occupancy-based control variables and buildings based on building energy simulations in this study. In the simulations, weather-independent occupancy-based control variables dominated energy use reduction, and the energy use reduction from weather-dependent occupancy-based building control variables is limited according to climate zone, WWR, and HVAC system type.



(a) Houston (b) Chicago

Figure 92. Example: OBC Energy Use Reduction Contribution Rates of WWR 40% Models

Figure 92 shows energy use reduction contribution rates of "OBC 100% - OBC 0%" in WWR 40% models by energy end-use type in Houston, TX and Chicago, IL. The energy use reduction ratios indicate that building HVAC system type and climate zone can be the dominant factors to determine OBC reduction in Houston and Chicago. Also, in terms of load components, lighting and equipment occupied 69.3-75.6% of OBC energy use reduction in Houston and 78.4-81.9% of OBC reduction in Chicago. In the PSZ systems, heating loads raised building energy use and in PVAV systems, the effect of occupancy-based building controls was varied depending on building designs. For the weather-dependent loads, the cooling load reduction of occupancy-based controls were the most effective to reduce building energy use in Houston. On the contrary, in Chicago PSZ systems, cooling and ventilation occupancy-based control reduction was almost offset by increases in heating loads.

Therefore, with the potential of occupancy-based building modeling, occupancy-based building control credits can be proposed for occupancy-based building modeling to support estimations of smart control-based office buildings in the U.S. The occupancy-based modeling credits for office buildings were proposed for whole-building applications and for specific zone occupancy-based building operations in Houston and Chicago in the next chapters.

6.2. Proposed Occupancy-Based Control Credits for Whole Buildings

This study calculated the energy performance of occupancy-based controls in small office buildings using the DOE-2.1e simulation that was cross-checked with EnergyPlus. Based on the results of occupancy modeling energy use reduction in simulations, occupancy modeling credits were developed as proposed in Table 80 and Appendix H for whole-building occupancy-based control operations. In the tables, occupancy modeling credits present potential energy use reduction ratios at particular usage intensity (i.e., max-100%, standard-90%, medium-50%, min-0%) in each case of building design and HVAC conditions (i.e., reference/raised floor LW/HW, WWR 10-40%, PSZ, PVAV) compared to 100% operations from 9 AM to 5 PM on weekdays. Blue colors mean high energy use reduction potential from occupancy-based control applications, and red colors indicate low or negative energy use reduction potential from occupancy-based control operations. This would be a simplified, easy-to-use approach for estimating and diagnosing energy use reduction from occupancy-based controls. Energy modelers and architects could use the tables to estimate using occupancy modeling credits depending on their occupancy usage intensity in office buildings.

Occupancy-based control credits could be used to supplement the current deterministic building modeling schedules and improve the energy modeling requirement of the current performance paths (i.e., ECB method, Appendix G method) in Standard 90.1-2019. Since the recent code-compliant modeling provides partial credits only for lighting systems from Standard 90.1-2016, the other load components (i.e., equipment, occupancy, ventilation) should be considered in the future code-compliance to develop more realistic energy models for practices. More credit information is described in Appendix H.

Table 80. Example: Houston PSZ- Percentage-Based Energy Reduction Credits of Total Building Occupancy-Based Controls

	Reference PSZ															
	WWR 10%				**WWR 21%**				**WWR 30%**				**WWR 40%**			
	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%
Lights	0.0%	6.6%	33.0%	54.1%	0.0%	6.6%	33.0%	54.1%	0.0%	6.6%	33.0%	54.1%	0.0%	6.6%	33.0%	52.8%
Equipment	0.0%	6.4%	31.8%	50.9%	0.0%	6.4%	31.8%	50.9%	0.0%	6.4%	31.8%	50.9%	0.0%	6.4%	31.8%	50.9%
Heating	0.0%	-19.3%	-205.8%	-465.6%	0.0%	-15.6%	-132.2%	-386.1%	0.0%	-10.6%	-103.7%	-340.8%	0.0%	-10.5%	-99.2%	-302.6%
Cooling	0.0%	6.6%	34.3%	59.5%	0.0%	6.1%	31.6%	55.8%	0.0%	5.7%	29.9%	54.6%	0.0%	5.6%	28.4%	49.9%
Ventilation	0.0%	5.8%	29.2%	49.9%	0.0%	4.8%	24.1%	41.2%	0.0%	4.2%	21.2%	35.2%	0.0%	3.7%	18.6%	29.4%

	Raised Floor Lightweight PSZ															
	WWR 10%				**WWR 21%**				**WWR 30%**				**WWR 40%**			
	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%
Lights	0.0%	6.6%	33.0%	54.1%	0.0%	6.6%	33.0%	54.1%	0.0%	6.6%	33.0%	54.1%	0.0%	6.6%	33.0%	54.1%
Equipment	0.0%	6.4%	31.8%	50.9%	0.0%	6.4%	31.8%	50.9%	0.0%	6.4%	31.8%	50.9%	0.0%	6.4%	31.8%	50.9%
Heating	0.0%	-4.8%	-21.1%	-31.2%	0.0%	-2.6%	-10.0%	-12.4%	0.0%	-1.9%	-5.1%	-4.5%	0.0%	-1.9%	-3.7%	-2.0%
Cooling	0.0%	5.1%	25.3%	43.7%	0.0%	4.6%	23.0%	40.1%	0.0%	4.3%	21.7%	38.3%	0.0%	4.1%	20.7%	36.7%
Ventilation	0.0%	5.1%	25.3%	43.3%	0.0%	4.3%	21.4%	36.4%	0.0%	3.9%	19.5%	33.5%	0.0%	3.6%	18.0%	30.7%

	Heavyweight PSZ															
	WWR 10%				**WWR 21%**				**WWR 30%**				**WWR 40%**			
	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%
Lights	0.0%	6.6%	33.0%	54.1%	0.0%	6.6%	33.0%	54.1%	0.0%	6.6%	33.0%	54.1%	0.0%	6.6%	33.0%	54.1%
Equipment	0.0%	6.4%	31.8%	50.9%	0.0%	6.4%	31.8%	50.9%	0.0%	6.4%	31.8%	50.9%	0.0%	6.4%	31.8%	50.9%
Heating	0.0%	-19.3%	-205.8%	-465.6%	0.0%	-15.6%	-132.2%	-386.1%	0.0%	-10.6%	-103.7%	-340.8%	0.0%	-10.5%	-99.2%	-329.7%
Cooling	0.0%	6.6%	34.3%	59.5%	0.0%	6.1%	31.6%	55.8%	0.0%	5.7%	29.9%	54.6%	0.0%	5.6%	28.4%	54.8%
Ventilation	0.0%	5.8%	29.2%	49.9%	0.0%	4.8%	24.1%	41.2%	0.0%	4.2%	21.2%	35.2%	0.0%	3.7%	18.6%	31.2%

* Red color: negative effect on energy reduction

6.3. Proposed Occupancy-based Control Credits for Individual Zone Control

This chapter provided occupancy modeling credits for partial occupancy-based control operations only in a particular zone. Table 81 and Appendix I describe occupancy modeling credits of office buildings in Houston, TX and Chicago, IL. To evaluate the energy performance of occupancy-based controls, the equation in Chapter 6.2 could be used to estimate the impact of occupancy controls in energy modeling. The energy use reduction impact of occupancy-based controls can vary depending on building materials, system type, window-to-wall ratio, and climate zone. Therefore, when developing occupancy modeling, these variables should be considered in the simulations. Figure 93 depicts the example trends of occupancy modeling credits for cooling loads. Depending on building design and system conditions, different usage intensity (i.e., max, standard, medium, min) could be calculated in energy models using occupancy modeling credits. Since occupancy-based controls have a significant influence on energy use and HVAC system operations, it should be carefully modeled in building energy estimations, especially in office buildings. More credit information is described in Appendix I.

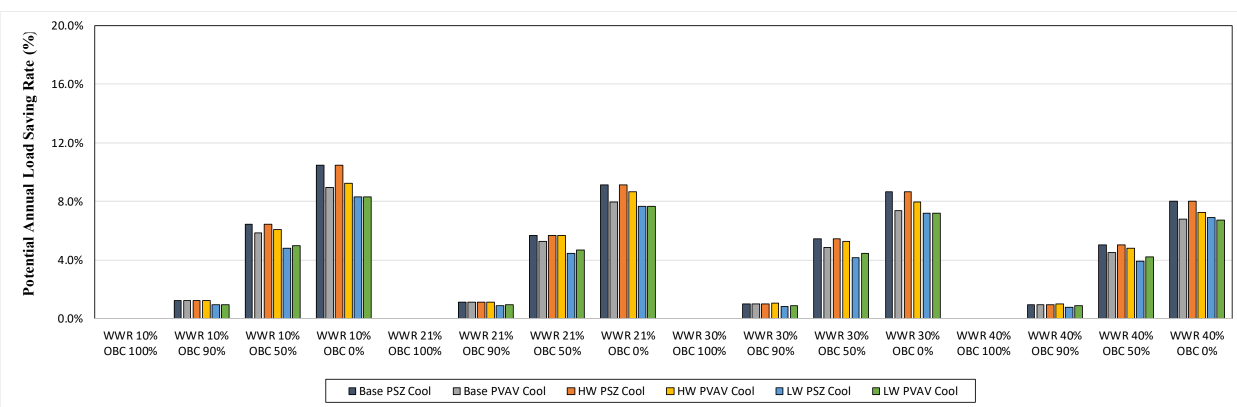


Figure 93. Example: Cooling Load Occupancy Modeling Credits of Space1-1 OBC in Houston

Table 81. Example: Houston PSZ Percentage-Based Energy Reduction Credits of Space1-1 OBC in Total Loads

	Reference PSZ															
	WWR 10%				**WWR 21%**				**WWR 30%**				**WWR 40%**			
	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%
Lights	0.0%	1.4%	7.1%	11.3%	0.0%	1.4%	7.1%	11.3%	0.0%	1.4%	7.1%	11.3%	0.0%	1.4%	7.1%	11.3%
Equipment	0.0%	1.2%	5.7%	9.2%	0.0%	1.2%	5.7%	9.2%	0.0%	1.2%	5.7%	9.2%	0.0%	1.2%	5.7%	9.2%
Heating	0.0%	-0.9%	-6.8%	-14.8%	0.0%	-0.7%	-5.5%	-11.2%	0.0%	-0.8%	-5.4%	-9.6%	0.0%	-0.3%	-4.2%	-7.1%
Cooling	0.0%	1.3%	6.4%	10.5%	0.0%	1.1%	5.7%	9.2%	0.0%	1.0%	5.4%	8.6%	0.0%	1.0%	5.0%	8.0%
Ventilation	0.0%	0.9%	4.6%	7.4%	0.0%	0.8%	3.8%	6.1%	0.0%	0.7%	3.4%	5.4%	0.0%	0.6%	3.0%	4.7%

	Raised Floor Lightweight PSZ															
	WWR 10%				**WWR 21%**				**WWR 30%**				**WWR 40%**			
	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%
Lights	0.0%	1.4%	7.1%	11.6%	0.0%	1.4%	7.1%	11.6%	0.0%	1.4%	7.1%	11.6%	0.0%	1.4%	7.1%	11.6%
Equipment	0.0%	1.2%	5.7%	9.2%	0.0%	1.2%	5.7%	9.2%	0.0%	1.2%	5.7%	9.2%	0.0%	1.2%	5.7%	9.2%
Heating	0.0%	-0.4%	-2.4%	-4.9%	0.0%	-0.2%	-1.5%	-3.1%	0.0%	-0.1%	-1.1%	-2.3%	0.0%	-0.1%	-0.9%	-1.8%
Cooling	0.0%	1.0%	4.8%	8.3%	0.0%	0.9%	4.4%	7.6%	0.0%	0.8%	4.2%	7.2%	0.0%	0.8%	3.9%	6.9%
Ventilation	0.0%	0.8%	4.1%	6.9%	0.0%	0.7%	3.7%	6.3%	0.0%	0.7%	3.4%	5.8%	0.0%	0.6%	3.1%	5.3%

	Heavyweight PSZ															
	WWR 10%				**WWR 21%**				**WWR 30%**				**WWR 40%**			
	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%
Lights	0.0%	1.4%	7.1%	11.3%	0.0%	1.4%	7.1%	11.3%	0.0%	1.4%	7.1%	11.3%	0.0%	1.4%	7.1%	11.3%
Equipment	0.0%	1.2%	5.7%	9.2%	0.0%	1.2%	5.7%	9.2%	0.0%	1.2%	5.7%	9.2%	0.0%	1.2%	5.7%	9.2%
Heating	0.0%	-0.9%	-6.8%	-14.8%	0.0%	-0.7%	-5.5%	-11.2%	0.0%	-0.8%	-5.4%	-9.6%	0.0%	-0.3%	-4.2%	-7.1%
Cooling	0.0%	1.3%	6.4%	10.5%	0.0%	1.1%	5.7%	9.2%	0.0%	1.0%	5.4%	8.6%	0.0%	1.0%	5.0%	8.0%
Ventilation	0.0%	0.9%	4.6%	7.4%	0.0%	0.8%	3.8%	6.1%	0.0%	0.7%	3.4%	5.4%	0.0%	0.6%	3.0%	4.7%

7. CONCLUSIONS AND FUTURE WORK

This study investigated occupancy-based controls (OBC) to evaluate the impact on building energy use for small office buildings. In the process, this study identified energy use reduction of OBC on total annual energy use and end-use energy use components depending on different building systems (i.e., PSZ, PVAV), different building envelope materials (i.e., lightweight, heavyweight), and building designs (i.e., window-to-wall ratio) in different climates (i.e., hot and cold climate zones)., and interpreted energy use reduction contributors in hot-humid and cold-humid climate zones. The results of this study will allow energy modelers, architects, and engineers to more easily estimate overlooked potential energy use reduction when their building design uses occupancy-based controls. This chapter presents the summary and conclusions of this study. Based on the findings, future work is also discussed.

7.1. Summary and Conclusions

In buildings, occupant behavior is a significant factor in building energy use. However, most previous literature focused on field measurement methods, data-driven occupant modeling strategies, integrated occupancy behavior model development with building energy simulation tools, application in building design an operation (IEA-EBC, Annex 66 2018; IEA-EBC, Annex 79 2018; Wagner et al. 2018), even though occupancy-based controls affect the usage of most load components in office buildings. Also, the current Standard 90.1 provided limited occupancy modeling credits only for lighting systems in the Appendix G method. Therefore, this study analyzed variations in annual energy use for different building types and designs with a long-term goal of developing a procedure for occupancy modeling credits for building energy codes.

Currently, occupancy modeling uses the following methods: 1) static and dynamic methods, 2) deterministic and stochastic methods, and 3) agent-based methods. Of them, deterministic models are only used in codes as preset parameters that remain the same for the standard building design and the proposed building design. Thus, this study investigated the impact of various OBC usage (i.e., 100%-0% on weekdays) on energy use to improve the current deterministic schedules in building standards to cover occupancy diversity in energy modeling.

To achieve the research goals, reference small office models were developed based on the PNNL prototype office buildings for Standard 90.1-2016 in DOE-2.1e. The models were simulated in hot-humid (CZ 2A: Houston, TX) and cool-humid (CZ 5A: Chicago, IL) to estimate the impact in different climate zones.

First, thermal zoning models were determined between single-zone and five-zone models to evaluate the impact of occupancy-based controls accurately in office buildings. The results showed that the single-zone models showed that it does not represent the same result as a 5-zone model. For example, a single-zone model mixes heat gains from the south surface or west surface because the simulation uses average temperatures in the thermal zones. This fact in the single-zone model provides different daily indoor air temperature changes versus the five-zone model since the single-zone model cannot discriminate indoor air temperatures between perimeter zones or space types. Therefore, this study used the five-zone model in Houston and Chicago.

Second, a sensitivity analysis of different OBC schedules (i.e., occupancy, lighting, equipment) was conducted in 100%-0% variations of OBC to determine interactions between OBC energy variables and to identify building energy use patterns of OBC in office buildings. In Houston, the result of the sensitivity analysis showed that the lighting schedule had a variation of up to 31.0%, and the equipment schedule had a variation of up to 24.7%. The occupancy schedule showed a sensitivity of up to 4.5% in total EUI. Also, in Chicago, the OBC schedule showed a sensitivity of up to 25.9% in lighting schedules, up to 20.9% in equipment schedules, and up to 0.4% in occupancy schedules. Many of the trends of sensitivity in the EUI reduction of each OBC schedule showed almost linear patterns in the load components (i.e., lighting, equipment, heating, cooling, ventilation).

Based on the results of varying OBC schedules, a set of OBC schedules (i.e., occupancy, lighting, equipment) were applied to analyze building energy use reduction of occupancy-based controls for different building design conditions (i.e., reference model, raised floor lightweight and heavyweight models, window-to-wall ratio 10-40%, PSZ and PVAV systems) in different climate zones. As a result, architectural design elements affected cooling, heating, and ventilation loads.

The results showed that raised floor, lightweight (LW) models showed more energy use in all load types (i.e., heating, cooling, ventilation) in Houston and Chicago compared to the reference and heavyweight (HW) models that had a slab-on-grade construction. The results showed that the impact of occupancy-based controls using PVAV systems in the HW models was 6.5-9.9% less energy for heating, cooling, and ventilation loads than the reference U.S.DOE models in Houston and a 3.8% increase in energy use in Chicago. The different ratios in PVAV systems were lower than PSZ systems.

In simulations, WWR 10-40% for whole-building application was significant in determining building performance. The results showed that the highest energy use reduction ratios of occupancy-based controls from heating, cooling, and ventilation in Houston. The energy use reduction ratios when varying WWR 10-40% were expected up to 47.1-50.2% of reference

PSZ, 40.5-45.7% of raised floor LW PSZ, 47.9-51.2% of HW PSZ, 46.0-49.6% of reference PVAV, 46.2-49.6% of raised floor LW PVAV, and 46.8-50.5% of HW PVAV. In Chicago, the maximum reduction of occupancy-based controls from heating, cooling, and ventilation were presented as 37.2-40.1% of raised floor LW PSZ, 38.4-42.4% of HW PSZ, 46.5-48.4% of reference PVAV, 45.4-47.8% of raised floor LW PVAV, and 46.6-48.3% of HW PVAV, respectively. The possible energy use reduction ratios of total loads were 41-51% of occupancy controls in Houston and 37-49% of occupancy controls in Chicago. The maximum energy use reduction potential percentage of occupancy-based controls was found in all cases of WWR 10% models, and the minimum energy use reduction potential percentage of occupancy-based controls occurred in all cases of WWR 40%.

Next, the potential energy use reduction of a specific zone occupancy-based building control were explored in five zone models. This analysis modeled a total of 960 combination cases using different HVAC (i.e., PSZ, PVAV), envelope material and design (i.e., reference, raised floor LW, HW, WWR 10-40%), occupancy-based control application (i.e., all zone OBC, single-zone OBC), and climate zone (i.e., Houston, Chicago). The energy use reduction potential and trends of occupancy-based controls provide a preliminary look at what OBC could provide for code-compliance with ASHRAE Standard 90.1. The findings of occupancy-based building controls in this study are summarized below:

- Occupancy-based controls in small office buildings showed substantial energy use reduction potential from varying energy factors and different building conditions.
- In terms of weather conditions, Climate Zone (CZ) significantly affected the range of energy use reduction due to an increase or decrease of weather-dependent loads (i.e.,

heating, cooling, ventilation). Houston, TX showed more energy use reduction potential than Chicago, IL, in all building types (i.e., reference, lightweight, heavyweight). This is because Houston, TX used more cooling energy and less heating energy, while Chicago, IL used more heating energy and less cooling energy. The increase of heating loads offset cooling and ventilation load reduction of OBC, especially in Chicago, PSZ systems.

- In terms of building materials, heavyweight models had higher energy use reduction potential ratios of OBC compared to the reference and lightweight models because lightweight, raised floor models had higher annual energy use. Lightweight models showed the largest energy consumption, and the reference models represented the second-largest energy consumption.
- In terms of window-to-wall ratio, the total load energy use reduction potential of occupancy-based controls using varying WWRs were larger in Houston and Chicago in this order: WWR 10% > WWR 21% > WWR 30% > WWR 40%. Smaller WWR models showed less total energy use than higher WWR models, which influenced the percentage energy use reduction ratios of WWR models.
- In terms of building system types, the energy use of building systems is related to weather-dependent variables (i.e., heating, cooling, and ventilation loads). Also, the operation of the HVAC system is different depending on the features of system types (i.e., variable air volume versus constant air volume). In this study, PVAV systems represented less total energy use than PSZ systems in Houston and Chicago, especially in heating and ventilation loads. PVAV systems showed higher total load reduction ratios of OBC than PSZ systems in Houston and Chicago. Due to difference in weather conditions, reduction ratios of Houston PSZ systems were larger versus Chicago PSZ systems, and

reduction ratios of Houston PVAV systems were larger compared to Chicago PVAV systems.

- In terms of ground-coupling, slab-on-grade models (i.e., reference, heavyweight) showed lower energy consumption and higher than raised floor models (i.e., lightweight). Raised floor models represented the largest energy use and lowest energy use reduction potential in Houston and Chicago compared to the reference and heavyweight models.
- In terms of whole-building OBC application, occupancy-based controls in 5 zone models showed 41-51% of total load reduction potential in Houston (CZ 2A) and 35-49% of total load reduction potential in Chicago (CZ 5A).
- In terms of single-zone OBC application, a single zone OBC represented 32% to 45% energy use reduction potential of selected zone EUIs in Houston and resulted in 24% to 43% energy use reduction potential of selected zone EUIs in Chicago. The total load reduction ratio of a specific zone occupancy-based control showed that west zone (Space4-1) models were larger than the east zone (Space2-1) models. In addition, as south zone (Space1-1) models were larger than the north zone (Space3-1) models. Maximum reduction ratios occurred in the core zone (Space5-1) occupancy-based building control in both Houston and Chicago due to the larger area. Minimum reduction ratios were found in the east zone (Space2-1) occupancy-based building control in Houston and Chicago.
- In terms of energy use reduction contributors, the largest contributors to occupancy modeling's energy use reduction were internal load factors (e.g., lighting, equipment) in energy simulations. Weather and design elements had a limited impact on occupancy modeling-driven energy use reduction. Weather and design elements mainly affected the

energy use of heating, cooling, and ventilation loads. The occupancy-based control energy use reduction of component loads increased in lighting, equipment, cooling, and ventilation loads, while heating loads varied depending on system type and OBC usage intensity.

- This study showed the U.S.DOE lightweight building with a slab-on-grade behaved like a heavyweight building. Therefore, a raised-floor lightweight model was developed to represent a lightweight building.

Last but not least, based on the results, occupancy control credits for office buildings were proposed as a reduction fraction basis for Houston and Chicago climates. The proposed occupancy-based control credits could be an easy-to-use and straightforward procedure to estimate the impact of occupancy-based controls in the energy modeling process for hot-humid and cool-humid climates. Also, occupancy modeling credits by total loads and load sub-types allow calculating occupancy modeling energy use reduction by load components, which would be useful as a reference to develop future occupancy modeling credits for total loads and load components in building codes and standards.

7.2. Future Work

This study attempted to investigate the impact of occupancy-based controls in building energy modeling with an integrated perspective. However, the result of this study still contains the limitations for future work as follows:

1) This study investigated the impact of occupancy-based control in a small office building. However, future work will need to systematically investigate: system type,

construction (i.e., lightweight, heavyweight), variations in window-to-wall ratios in cold, mild, and hot climates in order to develop occupancy-based control credits.

2) Occupancy-based controls in this study focused only on simulation schedules (i.e., occupancy, lighting, equipment, fan schedules). Therefore, other schedules should be analyzed.
3) Future work is needed to systematically determine how variations in simulation inputs would impact occupancy-based control simulation results.
4) Occupancy modeling-driven energy use reduction calculations in other U.S. climate zones (e.g., climate zone 1 to 8) should be performed.
5) Calculations of occupancy modeling in medium and large office buildings should be performed.
6) Different building shapes (i.e., square) should be evaluated.
7) No detailed thermal zone model over five zones was used to estimated building energy performance. Therefore, additional zones should be investigated.
8) All results were calculated in the DOE-2.1e building energy simulation program for easy-of-use, although a comparison was performed against EnergyPlus that showed similar results. Therefore, repeating the work in EnergyPlus should be used.
9) Other HVAC systems should be analyzed.
10) Varying schedules of occupancy, lighting, and equipment should be analyzed.
11) No infiltration was used to quantify ventilation based on occupant density.
12) The impact of WWR in simulations was partially limited due to shade by the attic roof in small office buildings. Therefore, additional study is needed.

13) The interaction of occupancy-related variables (e.g., window and thermostat set-temperature controls by the occupant, daylighting) was not modeled. Therefore, this needs further study.

Therefore, in summary, the following recommendations for future works are as the following:

1) Based on the results of this study, it is recommended that additional analysis be performed to develop the necessary library of results for OBC in different buildings.
2) The detailed impact of OBC on building loads needs further study, including more accurate ground-coupling and advanced window models using the latest algorithms (e.g., KIVA analysis) in different simulation tools (i.e., EnergyPlus, Radiance, CFD, TRNSYS).
3) Uncertainty analysis of input parameters on energy performance is required for hot, cool and cold climate zones to quantify the uncertainties on the building loads of occupancy-based controls.
4) Investigation of other building types (e.g., residential buildings, schools, industrial buildings, mixed-use, retails) and different building sizes (e.g., medium, large) is required for occupancy modeling.
5) Development of optimal thermal zoning methods for occupancy modeling based on space types in buildings.
6) Analysis of the impact of the ground-coupling in occupancy-based control models and the impact of occupancy-based controls in plenum models.
7) Analysis of the relations between occupancy-related parameters.

8) Development of more realistic occupancy-based control simulation schedules to cover different usage profiles (e.g., high, medium, low) by space type (e.g., office, auditorium, meeting room, kitchen).

9) Development of occupancy modeling credits by office layout (e.g., open space, private office).

10) Development of more sophisticated occupancy modeling approach taking account of occupant behavior for weekdays and weekends.

11) The occupancy modeling credit methodology developed in this study needs to be verified using case-study buildings and recommended to be confirmed for code-compliance in the future codes and standards.

REFERENCES

Abdeen, A. O'Brien, W. Gunay, B. Newsham, G. Knudsen, H. (2020). Comparative review of occupant-related energy aspects of the National Building Code of Canada, *Building and Environment*. 183. 107136. https://doi.org/https://doi.org/10.1016/j.buildenv.2020.107136.

Abushakra, B., D. Claridge (2001). Accounting for the Occupancy Variable in Inverse Building Energy Baselining Models. *The First International Conference for Enhanced Building Operations*, Austin, Texas.

Andolsun, S., Culp, C.H., Haberl, J. S. (2010). EnergyPlus vs DOE-2: The Effect of Ground Coupling on Heating and Cooling Energy Consumption of a Slab-On-Grade Code House in a Cold Climate. *SimBuild 2010*, August 11-13, New York City, New York, IBPSA-USA

Andolsun, S., Culp, C. (2011a). Comparison of DOE-2.1E with EnergyPlus and TRNSYS for Goudn Coupled Residential Buildings in Hot and Humid Climates: Stage 1. revised in 2013. College Station, TX. Energy Systems Laboratory. Texas A&M University.

Andolsun, S., Culp, C. (2011b). Comparison of DOE-2.1E with EnergyPlus and TRNSYS for Goudn Coupled Residential Buildings in Hot and Humid Climates: Stage 2. revised in 2013. College Station, TX. Energy Systems Laboratory. Texas A&M University.

Andolsun, S., Culp, C. (2012). Comparison of DOE-2.1E with EnergyPlus and TRNSYS for Goudn Coupled Residential Buildings in Hot and Humid Climates: Stage 3. revised in 2013. College Station, TX. Energy Systems Laboratory. Texas A&M University.

ASHRAE. (1980). ASHRAE/IES Standard 90A,B,C *Energy Conservation in New Building Design*. Atlanta, GA, American Society of Heating, Refrigerating and Air-Conditioning Engineers.

ASHRAE. (2010). ANSI/ASHRAE/IES Standard 90.1-2010. *Energy Standard for Buildings Except Low-Rise Residential Buildings*. Atlanta, GA, American Society of Heating, Refrigerating, and Air-conditioning Engineers.

ASHRAE. (2013a). ANSI/ASHRAE/IES Standard 90.1-2013 *Energy Standard for Buildings Except Low-Rise Residential Buildings*. Atlanta, GA, American Society of Heating, Refrigerating, and Air-conditioning Engineers.

ASHRAE. (2013b). ANSI/ASHRAE Standard 62.1-2013 *Ventilation for Acceptable Indoor Air Quality*. Atlanta, GA, American Society of Heating, Refrigerating, and Air-conditioning Engineers.

ASHRAE. (2014a). ANSI/ASHRAE Standard 140-2014. *Standard Method of Test for the Evaluation of Building Energy Analysis Computer Programs*. Atlanta, GA, American Society of Heating, Refrigerating, and Air-conditioning Engineers.

ASHRAE. (2014b). ANSI/ASHRAE/IES/USGBC Standard 189.1-2014. *Standard for the Design of High-Performance Green Buildings*. Atlanta, GA, American Society of Heating, Refrigerating, and Air-conditioning Engineers.

ASHRAE. (2014c). *Standard 90.1 User's Manual*. Atlanta, GA, American Society of Heating, Refrigerating, and Air-conditioning Engineers.

ASHRAE. (2015a). ANSI/ASHRAE/IES Standard 90.1-2013. *Energy Standard for Buildings Except Low-Rise Residential Buildings-Addenda 2015 Supplement*. Atlanta, GA, American Society of Heating, Refrigerating, and Air-Conditioning Engineers.

ASHRAE. (2015b). *2015 ASHRAE Handbook—HVAC Applications*. Atlanta, GA, American Society of Heating, Refrigerating, and Air-Conditioning Engineers.

ASHRAE. (2016a). ANSI/ASHRAE/IES Standard 90.1-2016 *Energy Standard for Buildings Except Low-Rise Residential Buildings*. Atlanta, GA, American Society of Heating, Refrigerating, and Air-conditioning Engineers.

ASHRAE. (2016b). ASHRAE/IES Publish 2016 Energy Efficiency Standard. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Retrieved from https://www.ashrae.org/news/2016/ashrae-ies-publish-2016-energy-efficiency-standard.

ASHRAE. (2016c). MTG.OBB Meeting Minutes: Full Committee conference Call. November 4th 2016, American Society of Heating, Refrigerating, and Air-conditioning Engineers.

ASHRAE. (2017a). Preliminary Energy Savings Announced For ASHRAE/IES 2016 Energy Standard. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Retrieved from https://www.ashrae.org/news/2017/preliminary-energy-savings-announced-for-ashrae-ies-2016-energy-standard.

ASHRAE. (2017b). *Standard 90.1-2016 User's Manual*. Atlanta, GA, American Society of Heating, Refrigerating, and Air-conditioning Engineers.

ASHRAE. (2017c). MTG.OBB Meeting Minutes. *2017 ASHRAE Winter Conference*, Las Vegas, NV. American Society of Heating, Refrigerating, and Air-conditioning Engineers.

ASHRAE. (2018). MTG.OBB Meeting Minutes: Draft for Review. *2018 ASHRAE Winter Conference*, Chicago, IL. American Society of Heating, Refrigerating, and Air-conditioning Engineers.

ASHRAE. (2019). ANSI/ASHRAE/IES Standard 90.1-2019 *Energy Standard for Buildings Except Low-Rise Residential Buildings*. Atlanta, GA, American Society of Heating, Refrigerating, and Air-conditioning Engineers.

Azar, E., C. C. Menassa (2012). A Comprehensive Analysis of the Impact of Occupancy Parameters in Energy Simulation of Office Buildings. *Energy and Buildings* 55: 841-853.

Aznar A. (2015). Phrase of the Day: Peak Load. National Renewable Energy Laboratory. Retrived from https://www.nrel.gov/state-local-tribal/blog/posts/phrase-of-the-day-peak-load.html.

Bartlett, R., M. A. Halverson and D. L. Shankle. (2003). *Understanding building energy codes and standards*. PNNL-14235, Richland, WA, Pacific Northwest National Laboratory.

Belazi, W., Ouldboukhitine, S.-E., Chateauneuf, A., Bouchair, A. (2018). Uncertainty analysis of occupant behavior and building envelope materials in office building performance simulation.

Journal of Building Engineering. 19, 434–448. https://doi.org/https://doi.org/10.1016/j.jobe.2018.06.005

Blissard, L. (2015). The IECC - 2009, 2012 and 2015: A Cross-Code Comparison. Green Builder Media, Retrieved from http://www.greenbuildermedia.com/codewatch/the-iecc-2009-2012-and-2015-a-cross-code-comparison.

Brooks, J., S. Goyal, R. Subramany, Y. Lin, T. Middelkoop, L. Arpan, L. Carloni, P. Barooah (2014). An Experimental Investigation of Occupancy-based Energy-efficient Control of Commercial Building Indoor Climate. *Decision and Control (CDC), 2014 IEEE 53rd Annual Conference on*, IEEE.

CBei. (2016). *2015 IECC: What's Changed Since 2012?* Consortium for Building Energy Innovation.

Chen, Y., Hong, T., Luo, X. (2018). An agent-based stochastic Occupancy Simulator. Build. Simul. 11, 37–49. https://doi.org/10.1007/s12273-017-0379-7

Christian, J. E. (1988). OT-88-02-4 Foundation Futures: Energy Saving Opportunities Offered by ASHRAE Standard 90.2P, *ASHRAE Transactions,*, Ottawa, Canada, ASHRAE.

Cowie, A., Hong, T., Feng, X., Darakdjian, Q. (2017). Usefulness of the obFMU Module Examined through a Review of Occupant Modelling Functionality in Building Performance Simulation Programs. *Building Simulation 2017*. San Francisco, CA, International Boarding & Pet Services Association.

Crawley, D.B., Hand, J.W., Kummert, M., Griffith, B.T. (2005). Contrasting the Capabilities of Building Energy Performance Simulation Programs. *9th Conference of International Building Performance Simulation Association*, Aug. 15-18, Montréal, Canada, IBPSA.

Crawley, D.B., Hand, J.W., Kummert, M., Griffith, B.T. (2008). Contrasting the Capabilities of Building Energy Performance Simulation Programs. *Building and Environment* 43(4): 661-673.

Davis, G. (2016). HVAC codes and standards: cooling and energy efficiency. Engineer, Retrieved from http://www.csemag.com/single-article/hvac-codes-and-standards-cooling-and-energy-efficiency/4f684e7f21eada9b13b825014bbfc464.html.

Degelman, L. O. (2000). A Model For Evaluation of Life-cycle Energy Savings of Occupancy Sensors For Control of Lighting and Ventilation in Office Buildings. *The Twelfth Symposium on Improving Building Systems in Hot and Humid Climates*, San Antonio, TX.

Deru, M., Field, K., Studer, D., Benne, K., Griffith, B., Torcellini, P., Liu, M.H.B., Winiarski, D., Rosenberg, M., Yazdanian, M., Huang, J., Crawley, D. (2011). *U.S. Department of Energy Commercial Reference Building Models of the National Building Stock* Golden, Colorado, National Renewable Energy Laboratory.

D'Oca, S., Hong T. (2015). Occupancy Schedules Learning Process through a Data Mining Framework. *Energy and Buildings* 88: 395-408.

Dogan, T., C. Reinhart, P. Michalatos. (2014). Automated Multi-zone Building Energy Model Generation for Schematic Design and Urban Massing Studies. *Proceedings of the 2014 IBPSA eSim conference*, Ottawa, Canada.

Dong, B., B. Andrews (2009). Sensor-based Occupancy Behavioral Pattern Recognition for Energy and Comfort Management in Intelligent Buildings. *Proceedings of Building Simulation 2009* Jul 27-30, Glasgow, Scotland, UK.

Ekwevugbe, T., N. Brown, V. Pakka (2013). Realt-Time Building Occupancy Sensing for Supporting Demand Driven HVAC Operations. *Proceedings of the 13th International Conference for Enhanced Building Operations*, Oct 8-11, Montreal, Quebec,CA.

EnergyPlus. (2010). Engineering Reference, The Reference to EnergyPlus Calculations, Ernest Orlando Lawrence Berkeley National Laboratory and U.S. Department of Energy.

EnergyPlus. (2013). Input Output Reference. The Encyclopedic Reference to EnergyPlus Input and Output, Ernest Orlando Lawrence Berkeley National Laboratory and U.S. Department of Energy.

EnergyPlus. (2019a). EnergyPlus. 2019, Retrieved from https://energyplus.net/.

EnergyPlus. (2019b). Weather Data. 2019, Retrieved from https://energyplus.net/weather.

EnergyPlus. (2019c). Weather Data for Simulation. 2019, Retrieved from https://energyplus.net/weather/simulation.

Erickson, V. L., A. E. Cerpa (2010). Occupancy Based Demand Response HVAC Control Strategy. *Proceedings of the 2nd ACM Workshop on Embedded Sensing Systems for Energy-Efficiency in Building*, ACM.

Feng, X., D. Yan, T. Hong (2015). Simulation of Occupancy in Buildings. *Energy and Buildings* 87: 348-359.

Gaetani, I., Hoes, P.-J., Hensen, J. L. (2016). Occupant Behavior in Building Energy Simulation: towards a Fit-for-Purpose Modeling Strategy. *Energy and Buildings*, 121, 188-204.

Georgescu, M. (2014). Analysis of Systems in Buildings using Spectral Koopman Operator Methods. Doctoral Dissertation, Department of Mechanical Engineering, University of California, Santa Barbara.

Glazer, J. (2015). *Development of Maximum Technically Achievable Energy Targets for Commercial Buildings-Ultra-Low Energy Use Building Set*. ASHRAE 1651-RP. Atlanta, GA, American Society of Heating, Refrigerating and Air-Conditioning Engineers.

Goel, S., M. Rosenberg, R. Athalye, Y. Xie, W. Wang, R. Hart, J. Zhang and V. Mendon (2014). *Enhancements to ASHRAE standard 90.1 prototype building models*. PNNL-23269. Richland, WA, Pacific Northwest National Laboratory.

Guo, X., D. Tiller, G. Henze, C. Waters (2010). The Performance of Occupancy-Based Lighting Control Systems: A Review. *Lighting Research & Technology* 42(4): 415-431.

Haberl, J. S., P. Komor (1989). Investigating An Analytical Framework For Improving Commercial Energy Audits: Results From A New Jersey Mall, Princeton University.

Haberl, J. S., M. Shin, H. Zhou, P. Parker, J.-C. Baltazar. (2015). *Final Report for The Fort Hood Army Base Project*. ESL-ITR-15-07-02. College Station, TX, Energy Systems Laboratory, Texas A&M University.

Haberl, J. S., M. Shin, P. Parker, J.-C. Baltazar. (2016). *Final Report for The Fort Hood Army Base Project*. ESL-TR-16-12-01. College Station, TX, Energy Systems Laboratory, Texas A&M University.

Halverson, M. A., B. Shui, M. Evans. (2009). *Country Report on Building Energy Codes in the United States*. PNNL-17979. Richland, WA, Pacific Northwest National Laboratory.

Haq, M. A. u., M. Y. Hassan, H. Abdullah, H. A. Rahman, M. P. Abdullah, F. Hussin, D. M. Said (2014). A Review on Lighting Control Technologies in Commercial Buildings, Their Performance and Affecting Factors. *Renewable and Sustainable Energy Reviews* **33**: 268-279.

Hoes, P., J. Hensen, M. Loomans, B. De Vries, D. Bourgeois (2009). User Behavior in Whole Building Simulation. *Energy and buildings* 41(3): 295-302.

Hong, T. (2014). Occupant Behavior: Impact on Energy Use of Private Offices. *ASim 2012-1st Asia Conference of International Building Performance Simulation Association*, 11/25/12-11/27/12, Shanghai, China.

Hong, T., S. D'Oca, W. J. N. Turner, S. C. Taylor-Lange (2015a). An Ontology to Represent Energy-Related Occupant Behavior in Buildings. Part I: Introduction to the DNAs Framework. *Building and Environment* 92: 764-777.

Hong, T., S. D'Oca, S. C. Taylor-Lange, W. J. N. Turner, Y. Chen, S. P. Corgnati (2015b). An Ontology to Represent Energy-Related Occupant Behavior in Buildings. Part II: Implementation of the DNAS Framework using an XML Schema. *Building and Environment* 94: 196-205.

Hottel, H.C., Sarofim, A.F. (1967). *Radiative Transfer*. New York, McGraw-Hill.

Huang & Associates. (2000). DrawBDL user’s guide. El Cerrito, CA, Huang & Associates.

Huang, Y.J., V. Bazjanac., Winkelmann, F.C. (2000). DOE-2 Modeling of Two-Dimensional Heat Flow in Underground Surface. Unpublished.

Huang, Y.J., L. Shen, J. Bull, L. Goldberg. (1988). Whole-House Simulation of Foundation Heat Flows using the DOE-2.1c Program. *ASHRAE Transactions* 88(2): 936-958.

Hunn, B. D., D. R. Conover, R. E. Jarnagin, M. Schwedler (2010). 35 Years of Standard 90.1. *ASHRAE Journal* (ASHRAE).

ICC. (2015a). *2015 International Energy Conservation Code (IECC)*, The International Code Council

ICC. (2015b). *2015 International Green Construction Code (IgCC)*, The International Code Council

ICC. (2018). *2018 International Energy Conservation Code (IECC)*, The International Code Council

IEA-EBC, Annex 66. (2013). Introduction. IEA-EBC Annex 66 -Definition and Simulation of Occupant Behavior in Buildings, Energy in Building and Communities Programme (EBC), Retrieved from https://www.annex66.org/.

IEA-EBC, Annex 53. (2013a). Total Energy Use in Buildings: Analysis and Evaluation Methods: Final Report Annex 53. International Energy Agency-Energy in Buildings and Communities Programme.

IEA-EBC, Annex 53. (2013b). Total Energy Use in Buildings: Analysis and Evaluation Methods: Final Report Annex 53, Occupant behavior and modeling: Separate Document Volume II. International Energy Agency-Energy in Buildings and Communities Programme.

IEA-EBC, Annex 53. (2016). Total Energy Use in Buildings: Analysis and Evaluation Methods (Annex 53): Project Summary Report. International Energy Agency-Energy in Buildings and Communities Programme.

IEA-EBC, Annex 66. (2017a). Introduction. IEA-EBC Annex 66 -Definition and Simulation of Occupant Behavior in Buildings. Energy in Building and Communities Programme (EBC), Retrieved from https://www.annex66.org/.

IEA-EBC, Annex 66. (2017b). Definition and Simulation of Occupant Behavior in Buildings: Annex 66, Technical Report: Occupant Behavior Case Study Sourcebook. International Energy Agency-Energy in Buildings and Communities Programme.

IEA-EBC, Annex 66. (2017c). Definition and Simulation of Occupant Behavior in Buildings: Annex 66, Technical Report: An International Survey of Occupant Behavior in Workspaces. International Energy Agency-Energy in Buildings and Communities Programme.

IEA-EBC, Annex 66. (2017d). Definition and Simulation of Occupant Behavior in Buildings : Annex 66, Technical Report: Surveys to understand current needs, practice and capabilities of occupant modeling in building simulation. International Energy Agency-Energy in Buildings and Communities Programme.

IEA-EBC, Annex 66. (2018). Definition and Simulation of Occupant Behavior in Buildings : Annex 66 Final Report. International Energy Agency-Energy in Buildings and Communities Programme.

IEA-EBC, Annex 79. (2018). Annex 79 Subtasks. International Energy Agency-Energy in Buildings and Communities Programme. Retrieved from https://annex79.iea-ebc.org/subtasks.

IEA-EBC, Annex 79. (2019). Factsheet: Occupant-Centric Building Design and Operation. International Energy Agency-Energy in Buildings and Communities Programme.

IFSEC Global. (2017). The smart buildings report 2017. https://www.ifsecglobal.com/global/the-smart-buildings-report-2017/.

Im, P., New, J. (2018). Updated OpenStudio (OS) Small Office Prototype Model. ORNL/SPR-2018/885. Oak Ridge, TN, Oak Ridge National Laboratory.

Im, P., New, J.R., Bae, Y. (2019). Updated OpenStudio Small and Medium Office Prototype Models. *International Conference & Exhibition on Building Simulation 2019*. Rome, Italy.

JJH. (2018). Welcome to DOE2.com. James J. Hirsch & Associates, Retrieved from http://www.doe2.com/.

J. King and C. Perry. (2017). Smart Buildings: Using Smart Technology to Save Energy in Existing Buildings, Washington, DC, USA.

Krarti, M. Chuangchid, P. Ihm, P. (2001). Foundation Heat Transfer Module for EnergyPlus Program, *Seventh International IBPSA Conference*, Rio de Janeiro, Brazil.

Kim, S. (2006). An Analysis of International Energy Conservation Code (IECC)-Compliant Single-Family Residential Energy Use. Doctoral dissertation. College Station, Texas, Texas A&M University.

Kreider, J., J. Haberl, A. Armor, P. E. A. Armstrong (2001). *The Mechanical Engineering Handbook Series* CRC Press LLC.

Labeodan, T., W. Zeiler, G. Boxem, Y. Zhao (2015). Occupancy Measurement in Commercial Office Buildings for Demand-Driven Control Applications—A Survey and Detection System Evaluation. *Energy and Buildings* 93: 303-314.

LBL and LASL (1980a). DOE-2 Reference Manual Part1 version 2.1, Berkeley, CA, Lawrence Berkeley National Laboratory and Los Alamos, NM, Los Alamos National Laboratory

LBL and LASL (1980b). DOE-2 Reference Manual Part2 version 2.1, Berkeley, CA, Lawrence Berkeley National Laboratory and Los Alamos, NM, Los Alamos National Laboratory

LBL and LANL (1982). DOE-2.1A Engineers Manual. Berkeley, CA, Lawrence Berkeley National Laboratory and Los Alamos, NM, Los Alamos National Laboratory

LBL (1991). DOE-2.1E Basics Manual. Berkeley, California, Lawrence Berkeley National Laboratory

LBNL and JJA. (2015). DOE-2.2: Building Energy Use and Cost Analysis Program Volume 3: Topics. Berkeley, CA, Lawrence Berkeley National Laboratory and Santa Rosa Valley, CA, James J Hirsch & Associates

LBNL. (2017). Occupancy Simulator. Lawrence Berkeley National Laboratory, Retrieved from http://occupancysimulator.lbl.gov/.

LBNL. (2018). Occupant Behavior Research at LBNL BTUS. Lawrence Berkeley National Laboratory, Retrieved from https://behavior.lbl.gov/.

Liu, B., et al. (2018). National Impact of ANSI/ASHRAE/IES Standard 90.1-2016. *2018 Building Performance Analysis Conference and SimBuild.* Chicago, IL, The United States Regional Affiliate of the International Building Performance Simulation Association.

L. Troup, R. Phillips, M.J. Eckelman, D. Fannon. (2019). Effect of window-to-wall ratio on measured energy consumption in US office buildings, *Energy & Buildings*. 203. 109434. https://doi.org/https://doi.org/10.1016/j.enbuild.2019.109434.

Martin, S. (2010) Trends in Energy Codes.

Meldem, R., Winkelmann, F. (1998). Comparison of DOE-2 with Temperature Measurements in the Pala Test Houses. *Energy and Buildings* 27: 69-81.

Mendon, V., A. Selvacanabady, M. Zhao and Z. Taylor (2015). *National Cost-Effectiveness of the Residential Provisions of the 2015 IECC*, PNNL-24240. Richland, WA, Pacific Northwest National Laboratory.

NREL. (2017). *Testing and Validation reports*, Golden, CO, National Renewable Energy Laboratory.

O'Brien, W., H. B. Gunay., Beausoleil-Morrison, I. (2013). A Critical Review of State-of-the-Art Energy and Comfort Related Occupant Behavior in Office Buildings. *Building and Environment* 70: 31-47.

O'Brien, W., H. B. Gunay. (2016). Occupant Behaviour Diversity Modelling and Its Applications. *eSIM 2016*, May 3-6, Hamilton, ON, CA, IBPSA-Canada.

O'Brien, W. Abdelalim, A, Abuimara, T. Beausoleil-Morrison, I, Carrizo, J.S. Danks, R. Gilani, S. Gunay, B. Kesik, T. Ouf, M. (2018a). Roadmap for Occupant Modelling in Building Codes and Standards. *eSIM 2018*, IBPSA Canada.

O'Brien, W., Ouf, M., H. B. Gunay., Gilani, S., Abuimara, T., Abdelalim, A. (2018b). Roadmap for the Advancement of Occupant Modelling for Building Codes, Standards, and Design Practice, Human Building Interaction Lab, Carleton University, Ottawa, Canada

O'Brien, W., Gunay, H.B. (2019). Do building energy codes adequately reward buildings that adapt to partial occupancy?. *Science and Technology for the Built Environment*. 25, 678–691. https://doi.org/10.1080/23744731.2019.1581015.

O'Brien, W. Tahmasebi, F. Andersen, R.K. Azar, E. Barthelmes, V. Belafi, Z.D. Berger, C. Chen, D. De Simone, M. D'Oca, Simona Hong, T. Jin, Q. Khovalyg, D. Lamberts, R. Novakovic, V. Park, J.Y. Plagmann, M. Rajus, V.S. Vellei, M. Verbruggen, S. Wagner, A. Willems, E. Yan, D. Zhou, J. (2020a). An international review of occupant-related aspects of building energy codes and standards. *Building and Environment*. 179, 106906. https://doi.org/https://doi.org/10.1016/j.buildenv.2020.106906.

O'Brien, W., Wagner, A., Schweiker, M., Mahdavi, A., Day, J., Kjærgaard, M.B., Carlucci, S., Dong, B., Tahmasebi, F., Yan, D., Hong, T., Gunay, H.B., Nagy, Z., Miller, C., Berger, C. (2020b). Introducing IEA EBC annex 79: Key challenges and opportunities in the field of occupant-centric building design and operation. *Building and Environment*. 178, 106738. https://doi.org/https://doi.org/10.1016/j.buildenv.2020.106738

Oh, S. (2013). Origins of Analysis Methods in Energy Simulation Programs Used for High Performance Commercial Buildings. Master Thesis. College Station, TX, Texas A&M University.

Ouf, M.M., Gunay, H.B., O'Brien, W. (2019). A method to generate design-sensitive occupant-related schedules for building performance simulations. *Science and Technology for the Built Environment*. 25, 221–232. https://doi.org/10.1080/23744731.2018.1514855.

Page, J., D. Robinson, N. Morel, J.-L. Scartezzini. (2008). A Generalised Stochastic Model for the Simulation of Occupant Presence. *Energy and Buildings* 40.

Park, J.Y., Ouf, M.M., Gunay, B., Peng, Y., O'Brien, W., Kjærgaard, M.B., Nagy, Z. (2019). A critical review of field implementations of occupant-centric building controls. *Building and Environment*. 165, 106351. https://doi.org/https://doi.org/10.1016/j.buildenv.2019.106351

PNNL and U.S.DOE. (2014). Commercial Prototype Building Models. U.S. Department of Energy (DOE). Retrieved from https://www.energycodes.gov/development/commercial/prototype_models.

PNNL and U.S.DOE. (2018). Commercial Prototype Building Models. U.S. Department of Energy (DOE). Retrieved from https://www.energycodes.gov/development/commercial/prototype_models.

Rallapalli, H. S. (2010). A Comparison of EnergyPlus and eQUEST Whole Building Energy Simulation Results for a Medium Sized Office Building, Arizona State University. Master of Science.

Rosenberg, M., C. Eley (2013). A Stable Whole Building Performance Method for Standard 90.1. *ASHRAE Journal* 55(5): 33.

Rosenberg, M., P. R. Hart. (2016). *Developing Performance Cost Index Targets for ASHRAE Standard 90.1 Appendix G. -Performance Rating Method*. PNNL-25202 Rev. 1. Richland, WA, Pacific Northwest National Lab.

R. Phillips, L. Troup, D. Fannon, M.J. Eckelman. (2020). Triple bottom line sustainability assessment of window-to-wall ratio in US office buildings, *Buildign and Environment*. 182. 107057. https://doi.org/https://doi.org/10.1016/j.buildenv.2020.107057

Selvacanabady, A., Judd, K.S. (2017). *The Influence of Occupancy on Building Energy Use Intensity and the Utility of an Occupancy-Adjusted Performance Metric*. PNNL-26019. Richland, WA, Pacific Northwest National Laboratory.

Shin, M., J.-C. Baltazar, J. S. Haberl, E. Frazier, B. Lynn (2017). Side-by-Side Tests of a Net-Zero Energy Building. *Building Simulation 2017*, San Francisco, CA, International Building Performance Simulation Association.

Shin, M. (2018). Development of a Procedure for Automating Thermal Zoning for Building Energy Simulation. Doctoral dissertation, Texas A&M University. Retrived from http://hdl.handle.net/1969.1/173914.

Sullivan, R. Bull, J. Davis, P. Nozaki, S. Cumali, Z. Meixel, G. (1985) Description of an Earth-contact Modeling Capability in the DOE-2.1B, Energy Analysis Program 91 (1A), pp.15-29.

TESS. (2017). TESS Component Libraries: General Descriptions TESS: Experts in Energy Modeling & Analysis.

Thornton, B., E. Richman, M. Rosenberg, W. Wang, Y. Xie, J. Zhang, H. Cho, V. Mendon, R. Athalye, B. Liu. (2011). *Achieving the 30% Goal:. Energy and Cost Savings Analysis of ASHRAE Standard 90.1-2010*. PNNL-20405. Richland, WA, Pacific Northwest National Laboratory.

Tian, W., Heo, Y., de Wilde, P., Li, Z., Yan, D., Park, C.S., Feng, X., Augenbroe, G. (2018). A review of uncertainty analysis in building energy assessment. *Renewable and Sustainable Energy Reviews*. 93, 285–301. https://doi.org/https://doi.org/10.1016/j.rser.2018.05.029

U.S.BLS. (2017). Average Hours per Day Spent in Selected Activities on Days Worked by Employment Status and Sex, U.S. Bureau of Labor Statistics.

U.S.DOE. (2016a). EnergyPles version 8.5 Documentation: Engineering Reference, U.S. Department of Energy.

U.S.DOE. (2016b). EnergyPles version 8.5 Documentation: Guide for Module Developers, U.S. Department of Energy.

U.S.DOE. (2016c). EnergyPles version 8.5 Documentation: Using EnergyPlus for Compliance, U.S. Department of Energy.

U.S.DOE. (2020). Status of State Energy Code Adoption, U.S. Department of Energy (DOE), Retrieved from https://www.energycodes.gov/status-state-energy-code-adoption.

U.S.EIA. (2012). *Annual Energy Review 2011*. DOE/EIA-0384(2011), U.S. Energy Information Administration.

U.S.EIA. (2016). *2012 Commercial Buildings Energy Consumption Survey: Energy Usage Summary (CBECS)*, U.S. Energy Information Administration.

U.S.EIA. (2017). Energy Consumption Estimates by Sector. U.S. Energy Information Administration (EIA), Retrieved from https://www.eia.gov/consumption/.

USGBC. (2017). LEED v4 for Building Design and Construction - Current Version. 2101 L Street NW, Suite 500 Washington, DC 20037, U.S. Green Building Council.

Wagner, A. O'Brien, W. Dong, B. (2018). *Exploring Occupant Behavior in Buildings- Methods and Challenges*. Springer.

Wilcox, S., Marion, W. (2008). Users Manual for TMY3 Data Sets. Golden, CO, National Renewable Energy Laboratory

Winkelmann, F.C., Birdsall, B.E., Buhl, W.F., Ellington, K.L., Erdem, A.E., Hirsch, J.J., Gates, S. (1993). DOE-2 BDL Summary, Version 2.1E. Berkeley, CA, Lawrence Berkeley Laboratory and Camarillo, CA, Hirsch & Associates.

Winkelmann, F.C. (1998). Underground surfaces: How to Get a Better Underground Surface Heat Transfer Calculation in DOE-2.1e. *Building Energy Simulation User News* 19(1): 5-14.

Winkelmann, F.C. (2002). Underground Surfaces: How to Get a Better Underground Surface Heat Transfer Calculation in DOE-2.1e. Corrected and Revised in *Building Energy Simulation User News* 23(6): 5-14.

Yan, D., W. O'Brien, T. Hong, X. Feng, H. B. Gunay, F. Tahmasebi, A. Mahdavi (2015). Occupant Behavior Modeling for Building Performance Simulation: Current State and Future Challenges. *Energy and Buildings* 107: 264-278.

Yang, Z., A. Ghahramani, B. Becerik-Gerber (2016). Building Occupancy Diversity and HVAC (Heating, Ventilation, and Air conditioning) System Energy Efficiency. *Energy* 109: 641-649.

APPENDIX A

HISTORY OF BUILDING CODES AND STANDARDS

In history, the U.S. building energy codes and standards started in the 1970s based on the public reaction to the oil crisis. Since then, numerous codes and standards have been developed to provide minimum requirements for a residential and a commercial building to regulate whole-building energy use and increase energy efficiency.

In the early 1970s, the U.S. consumed one-third of its total energy use for buildings, such as heating, cooling, and lighting (U.S.EIA 2012) with only a modest awareness of energy waste. However, energy crises in 1973, which was triggered by oil embargoes, increased the public interest in building energy efficiency. Before this, in 1967 the oil embargo involved in the Six-Day war did not have a critical influence on the price of oil in the U.S. However, the 1973 oil embargo, which targeted nations that supported Israel in the Yom Kippur War, significantly limited oil supplies and caused energy security issues in the world. Increasing energy prices also made countries aware of their dependence on imported energy and increased social awareness for energy performance and building energy codes. As a result, the National Conference of States on Building Codes and Standards (NCSBCS) urged the National Bureau of Standards (NBS, now the National Institute for Standards and Technology, NIST) to embark on the development of energy conservation guidelines in buildings for adoption by states and local governments to be used in local building codes. In February 1974, after several years of study, the NBS published an energy-conserving guideline, the NBSIR 74-452, *Design and Evaluation Criteria for Energy Conservation in New Buildings*. The NBSIR 74-452 provided a component performance approach and prescriptive provisions to design HVAC and lighting systems with three compliance paths for building energy design: 1) A prescriptive path, 2) A performance path with equal or higher performance than the basic prescriptive design, 3) An alternative path including a bonus for renewable energy. Soon after this, ASHRAE was requested by NCSBCS to take charge of the previous 1974 NBS energy conservation report and to develop national building energy standards (Hunn et al. 2010). Using the 1974 NBS report as a foundation, ASHRAE published Standard 90 -75, *Energy Conservation in New Building Design* in 1975 for residential and commercial buildings with technical support from the Illuminating Engineering Society (IES) (Halverson et al. 2009, Hunn et al. 2010).

In 1980 a revised edition of Standard 90 was published as ANSI/ASHRAE/IES 90A-1980 that provided revised Sections 1 through 9 of Standard 90-75 (Hunn et al. 2010). The new revision of Standard 90-75 was accomplished by splitting the standard into three parts: 1) 90A-1980 for the prescriptive path (Sections 1 to 9 of 90-75), 2) 90B-1975 for the alternative performance path (Sections 10 and 11 of 90-75), and 3) 90C-1977 (Section 12) for "annul fuel and energy resource determination" (ASHRAE 1980).

In 1982, to supplant the existing energy criteria of the Housing and Urban Development (HUD) Minimum Property Standards, ASHRAE further divided the original Standard 90 A,B,C Standards and into commercial and residential standards that were called Standard 90.1 and 90.2 Standards. ASHRAE first published Standard 90.1 in 1989 and Standard 90.2 in 1987 to upgrade Standard 90A-1980 and Standard 90B-1975 (Hunn et al. 2010, Christian 1988)

In 1992, the U.S. Energy Policy Act of 1992 (EPACT) became effective, and it was a critical turning point for Standard 90.1 because the new Energy Policy Act included general provisions for energy that required all state governments to institute building energy codes. In addition, EPACT indicated that state governments should upgrade their energy codes to meet or exceed Standard 90.1. After the 1992 EPACT, Standard 90.1-1999 took 10 years to develop the next revision to Standard 90.1-1989 with increased interest and participation from stakeholders. In Standard 90.1-1999, ASHRAE introduced a simplified National Energy Model to evaluate the total energy savings potential. The new standard was also written in an enforceable language, which would be acceptable as a building code (Hunn et al. 2010).

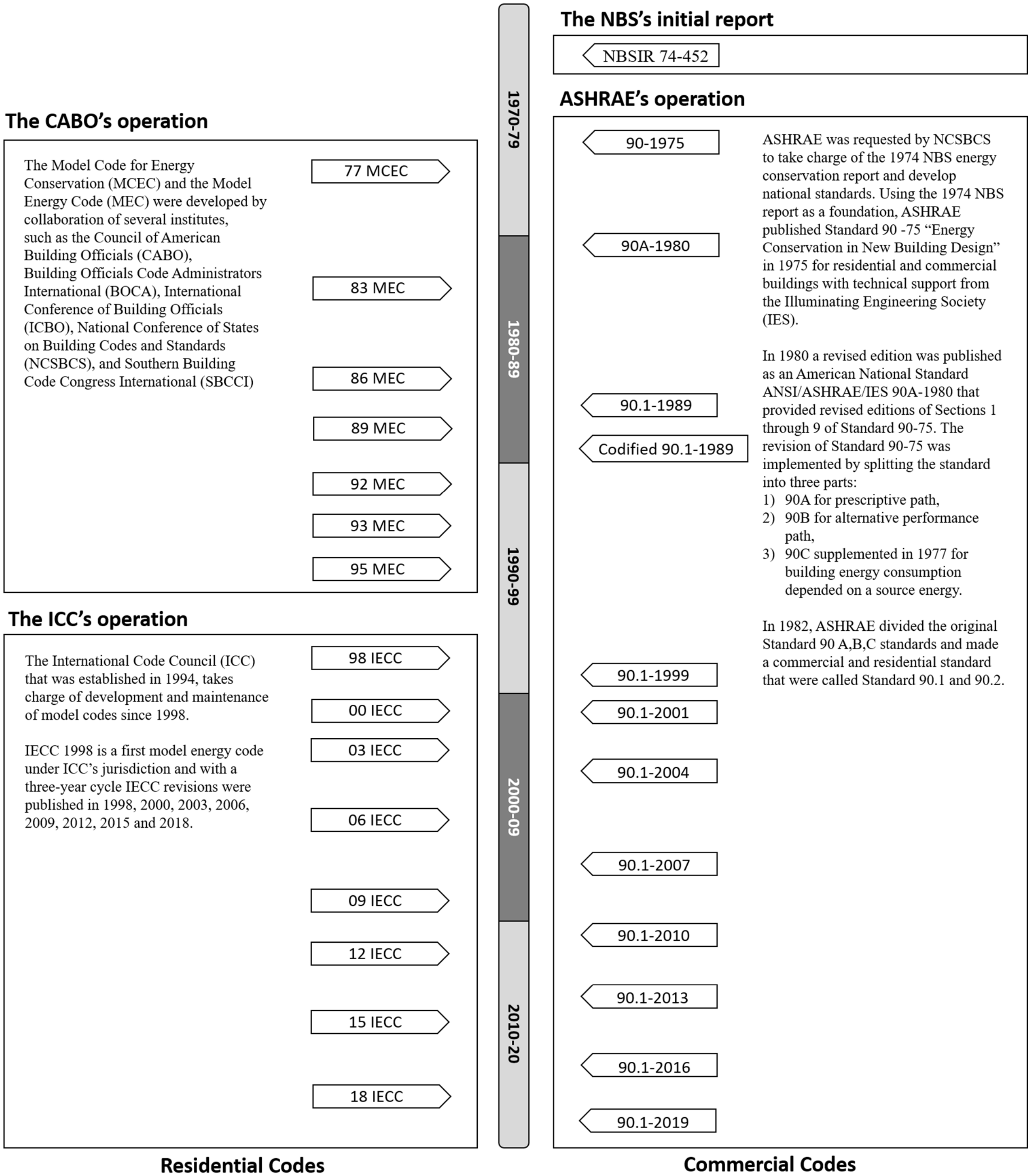
In 1999, the ASHRAE Board of Directors approved continuous maintenance on the standard to correspond to the publication update periods of the International Energy Conservation Code (IECC). Accordingly, in 2001, Standards 90.1-2001 commercial and 90.2-2001 residential were published as the first revised standards under continuous maintenance. Following this, six revisions were published every third year, beginning in 2004 through 2019 (2004, 2007, 2010, 2013, 2016, 2019). Standard 90.1-2004 had significant changes, which included the introduction of Appendix G, the Performance Rating Method, to evaluate the energy performance of proposed designs that must be at least equivalent to the performance level of provisions of the standard. In 2016, ASHRAE published Standard 90.1-2016, which was 30% more stringent than Standard 90.1-2004. To accomplish this, the Pacific Northwest National Laboratory PNNL and U.S.DOE performed the energy savings analysis, using ASHRAE Standard 90.1-2004 as a benchmark (ASHRAE 2017a). Standard 90.1 2016 allowed Appendix G to be used as a performance path for compliance with the standard for the first time. Prior to Standard 90.1-2016, Appendix G could be only used to evaluate the "beyond code" performance of buildings, such as the U.S. Green Building Council USGBC LEED rating system (ASHRAE 2016b). Finally, of importance to this study, the new Appendix G in 90.1-2016 also gave a credit for occupancy sensors by lighting power allowances that efficiently control lighting fixtures when spaces were not occupied or partially occupied.

Although Standard 90.1 is widely used as the national energy standard for commercial buildings, the International Energy Conservation Code (IECC) has been adopted by many states and municipal governments for both residential and commercial buildings (Mendon et al. 2015). The IECC also provides minimum provisions for the energy efficiency of buildings through prescriptive and performance paths.

In the U.S. the Model Code for Energy Conservation (MCEC) was the first national building energy code that described the technical requirements for energy efficiency in buildings as an enforceable code language (Hunn et al. 2010). The first model code was the MCEC 77 that was developed by a collaboration of multiple organizations headed by the Council of American Building Officials (CABO), which included by CABO, the Building Officials Code Administrators International (BOCA), the International Conference of Building Officials (ICBO), the National Conference of States on Building Codes and Standards (NCSBCS), and the Southern Building Code Congress International (SBCCI) in 1983. Since 1977, the CABO had published subsequent codes every couple of years until 1998 (1983, 1986, 1989, 1992, 1993, and 1995). In 1998 the International Code Council (ICC) took charge of the development and maintenance of the model codes. In 1994 the ICC was established by former members of the Building Officials and Code Administrators International, Inc. (BOCA), the International Conference of Building Officials (IBCO), and the Southern Building Code Congress International, Inc. (SBCCI) (Blissard 2015, ICC 2015a). The 1998 IECC was the first model energy code under the ICC's jurisdiction (Martin 2010). Since 1998 the ICC has published revisions to the IECC beginning in 1998, 2000, 2003, 2006, 2009, 2012, 2015, and 2018.

2015 version of the IECC introduced a new compliance path for architects and engineers to have more diversity and flexibility in their design with meeting energy efficiency and code-compliance uses an Energy Rating Index (ERI) to allow building owners and contractors to understand energy efficiency, similar with the Home Energy Rating System (HERS) ratings that have been widely applied to evaluate homes and provide useful information to consumers. The ERI is an alternative path that uses a 0 to 100 linear scale that accounts for the percent change of the total energy use of the proposed design proportional to the reference design. For example, an ERI 0 is a level to express a net-zero energy home and an ERI 100 is a level that is equal to the 2006 IECC. In other words, the lower ERI value represents a more energy-efficient home. Such model codes have contributed to efficient building design in the United States, along with ASHRAE Standards (ICC 2015a, CBei 2016).

The figure A-1 shows the history of the Model codes (i.e., IECC) and Standard 90.1 codes that are the most national-widely used codes and standards in the U.S.



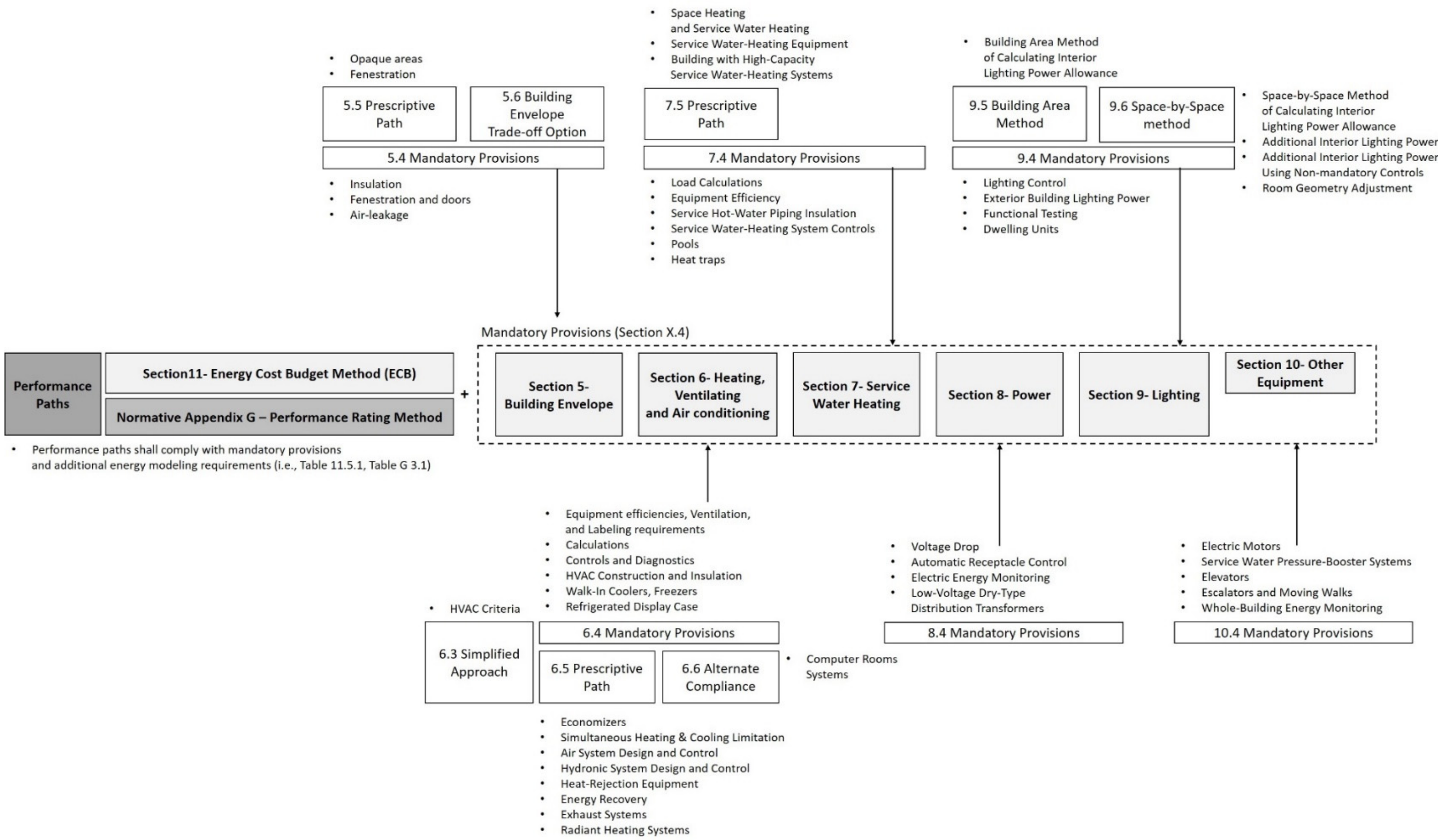
Source – Halverson et al. 2009, Hunn 2010, Conover 2010, Martin 2010, Blissard 2015, ICC 2015a, BECP 2016, ICC 2018, ASHRAE 2019

Figure A-1. The U.S. History of Building Codes and Standards

APPENDIX B

PERFORMANCE CODE-COMPLIANCE PATHS IN STANDARD 90.1-2016 and 90.1-2019

ASHRAE Standard 90.1-2016 and 90.1-2019 contains two types of code-compliance paths: a prescriptive path and a performance path. The prescriptive path describes design requirements using the provisions from Section 5 to Section 10 of 90.1. The performance path includes two options, which include Section 11, Energy Cost Budget Method (ECB); and Appendix G. Performance Rating Method as below.



APPENDIX C

PERFORMANCE CALCULATION METHOD FOR APPENDIX G

IN ASHRAE STANDARD 90.1-2019

ASHRAE Standard 90.1-2016, Appendix G. Performance Rating Method was approved as a new performance path with the current Energy Cost Budget (ECB) path in Standard 90.1-2016. In 2016 Appendix G introduced a new metric to calculate building energy performance, which is referred to as Performance Cost Index (PCI) (ASHRAE 2016a). In Standard 90.1-2019, to comply with code-requirements, the PCI shall not be more than the Performance Cost Index Target (PCI_t). The formula for proposed building design in Section G1.2.2 is as below (ASHRAE 2019):

$$Performance\ Cost\ Index\ (PCI) = \frac{Proposed\ Building\ Performance}{Baseline\ Building\ Performance} \quad \text{(Eq. 1)}$$

Where: Proposed Building Performance = The annual energy cost estimated for a proposed design, Baseline Building Performance = The annual energy cost estimated for a baseline design

To determine a baseline building performance, the PCI targets should be calculated using the following equation, which is suggested in Section 4.2.1.1 New Buildings:

$$PCI_t = \frac{(BBUEC+(BPF\times BBREC))}{BBP} \quad \text{(Eq. 2)}$$

Where (Rosenberg and Hart 2016, ASHRAE 2019):

PCI_t= The maximum Performance Cost Index for a proposed design to comply with a target version of Standard 90.1.

BBUEC = Baseline Building Unregulated Energy Cost. The portion of the annual energy cost of a baseline building design that is due to unregulated energy use.

BBREC = Baseline Building Regulated Energy Cost. The portion of the annual energy cost of a baseline building design that is due to regulated energy use.

BPF = Building Performance Factor (BPF) from Table 4.2.1.1. For building area types not listed in Table 4.2.1.1. use "All others." Where a building has multiple building area types, the regulated BPF shall be equal to the area-weighted average of the building area types.

BBP = Baseline Building Performance.

Table C-1. Building Performance Factor (BPF) (a portion of the table 4.2.1.1)

Building Area type	**Climate Zone**											
	0A and 1A	**0B and 1B**	**2A**	**2B**	**3A**	**3B**	**3C**	**…...**	**6A**	**6B**	**7**	**8**
Multi-family	0.68	0.70	0.66	0.66	0.69	0.68	0.59	…...	0.68	0.71	0.68	0.72
Healthcare/ Hospitality	0.60	0.60	0.58	0.54	0.56	0.55	0.55	…...	0.57	0.52	0.57	0.57
Hotel/Motel	0.55	0.53	0.53	0.52	0.53	0.54	0.54	…...	0.50	0.50	0.50	0.50
Office	0.52	0.57	0.50	0.56	0.53	0.56	0.48	…...	0.52	0.52	0.49	0.51
Restaurant	0.63	0.64	0.60	0.60	0.60	0.61	0.58		0.65	0.65	0.67	0.70
Retail	0.51	0.54	0.49	0.55	0.51	0.55	0.53	…...	0.50	0.50	0.48	0.50
School	0.39	0.47	0.38	0.43	0.38	0.42	0.40	…...	0.36	0.36	0.36	0.37
Warehouse	0.38	0.42	0.40	0.42	0.43	0.44	0.43		0.54	0.54	0.57	0.57
All others	0.56	0.57	0.50	0.52	0.50	0.54	0.53	…...	0.50	0.50	0.50	0.46

APPENDIX D

OCCUPANCY SENSOR REDUCTIONS USING THE SPACE-BY-SPACE METHOD IN ASHRAE STANDARD 90.1-2019

ASHRAE introduced a new credit for occupancy-based lighting controls to calculate lighting power density allowances for Appendix G Performance Rating Method (RPM) in Standard 90.1-2016. This modification is based on addenda dx to Standard 90.1-2013 that gives a reduction rate in lighting power allowances for occupancy sensors in the Space-by-Space Method (ASHRAE 2016a, Table G3.7). For example, it provides a 15% to 30% reduction of the lighting power density in an office. Table D-1 provides a portion of the G3.7 Table in Standard 90.1-2019.

Table D-1. Performance Rating Method Lighting Power Density Allowances and Occupancy Sensor Reductions Using the Space-by-Space Method in ASHRAE Standard 90.1-2019 (portion of the table G 3.7, pp333-335)

Common Space Types[a]	**Lighting Power Density, W/ft^2**	**Occupancy Sensor Reduction[b]**
Laboratory		
In or as a classroom	1.40	None
All other laboratory	1.40	10%
Laundry/Washing Area	0.60	10%
Loading Dock, Interior	0.59	10%
Lobby		
Facility for the visual impaired (and used primarily by residents)	2.26	25%
Elevator	0.80	25%
Hotel	1.10	25%
Motion picture theater	1.10	25%
Performing arts theater	3.30	25%
All other lobby	1.30	25%
Locker Room	0.60	25%
Lounge/ Breakroom		
Healthcare facility	0.80	None
All other lounge/breakroom	1.20	None

Table D-1. Performance Rating Method Lighting Power Density Allowances and Occupancy Sensor Reductions Using the Space-by-Space Method in ASHRAE Standard 90.1-2019 (portion of the table G 3.7, pp333-335) (cont.)

Common Space Types[a]	**Lighting Power Density, W/ft²**	**Occupancy Sensor Reduction**[b]
Office		
Enclosed	1.10	30%
Open plan	1.10	15%[C]
Parking Area, Interior	0.20	15%
Pharmacy Area	1.20	10%
Restroom		
Facility for the visual impaired (and used primarily by residents)	1.52	45%
All other restroom	0.90	45%
Sales Area	1.70	15%
Seating Area, General	0.68	10%
Stairwell	0.60	75%
Storage Room		
Hospital	0.90	45%
≥ 50 ft²	0.80	45%
< 50 ft²	0.80	45%
Vehicular Maintenance Area	0.70	10%
Workshop	1.90	10%

a. In cases where both a common space type and a building area-specific space type are listed, the building area-specific space type shall apply.
b. For manual-ON or partial-auto-ON occupancy sensors, the occupancy sensor reduction factor shall be multiplied by 1.25.
c. For occupancy sensors controlling individual workstation lighting, occupancy sensor reduction factor shall be 30%.

APPENDIX E

ENERGY SIMULATION PROGRAMS

Energy simulation is extensively used to analyze building energy performance and savings in practice and research because of substantial advantage to save costs and time. Also, performance paths using energy simulations in standards and codes provide a chance to have design flexibility compared to prescriptive methods. There have been several whole-building energy simulation programs to meet the requirement in the codes and standards. Among them, the DOE-2 and EnergyPlus programs are the most widely recognized programs to develop building energy models for code-compliance.

1) DOE-2

DOE-2 is one of the whole-building simulation programs for analyzing building energy use and fuel costs associated with commercial building operation in the U.S that has been widely used with Standard 90.1. This program was initially developed by the Lawrence Berkeley National Laboratory (LBNL) in 1978 in cooperation with Los Alamos Scientific Laboratory (LASL) and Argonne National Laboratory (ANL), with funding from the DOE (Kreider et al. 2001, Oh 2013, JJH 2018). DOE-2 can estimate the hour-by-hour energy performance of the 8,760 hr/yr using the Building Description Language (BDL) based on FORTRAN code language. The BDL Processor continuously confirms BDL instructions to check suitable format, syntax, and values from input variables and libraries (e.g., materials and weather libraries). This BDL Processor utilizes response factors to assess the transient heat flow on exterior walls and roofs under changing climatic conditions and can calculate system and plant loads (LBL and

LANL 1982, LBL 1991). The accuracy of DOE-2 in general engineering practice accomplished "10–12% in monthly peak demand, 8–10% in monthly energy use, 10–15% in annual peak demand, and 3–5% in annual energy use for large commercial buildings" (Kreider et al. 2001). This program was used in the Fort Hood Project performed by the ESL to develop energy estimating models for the case building.

2) EnergyPlus

EnergyPlus is a more recently developed tool that allows the modular simulation to design and analyze building performance and energy use, which can calculate heat flow from building surfaces and internal heat gains, and calculate the energy consumption for complex HVAC equipment to maintain thermal comfort. EnergyPlus was created by LBNL, the U.S. Army Construction Engineering Research Laboratory (CERL) and the University of Illinois Urbana-Champaign (UIUC), in collaboration with the staff of the previous DOE-2 and BLAST development groups. In a simulation fashion as TRNSYS, Energyplus introduced a modular simulation to improve program development in the future (Kreider et al. 2001). EnergyPlus also developed the *EnergyPlus Programming Standard* for programming style based on FORTRAN 90 or 95. Each module in EnergyPlus consists of a different package associated with source code in different files. The source code has a close relation with data structures, and processes in each module and the modules used are connected and implement simulation as the codes in EnergyPlus (U.S.DOE 2016b). As an integrated simulation, EnergyPlus can simultaneously calculate three major parts of building, system, and plant. In the difference to the previous sequential simulations (i.e., BLAST or DOE-2), integrated simulation can provide feedback between zone conditions, system and plant information that affects the simulation results for

HVAC systems (U.S.DOE 2016a). Also, EnergyPlus supports code-compliance modeling with output formats for Appendix G and beyond code programs (U.S.DOE 2016c). The DOE also provides reference models compliant with Standard 90.1 in an EnergyPlus format.

3) Features of Modeling Program: DOE2.1e and EnergyPlus (1st Review)

In the history of building energy simulations, numerous simulation programs have been developed to enhance calculation accuracy and reduce a gap in the prediction results against the practical building energy use. DOE-2 and EnergyPlus are the most preferred representative programs in energy simulations. Therefore, this study reviewed building energy models in both DOE-2.1e and EnergyPlus by developing small reference office building models in DOE-2.1e and comparing with the models in EnergyPlus. The following is a simple description and comparison of DOE-2 and EnergyPlus that are used simulation programs in this study.

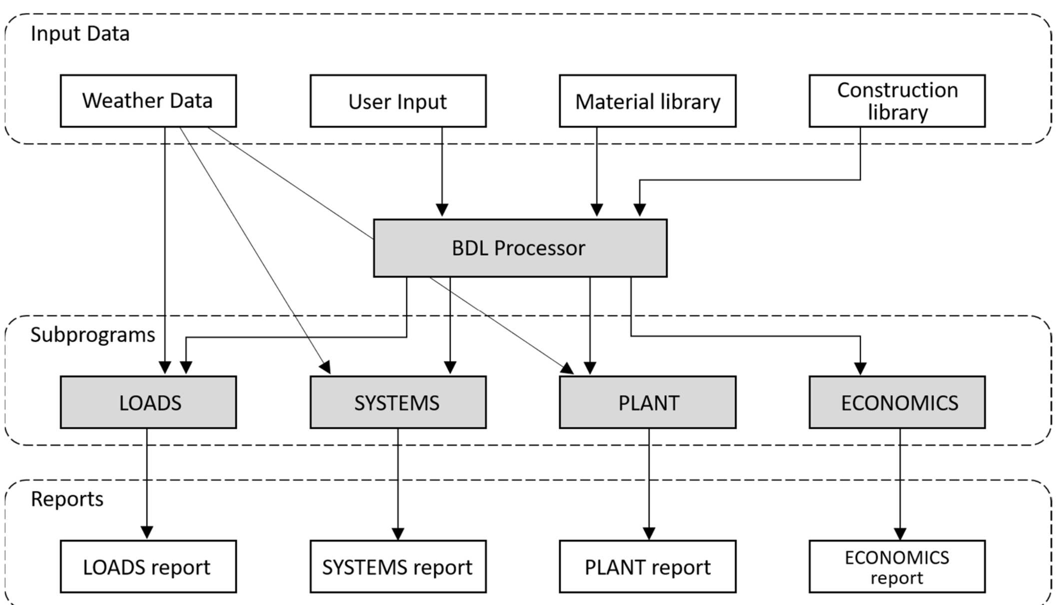


Figure E-1. DOE-2.1e simulation process (adapted from LBL 1991)

DOE-2 is a whole-building energy simulation program to estimate the hourly-based energy use and cost of a building using physical information such as hourly weather data, building geometry, geographical location, HVAC system and other building description (LBL 1991). DOE-2.1e was first released in 1993 and has been updated until 2003 for different window OS versions (i.e., Win 95/98/ME/2000/XP) (JJH 2018). DOE-2.1e is made up of one processor and four sub-programs: 1) BDL- the building description language processor; 2) LOADS- the loads simulation sub-program; 3) SYSTEMs- the secondary HVAC system simulation sub-program; 4) PLANT- the primary HVAC simulation sub-program and; 5) ECONOMICS- the economic analysis sub-program (LBL 1991).

DOE-2.1e has been extensively utilized for investigating energy conservation measures of retrofit projects and building performance designs in the U.S. and many other countries. Also, In the private sector, over 20 interfaces have been developed by adapting DOE-2 to make the program more comfortable to use (Crawley et al. 2005,2008).

eQUEST is a quick energy simulation tool derived from advanced DOE2.2 simulation that combines three building creation modules (i.e., schematic design wizard (SD wizard), design development wizard (DD wizard) and energy efficiency measure wizard (EEM wizard)) to help users with graphical 3D modeling view. The building creation wizard offers a step-by-step process to create a building model that provides easy-to-understand opportunities of building components and system designs (JJH 2018). Also, graphical support for modeling users is a strong understanding of architectural modeling and HVAC system components compared to DOE2.1e.

Table E-1. Key comparative factors for whole-building energy simulation tools

Description	DOE2.1e	eQUEST	EnergyPlus
General details			
Simulation engine	DOE2.1e	DOE2.2	EnergyPlus (based on BLAST and DOE2)
First release	1993	1999	2001
3D modeling/ Visualization	No/ DrawBDL	Yes	No/ SketchUp
Coding language	FORTRAN	FORTRAN	FORTRAN (2001-2014) C++ (2014-present)
Input data creation	BDL coding	wizard tools	modules
Usability	Normal - Intuitive process - direct coding available	Fairly easy - Intuitive and straight forward wizard process - 3D graphics	Difficult - modular simulations - complicated interface
Standard 140 test/ Standard 90.1-2016 requirements	Satisfied	Satisfied	Satisfied
Comprehensive/graphical interfaces	Visual DOE, eQUEST	Not available	Designbuilder, Revit, Honeybee & ladybug in Grasshopper
Load calculations			
Simulation of loads, systems, solutions, and economics	Yes	Yes	Yes
Calculation methods	Weighting Factor method	Weighting Factor method	Energy Balance Method
Weather data format	bin file	bin file	epw file
Hourly load calculation	Yes	Yes	Yes
Dynamic model calculation	Yes	Yes	Yes
Simulation Schedules			
Type	Deterministic	Deterministic	Deterministic
Input style	Fraction/temperature	Fraction/temperature	Fraction/temperature
Modeling of measured schedules	Partly available	Partly available	Partly available
Stochastic model	N/A	N/A	N/A
HVAC systems and components			
HVAC ideal mode	Sum mode		Ideal load system
User configuration of HVAC systems	Yes	Yes	Yes
Automatic sizing	Yes	Yes	Yes
Distribution system	Yes	Yes	Yes
Thermal zone	Yes	Yes	Yes
Natural and mechanical ventilation	Yes	Yes	Yes
Report			
Graphical presentations	No	Yes	No
Text	Yes	Yes	Yes

Source: JJH (2018), EnergyPlus (2019a), Oh (2013), Rallapalli (2010), Crawley et al. (2005, 2008)

For example, 3D modeling function in eQUEST through the building creation wizard depicts physical information of ongoing building design such as shape, window location, and HVAC zoning. Moreover, graphic chart for HVAC systems describes the diagrammatic composition of HVAC system and their options of its heating, cooling and ventilating and air-conditioning systems, which promotes better interpretation in process to build up HVAC design than EnergyPlus that consists of simulation modules that is not sometimes able to see the total HVAC system design and process for developing building simulations.

EnergyPlus is a console, module-based simulation programs for whole-building energy simulations that was developed based on the functions and capabilities of BLAST and DOE-2.1e (EnergyPlus 2019, Crawley et al. 2008) that contains several tools for pre-processing and post-process (i.e., IDF-Editor, EP-Launch, and EP-Compare). For instance, reading and writing of input and output data work in text files that can be modified and configured in IDF-Editor to create EnergyPlus input files using spreadsheet-similar interface. EP-Launch is to indicate weather and EnergyPlus input files to perform simulations in EneryPlus. Also, simulation results from the runs in EP-Launch can be graphically compared with two or more other results (Crawley et al. 2008). The graphical 3D modeling and input interface are not incorporated in EnergyPlus, but several graphical interfaces have been developed for EnergyPlus such as Sketch-up and OpenStudio. Even though the modular system for simulations in EnergyPlus is not intuitive to figure out the flow of systems, there is a strong point to relatively easily add simulation modules to correspond to new technologies.

4) Differences in Calculations Between DOE-2.1e and EnergyPlus 8.0 (1st Review)

In 2000, Huang & Associates (2000) compared DOE-2.1e to review California Title-24 compliance estimations in EnergyPlus. To evaluate the models in EnergyPlus, the 150 DOE-2 files to EnergyPlus were converted from the California Energy Commission's Alternate Compliance Method (ACM) manual. The 150 ACM test cases included: three partial compliance tests, eighteen envelope tests, twenty-three internal loads tests, and thirty-five system tests. Also, four prototype buildings were tested in different California climates: small single-story building, large two-stories building, large five stories, and single-story attached office or store. Table E-2 describes load discrepancies using different series of independent parameters between DOE2.1e and EnergyPlus, which showed substantial differences between DOE2.1e and EnergyPlus even though the same input or algorithms were applied to two simulation programs. Table E-3 addresses summarized problems, reasons, and solutions discussed to settle differences from simulation results.

Table E-2. Load Calculation discrepancies between DOE2.1e and EnergyPlus

Test Series	EnergyPlus: Heating	EnergyPlus: Cooling	EnergyPlus: Fan
Wall assemblies	Lower (< 20%)	Higher (< 10%)	similar
Window-to-wall ratios	Lower (30% - 60%)	similar	Higher (< 10%)
Lighting levels	Lower (60% - 70%)	Higher (15% - 20%)	similar
Ventilation rates	Lower (15% - 20%)	Higher (< 15%)	similar
HVAC system type	Higher (≈ 100%)	similar	similar

Ref. Huang et al. (2000)

Table E-3. Issues for energy modeling transition from DOE2.1e to EnergyPlus

Issues	Phenomenon	Reason	Solution
Window modeling	Different window modeling methods	DOE2 uses only properties of U-factor and Solar Heat Gain Coefficient (SHGC) for window modeling EnergyPlus defines thermal and optical properties for the window assembly by layer	Using fictitious window layers calculated by iterative LBNL Window software calculations within EnergyPlus to find the best match to the specified U-factor and SHGC e.g.) For a U-factor of a double glazing window, the gap thickness was tuned and then the inner glazing conductivity, and lastly the outer glazing conductivity e.g.) For matching an SHGC, the solar transmittance at normal incidence was firstly tuned, and then the front and back solar reflectances at normal incidence were adjusted
Window shading	Different Solar heat gain reduction calculations	The original DOE2 input files assumed a solar heat gain reduction of 0.80 because of the effects of drapes, curtains, or other window shading devices. To model this, DOE2 assumes a 20% reduction in the entering solar radiation EnergyPlus is much more stringent and complicated of modeling window interior blinds with the appropriate thermal properties matching with the same 0.20 solar reduction across the board	To solve out, no solar heat gain reduction was determined to model the windows in both EnergyPlus and DOE2
Infiltration	When simulated Simple Air Flow model in EnergyPlus, the airflow rates, as a result, were continuously higher by 30%	The DOE2 infiltration inputs for the air-changes per hour (ACH) method were converted into the Simple Air Flow model in EnergyPlus, which generated a discrepancy due to DOE2's reduction of the wind speed on the weather tape to account for local terrain effects. Whereas EnergyPlus similarly adjusts wind speed in cases of their thermal calculations, these adjusted values were not applied in the Simple Air Flow model	As a provisional approach, wind speed reduction in DOE-2 was excluded in order that the calculated infiltration rates will be matched between the two programs.

Table E-3. Issues for energy modeling transition from DOE2.1e to EnergyPlus (cont.)

Issues	**Phenomenon**	**Reason**	**Solution**
Thermostat throttling range	Zone average temperature difference due to throttling range in DOE2	The DOE2 files use a throttling range of 2.2ºC (4ºF), which generating were average 1ºC higher temperatures in the zones than the thermostat setting. While EnergyPlus does not simulate throttling ranges.	Throttling-range in DOE2 was changed to 0.20 because PID controls are widely used and do not have throttling ranges
Inconsistent fan inputs in DOE2	DOE2 allows unnecessary fan inputs (i.e., SUPPLY-CFM, SUPPLYDELTA-T, and SUPPLY-KW). Fan energy consumptions in EnergyPlus differed substantially against DOE2 calculations using the input SUPPLY-KW.	The discrepancy can occur as the DOE2 inputs for SUPPLY-DELTA-T and SUPPLY-KW are conflicting	SUPPLY-KW in the DOE2 files were overwritten with values to be consistent with SUPPLY-DELTA-T input values
Heating to the cooling setpoint	The supply air is heated to the cooling setpoint during the morning hours.	Temperature plots during the shoulder seasons showed that EnergyPlus roamed between the heating or cooling season control logic	This problem can be modified by updating the setpoint manager in EnergyPlus
Faulty economizer operating logic	The EnergyPlus heating used more than 50% higher for test runs using PSZ (Packaged Single Zone) systems in different climates with substantial economizer usage.	The economizer control in EnergyPlus caused overcooling in the swing season, which then required heating to turn back the thermostat setpoint	This problem can be modified by updating the economizer control in EnergyPlus
Abnormally low boiler temperatures	In some runs, the EnergyPlus heating energies were less than half, and yet in other runs, they showed 50% higher than the DOE2 heating energies.	Although DOE2 does not model the boiler water temperature, it used low default boiler temperature to deliver the loop temperature for a water-source heat pump. When such a low temperature was modeled in EnergyPlus for a boiler operating, it made tiny heat capacity and thus a very small amount of heat delivered to the building.	This problem can be modified by overwriting the DOE2 boiler temperature with a value of 48ºC (120 ºF)
Excessive pump heat displacing mechanical heating	In test runs, a hot water loop with a fixed-speed pump was modeled. EnergyPlus has utilized to size the pumps because DOE2 does not size water loop pumps. In California climates, EnergyPlus returned too large pump sizes several times.	The fixed-speed pump would add a constant amount of heat to the hot water loop when it was operated. Moreover, the constant water loop temperature in EnergyPlus without any distribution losses caused that the building obtains over time the pump heat gain, which is enough amount to meet heating load without the boiler operation.	There are several available solutions, such as (1) improving the EnergyPlus sizing routine, (2) updating the pump types from fixed to variable speed, or (3) adding a loss coefficient in the loop (DOE2 assumes 1%).

This project found that a stringent automated conversion tool (i.e., doe2ep[2]) is required to ensure consistency between the DOE-2.1e and EnergyPlus input files. This is because minor differences in input values or control algorithms resulted in high sensitivity.

In other studies, Andolsun et al. (2011a,b) investigated DOE-2.1e with EnergyPlus and TRANSYS for understanding differences of ground-coupled heat transfer calculations on slab-on-grade in residential buildings. Analyzed models in this study included two cases (i.e., sealed box models, IECC 2009 compliant houses) in four different climate regions (i.e., Austin, TX; Phoenix, AZ; Chicago, IL and Columbia Falls, MT).

In the first part, empty and adiabatic sealed boxes were developed in DOE-2.1e, EnergyPlus, and TRNSYS that were coupled only with the ground to separate the slab-on-grade heat transfer from other building components. In this comparative study, three different models were developed to compare the results, such as 1) DOE-2.1e model with the Winkelmann method, 2) EnergyPlus model using the Slab preprocessor, 3) TRNSYS model using the TRNSYS slab-on-grade method. In the second part, IECC compliant houses were modeled to quantify the effect of underground heat transfer on slab-on-grade and compared between the DOE-2.1e, EnergyPlus, and TRNSYS programs.

In calculations methods, DOE-2.1e defines the heat transfer between the zone air and the interior surfaces as the heat transfer between a massless fictitious air layer and an inside surface of the building construction. This fictitious air layer describes the combined effect of the inside radiation and convection heat transfer on the surface. Then, the combined heat transfer of

---

[2] doe2ep is a modified DOE-2.1e program to support the large number of file transition from DOE2.1e to EnergyPlus that would automatically transfer DOE2.1e input files to the corresponding EnergyPlus input files (Huang et al. 2000)

radiation and convection is integrated into the building envelope conduction calculations based on the one-dimensional conduction heat transfer equation (LBL and LANL 1982).

In the EnergyPlus calculations for the heat transfer between the slab and zone air, it contains four heat components such as 1) heat exchange of longwave radiation on the zone surfaces, 2) longwave radiation from internal sources, 3) shortwave radiation from lights and solar sources, 4) heat exchange of the convection with the zone air (EnergyPlus 2010). EnergyPlus used a matrix of exchange coefficients depending on surface configurations developed by Hottel and Sarofim (1967). For convection calculations, five options are available: 1) user-defined, 2) simple algorithm, 3) detailed algorithm, 4) ceiling diffuser, and 5) Trombe wall algorithm. Of these options, the user algorithm utilizes user input of the constant convection coefficients of the inside and outside surfaces, and the simple algorithm uses the constant convection coefficients of the different heat transfer configurations.

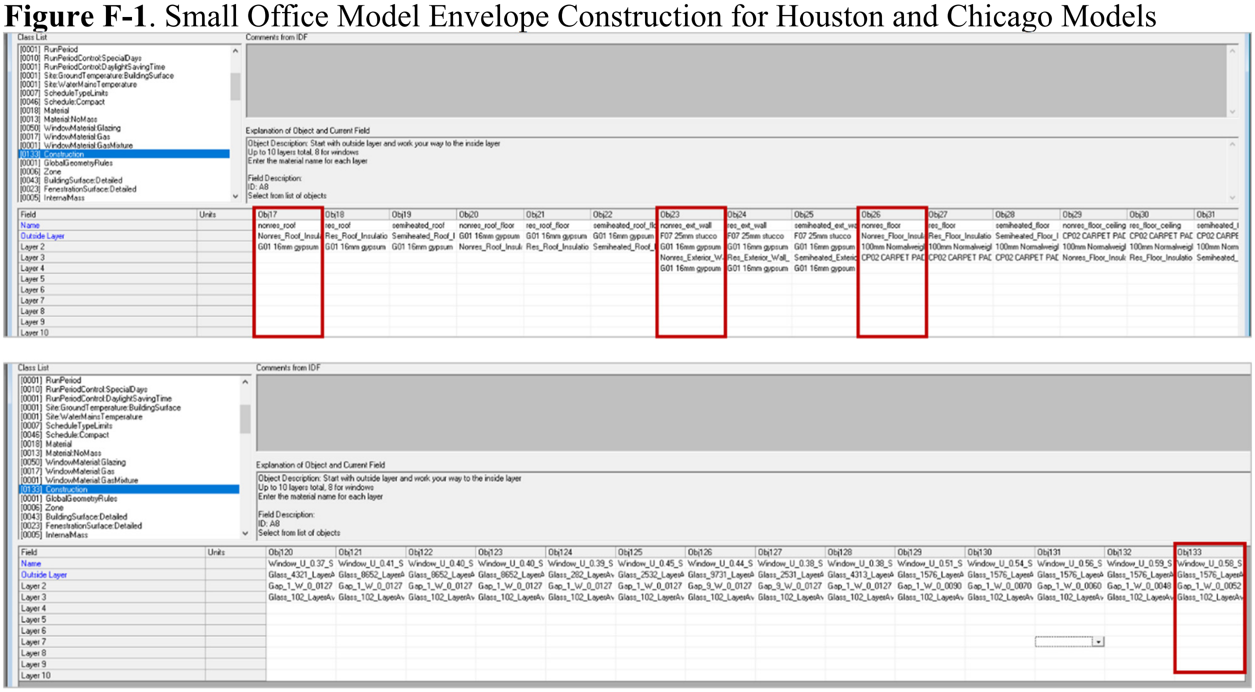
Therefore, Andolsun et al. (2011a,b) identified calculation differences of convection and radiation between the slab and zone air in DOE-2.1e and EnergyPlus. For example, calculation methods for ground-coupled heat transfer are significantly different in EnergyPlus and DOE-2.1e. EnergyPlus estimates z-transfer function coefficients in order to calculate the transient ground surface temperatures while DOE-2.1e uses a steady-state for the temperatures on the ground surfaces. Therefore, to reduce a gap between two programs, this study found a good estimation for $Q_{slab/zair}$ that used the inside air film resistance (I-F-R) of 0.136 m_2-K/W (0.77 hr-ft^2-°F/Btu). This value showed close floor heat transfer between the DOE-2.1e model with Winkelmann's method and the EnergyPlus with Winkelmann's method, which showed that the sealed box model in EnergyPlus resulted in slightly lower heat transfer (0.1-0.3W/m^2) than DOE-2.1e during the period of the target year. These studies also pointed out that other factors may additionally generate calculation differences in Winkelmann's methods between two programs. For example, two programs differ inside boundary conditions due to different slab-soil interface temperatures. The DOE-2.1e's zone air temperatures fluctuate during the year while EnergyPlus has constant temperature throughout a whole year. Also, in DOE-2.1e models, the inside surface temperatures of the floor are assumed as equal values to zone air temperatures. However, EnergyPlus models estimated the inside surface temperatures of the floor at each time step along with its inside heat balance calculation processes. At the end of these studies, the sealed boxes concluded that the floor heat transfer using the Winkelmann's models and EnergyPlus Slab models are different from those of the TRNSYS's slab-on-grade models in the magnitudes, the peak months and the peak-to-peak amplitudes of the floor heat transfers.

APPENDIX F

REFERENCE MODEL INPUT VARIABLES AND REPORTS

This study developed reference models for evaluating the impact of occupancy-based building system controls in office buildings. The reference models in this study used the same building shape, dimension, and material property with the PNNL commercial building prototype models for Standard 90.1-2016. The summary of the reference models is explained in Table 6. The description of the envelope material and construction is presented in Table 10 to Table 12. This Appendix provides the verification of input variables of reference models in this study based on the PNNL small office prototype models.

Figure F-1. Small Office Model Envelope Construction for Houston and Chicago Models



* Note: Chicago and Houston models have the same configurations of construction layers, but the properties of exterior wall insulation and roof insulation are different. Also, window materials were different, which was design based on the weighting process (Thornton et al. 2011, Section 4.3)

Figure F-2. Mass and No Mass Envelope Materials for Houston Models

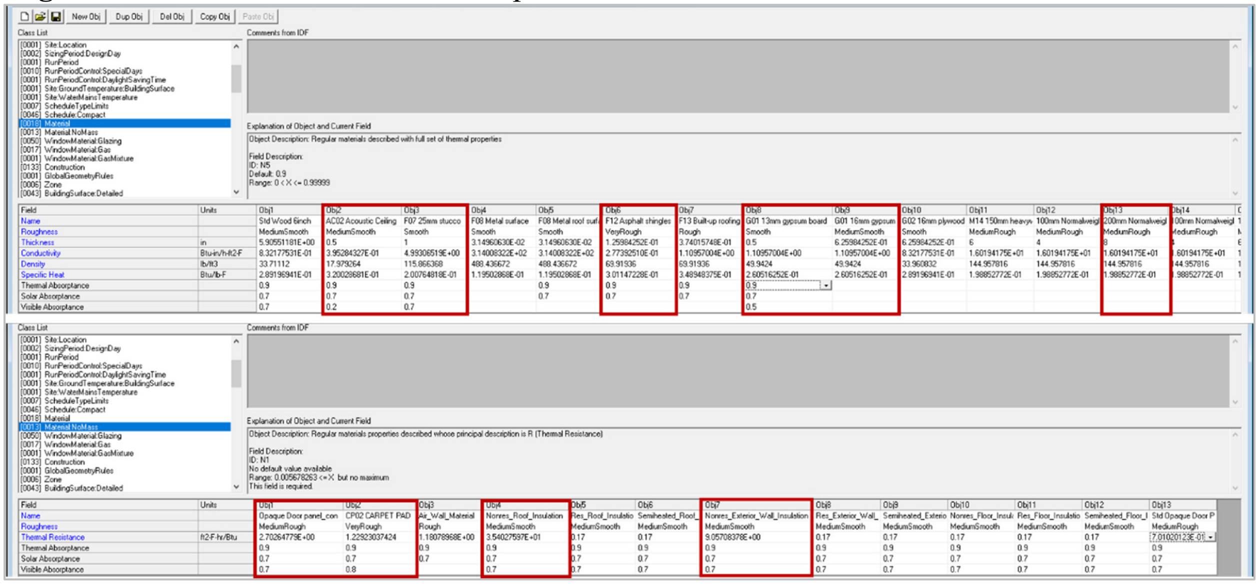


Figure F-3. Mass and No Mass Envelope Materials for Chicago Models

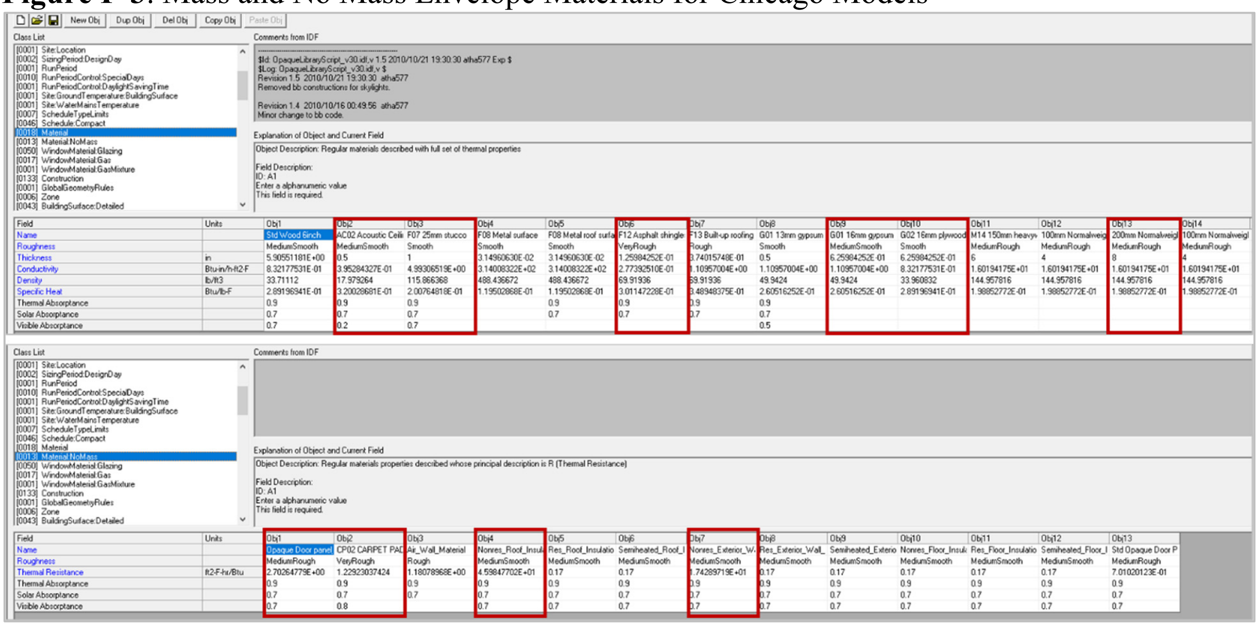


Figure F-4. Window Materials for Houston Models

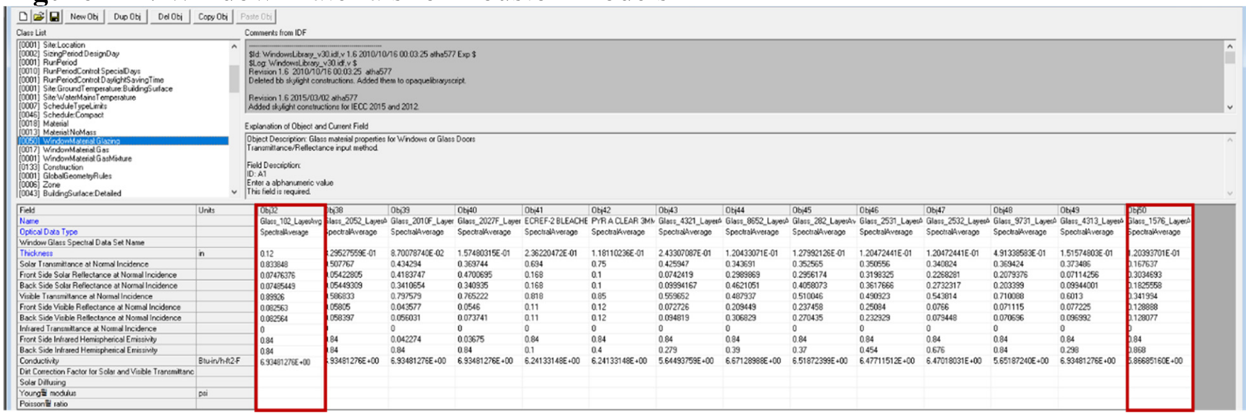


Figure F-5. Window Materials for Chicago Models

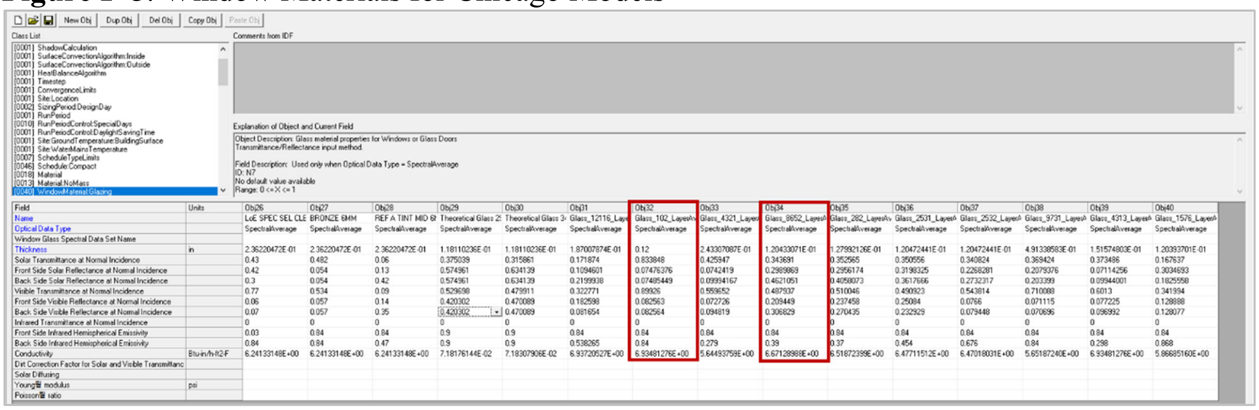


Figure F-6. Internal Heat Gain: People

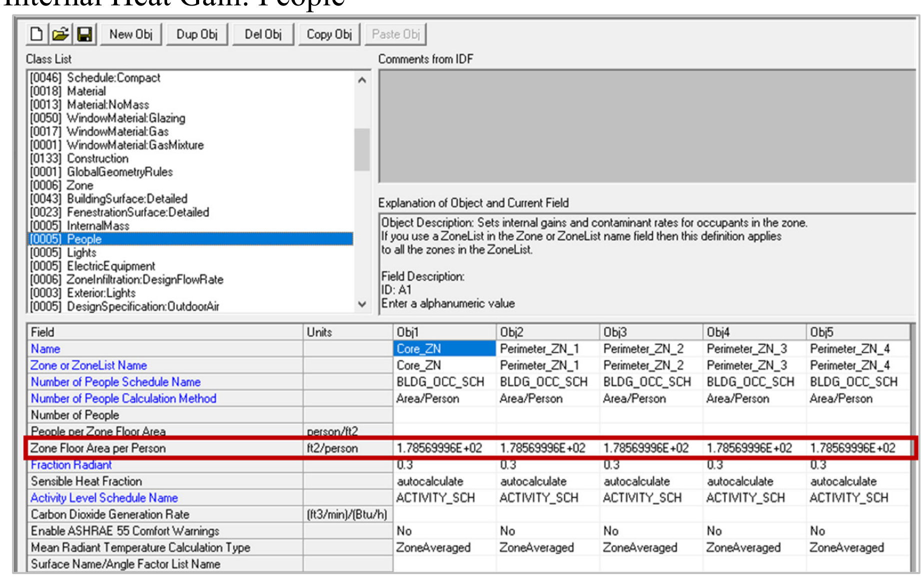


Figure F-7. Internal Heat Gain: Lighting

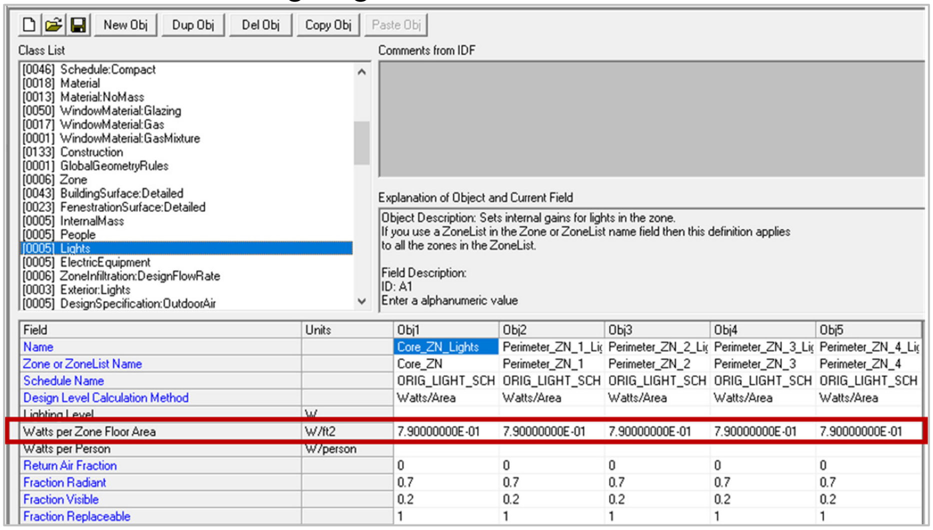


Figure F-8. Internal Heat Gain: Equipment

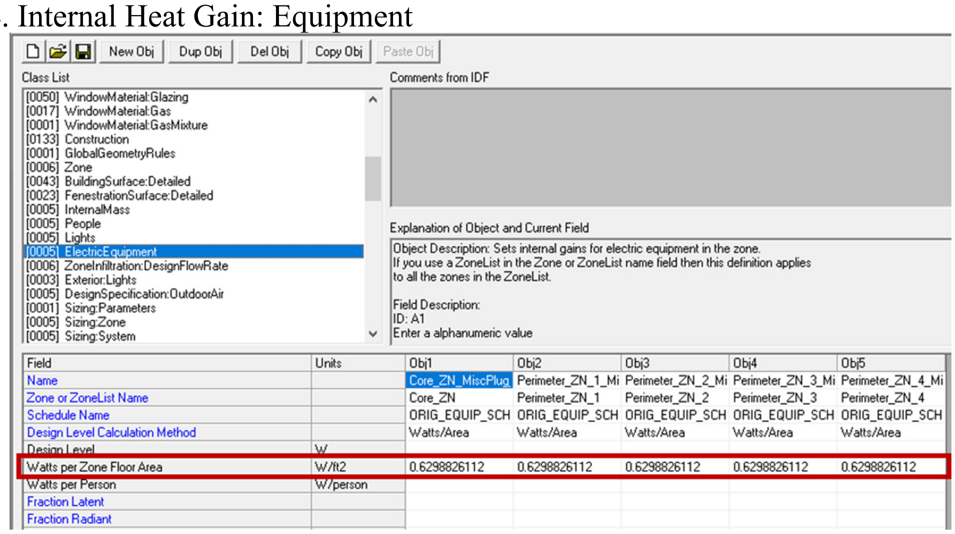


Figure F-9. Zone Supply Temperature

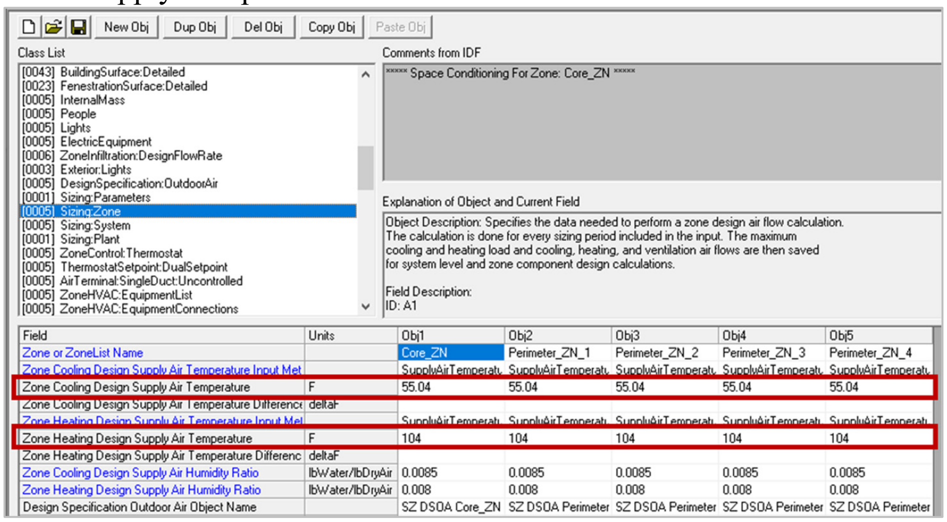


Figure F-10. System Type and Cooling COP

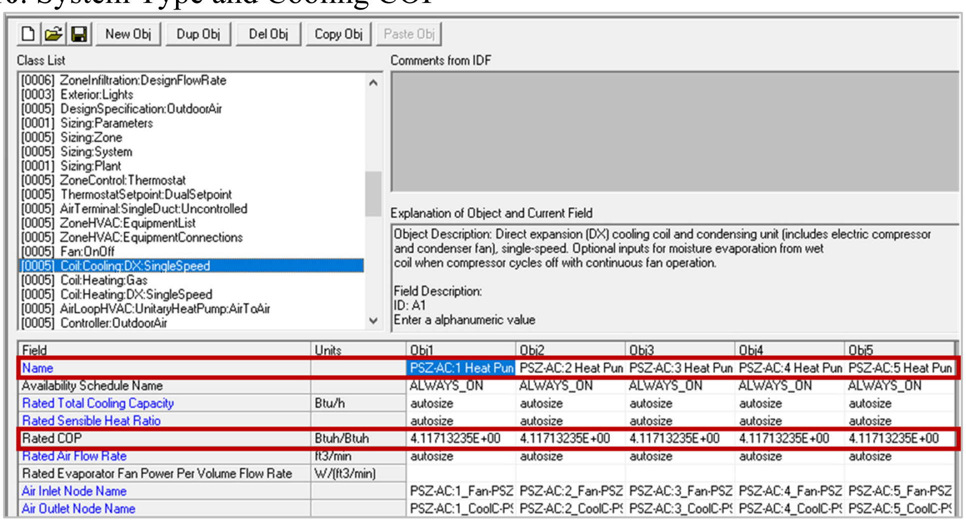


Figure F-11. Heating System COP

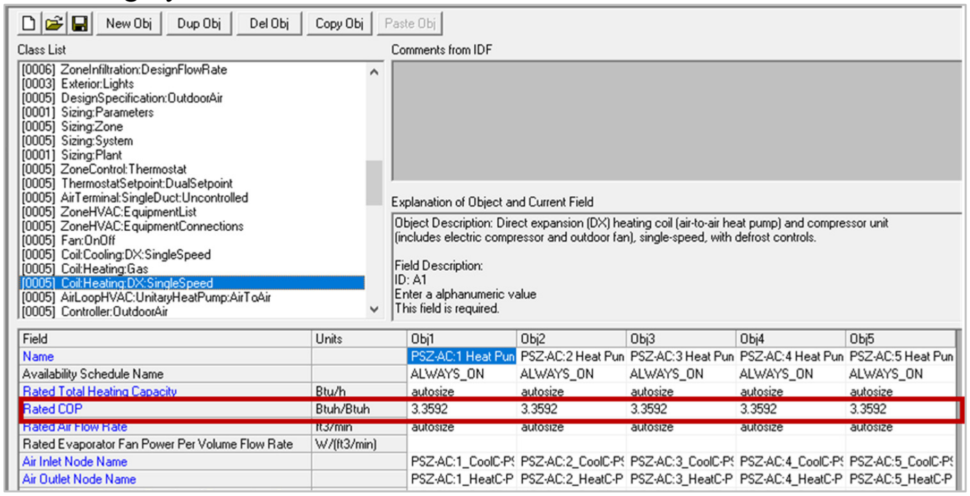


Figure F-12. Supply Fan Efficiency

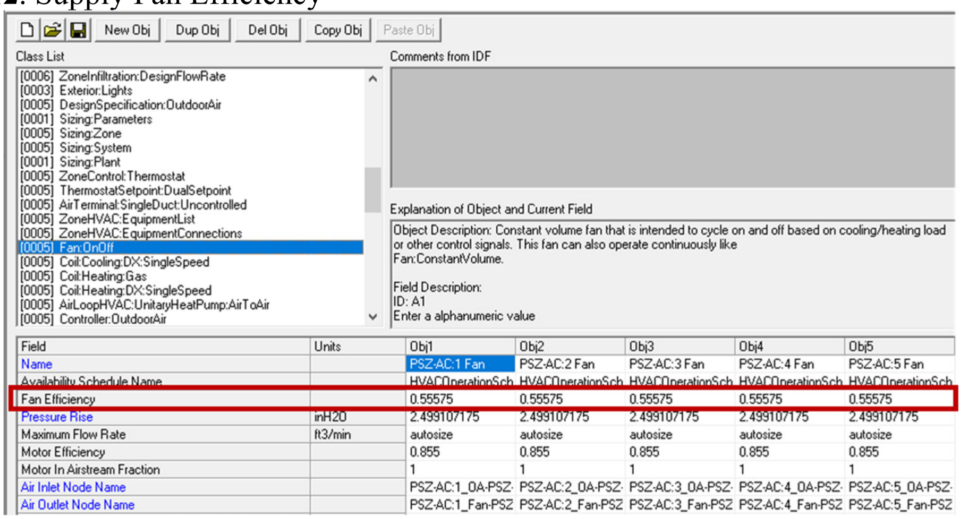


Table F-1. Simulation Schedules for Lighting, Equipment, Occupancy, HVAC Fan, and Setpoint Temperature

Schedule	Type	Through	Day of Week	1 am	2 am	3 am	4 am	5 am	6 am	7 am	8 am	9 am	10 am	11 am	Noon	1 pm	2 pm	3 pm	4 pm	5 pm	6 pm	7 pm	8 pm	9 pm	10 pm	11 pm	12 pm
Internal Loads Schedules																											
BLDG_LIGHT_SCH	Fraction	Through 12/31	WeekDay	0.18	0.18	0.18	0.18	0.18	0.23	0.23	0.42	0.9	0.9	0.9	0.9	0.8	0.9	0.9	0.9	0.9	0.61	0.42	0.42	0.32	0.32	0.23	0.18
			Weekend	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18
			WinterDesignDay	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
			SummerDesignDay	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
BLDG_EQUIP_SCH	Fraction	Through 12/31	WeekDay	0.5	0.5	0.5	0.5	0.5	1	1	1	1	1	1	1	0.94	1	1	1	1	0.5	0.2	0.2	0.2	0.2	0.2	0.2
			Weekend	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
			WinterDesignDay	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
			SummerDesignDay	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
BLDG_OCC_SCH	Fraction	Through 12/31	WeekDay	0	0	0	0	0	0	0.11	0.21	1	1	1	1	0.53	1	1	1	1	0.32	0.11	0.11	0.11	0.11	0.05	0
			Weekend	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
			WinterDesignDay	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
			SummerDesignDay	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
HVAC Schedules																											
HVACOperationSchd	On/off	Through 12/31	WeekDay	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0
(Fan Schedule)			Weekend	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
HTGSETP_SCH	Temperature	Through 12/31	WeekDay	60.08	60.08	60.08	60.08	60.08	60.08	69.98	69.98	69.98	69.98	69.98	69.98	69.98	69.98	69.98	69.98	69.98	69.98	69.98	60.01	60.01	60.01	60.01	60.01
	(°F)		Weekend	60.01	60.01	60.01	60.01	60.01	60.01	60.01	60.01	60.01	60.01	60.01	60.01	60.01	60.01	60.01	60.01	60.01	60.01	60.01	60.01	60.01	60.01	60.01	60.01
			WinterDesignDay	70.00	70.00	70.00	70.00	70.00	70.00	70.00	70.00	70.00	70.00	70.00	70.00	70.00	70.00	70.00	70.00	70.00	70.00	70.00	70.00	70.00	70.00	70.00	70.00
CLGSETP_SCH	Temperature	Through 12/31	WeekDay	84.99	84.99	84.99	84.99	84.99	84.99	75.00	75.00	75.00	75.00	75.00	75.00	75.00	75.00	75.00	75.00	75.00	75.00	84.99	84.99	84.99	84.99	84.99	84.99
	(°F)		Weekend	84.99	84.99	84.99	84.99	84.99	84.99	84.99	84.99	84.99	84.99	84.99	84.99	84.99	84.99	84.99	84.99	84.99	84.99	84.99	84.99	84.99	84.99	84.99	84.99
			SummerDesignDay	75.00	75.00	75.00	75.00	75.00	75.00	75.00	75.00	75.00	75.00	75.00	75.00	75.00	75.00	75.00	75.00	75.00	75.00	75.00	75.00	75.00	75.00	75.00	75.00

* Note: simulation schedules were extracted from small office building scorecards (PNNL and U.S.DOE 2018)

The building envelope materials from EnergyPlus prototype models were converted from the SI unit to the IP unit in DOE-2.1e, which was presented, such as Figure 13 and Figure 14.

Figure F-13. Building Roof Materials in DOE-2.1e for Houston

```
$========================== BUILDING CONSTRUCTION ==========================


$  CONSTRUCTION AND GLASS-TYPES

$  MATERIAL PROPERTY (IP UNITS)
$  ALL VALUES CONVERTED FROM SI UNITS IN PNNL SMALL OFFICE MODEL FOR 90.1-2016
$  ROOF AND CEILING PROPERTY
ROOF_BUIL      = MAT              THICKNESS = 0.03116798                 $ F13 Built-up roofing
                                  CONDUCTIVITY = 0.092446272
                                  DENSITY = 69.9193264
                                  SPECIFIC-HEAT = 0.348715014  ..

ROOF_INS_1     = MAT              RESISTANCE = 24.52377767  ..           $ Nonres_Roof_Insulation

ROOF_INS_2     = MAT              RESISTANCE = 35.40275850  ..           $ Nonres_Roof_Insulation

ROOF_SUR_1     = MAT              THICKNESS = 0.002624672                $ F08 Metal surface
                                  CONDUCTIVITY = 26.16229498
                                  DENSITY = 488.4364373
                                  SPECIFIC-HEAT = 0.11942295  ..

CEIL_MAT       = MAT              THICKNESS = 0.041666668                $ AC02 Acoustic Ceiling
                                  CONDUCTIVITY = 0.032933984
                                  DENSITY = 17.97925536
                                  SPECIFIC-HEAT = 0.31981466  ..

ROOF_ASPHT     = MAT              THICKNESS = 0.010498688                $ (FIXED 4/10/2019) F12 Asphalt Shingles
                                  CONDUCTIVITY = 0.023111568
                                  DENSITY = 69.9193264
                                  SPECIFIC-HEAT = 0.300945834  ..

ROOF_WOOD      = MAT              THICKNESS = 0.052165356                $ (FIXED 4/10/2019) G02 16mm Plywood
                                  CONDUCTIVITY = 0.069334704
                                  DENSITY = 33.96081568
                                  SPECIFIC-HEAT = 0.289003539  ..
```

Figure F-14. Building Wall and Slab Materials in DOE-2.1e for Houston

```
$  SLAB PROPERTY
SLAB_CONC200   = MAT              THICKNESS = 0.666666688                $ 200mm Normalweight concrete floor
                                  CONDUCTIVITY = 1.334693052
                                  DENSITY = 144.9577463
                                  SPECIFIC-HEAT = 0.198719789  ..

SLAB_CONC100   = MAT              THICKNESS = 0.333333344                $ 100mm Normalweight concrete floor
                                  CONDUCTIVITY = 1.334693052
                                  DENSITY = 144.9577463
                                  SPECIFIC-HEAT = 0.198719789  ..

SLAB_CARP      = MAT              RESISTANCE = 1.22923033  ..            $ CP02 CARPET PAD


$  WALL PROPERTY
WALL_STU       = MAT              THICKNESS = 0.083333336                $ F07 25mm stucco
                                  CONDUCTIVITY = 0.416008224
                                  DENSITY = 115.8663123
                                  SPECIFIC-HEAT = 0.200630556  ..

WALL_GYP1      = MAT              THICKNESS = 0.052165356                $ G01 16mm gypsum board
                                  CONDUCTIVITY = 0.092446272
                                  DENSITY = 49.942376
                                  SPECIFIC-HEAT = 0.260342031  ..

WALL_GYP2      = MAT              THICKNESS = 0.041666668                $ G01 13mm gypsum board
                                  CONDUCTIVITY = 0.092446272
                                  DENSITY = 49.942376
                                  SPECIFIC-HEAT = 0.260342031  ..

WALL_INS_1     = MAT              RESISTANCE = 9.72589032  ..            $ Nonres_Exterior_Wall_Insulation

WALL_INS_2     = MAT              RESISTANCE = 9.05708346  ..            $ Nonres_Exterior_Wall_Insulation
```

Figure F-15. Building Window Materials in DOE-2.1e for Houston

```
$  WINDOW PROPERTY
WIN_GLS3        = GLASS-TYPE         GLASS-CONDUCTANCE = 0.5794                    $ Glass_102_LayerAvg+Glass_1576_LayerAvg
                                     VIS-TRANS = 0.312
                                     SHADING-COEF = 0.286206897
                                     PANES = 2                 ..

DOOR1           = GLASS-TYPE         GLASS-CONDUCTANCE = 0.370                     $ Swinging Door_con
                                     SHADING-COEF = 0.7  ..
```

In this study, the result of the reference models was extracted from the BEPS/BEPU reports and the annual building utility performance summary to compare DOE-2.1e and EnergyPlus. Figures 16 to 18 showed the original report examples for Houston models.

Figure F-16. DOE-2.1e BEPS report for Houston

```
1SAMP1E PROVIDED BY PROF.JEFF HABERL     HOUSTON, TX, CLIMATE ZONE 2A
 ASHRAE 90.1-2016 REQUIREMENTS SATISFIED STUDY FOR BUILDING OCCUPANCY PROFILE ANA
 REPORT- BEPS  BUILDING ENERGY PERFORMANCE SUMMARY
 ---------------------------------------------------------------------------------



                                ENERGY TYPE:   ELECTRICITY
                                UNITS: MBTU

                             CATEGORY OF USE
                             ---------------

                                 AREA LIGHTS           53.2

                                MISC EQUIPMT           54.5

                                  SPACE HEAT            2.9

                                  SPACE COOL           29.9

                                PUMPS & MISC            0.1

                                   VENT FANS           21.1
                                                 ----------

                                       TOTAL          161.7
```

Figure F-17. DOE-2.1e BEPU report for Houston

```
1SAMP1E PROVIDED BY PROF.JEFF HABERL     HOUSTON, TX, CLIMATE ZONE 2A
 ASHRAE 90.1-2016 REQUIREMENTS SATISFIED STUDY FOR BUILDING OCCUPANCY PROFILE ANA
 REPORT- BEPU  BUILDING ENERGY PERFORMANCE SUMMARY (UTILITY UNITS)
 ---------------------------------------------------------------------------------



                                  ENERGY TYPE:   ELECTRICITY
                                   SITE UNITS:       KWH

                               CATEGORY OF USE
                               ---------------

                                   AREA LIGHTS       15574.

                                  MISC EQUIPMT       15981.

                                    SPACE HEAT         860.

                                    SPACE COOL        8764.

                                  PUMPS & MISC          16.

                                     VENT FANS        6184.
                                                 ----------

                                         TOTAL       47379.
```

Figure F-18. EnergyPlus annual building utility performance summary for Houston

Report: **Annual Building Utility Performance Summary**

For: **Entire Facility**

Timestamp: **2020-03-23 19:41:39**

Values gathered over 8760.00 hours

End Uses

	Electricity [GJ]	Natural Gas [GJ]	Additional Fuel [GJ]	District Cooling [GJ]	District Heating [GJ]	Water [m3]
Heating	2.18	0.00	0.00	0.00	0.00	0.00
Cooling	31.54	0.00	0.00	0.00	0.00	0.00
Interior Lighting	56.06	0.00	0.00	0.00	0.00	0.00
Exterior Lighting	0.00	0.00	0.00	0.00	0.00	0.00
Interior Equipment	57.51	0.00	0.00	0.00	0.00	0.00
Exterior Equipment	0.00	0.00	0.00	0.00	0.00	0.00
Fans	22.24	0.00	0.00	0.00	0.00	0.00
Pumps	0.00	0.00	0.00	0.00	0.00	0.00
Heat Rejection	0.00	0.00	0.00	0.00	0.00	0.00
Humidification	0.00	0.00	0.00	0.00	0.00	0.00
Heat Recovery	0.00	0.00	0.00	0.00	0.00	0.00
Water Systems	18.01	0.00	0.00	0.00	0.00	29.16
Refrigeration	0.00	0.00	0.00	0.00	0.00	0.00
Generators	0.00	0.00	0.00	0.00	0.00	0.00
Total End Uses	187.53	0.00	0.00	0.00	0.00	29.16

Note: Electricity appears to be the principal heating source based on energy usage.

GJ to MMBtu: 0.947817

APPENDIX G

THE IMPACT OF GROUND-COUPLED HEAT TRANSFER

The ground-coupled floor is one of key factors in building energy use by affecting heat transfer in buildings. Therefore, in energy simulation programs, several algorithms have been developed to calculate ground heat transfer in buildings. For example, EnergyPlus used z-transfer function coefficients to calculated the unsteady ground-coupled surface temperatures (Krarti 2001), and DOE-2 used the ground-coupled surface temperatures as steady (Sullivan 1985). Thus, in the previous studies, Huang et al. (1988), Winkelmann (1998, 2002), Meldem and Winkelmann (1998), and Huang et al. (2000) have tried to figure out to get a better calculation of underground surfaces (i.e., wall and floor) in DOE2.

Therefore, this study simply compared different ground heat transfer calculations for reference small office buildings (Chapter 4.2.1) in DOE-2.1e and EnergyPlus v8.0 to analyze the impact of ground heat transfer. Firstly, the ground temperature models were used in DOE-2.1e using average monthly ground temperature from the PNNL prototype models and using “Site: Ground Temperature: Building Surface in EnergyPlus. This model is the default calculation methods in the PNNL prototype models. On the second, U-EFFECTIVE command was used in DOE-2.1e based on Winklemann’s methods, which mainly focused on heat transfer in perimeter zones using effective resistance on the ground surfaces that consist of soil, air film, and fictitious insulation layer (Kim 2006). Also, for Winklemann’s methods in EnergyPlus, the fictitious layers were directly added on the slab-on-grade using Andolsun et al. (2012)’s modeling approach. Lastly, adiabatic floor models were developed to compare the impact of ground heat transfer in both simulations.

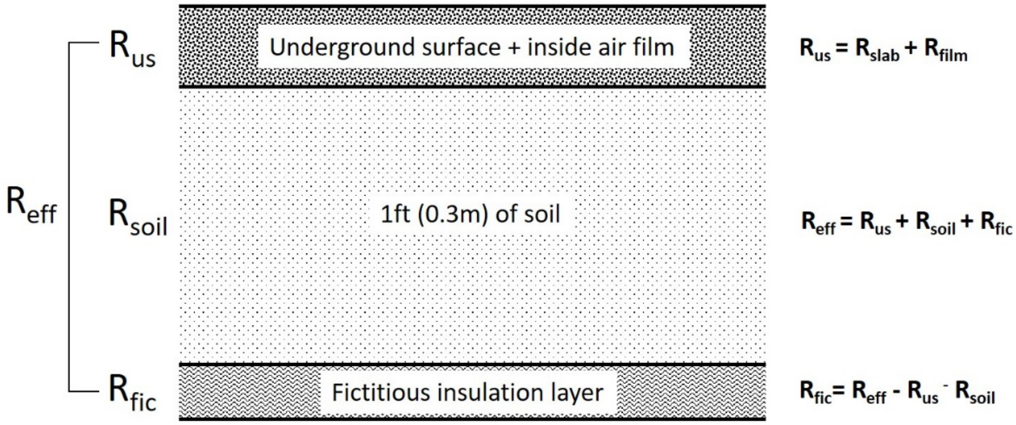


Figure G-1. Section of Ground Floor Construction for DOE2.1e models (adapted from Winkelmann 2002, p6)

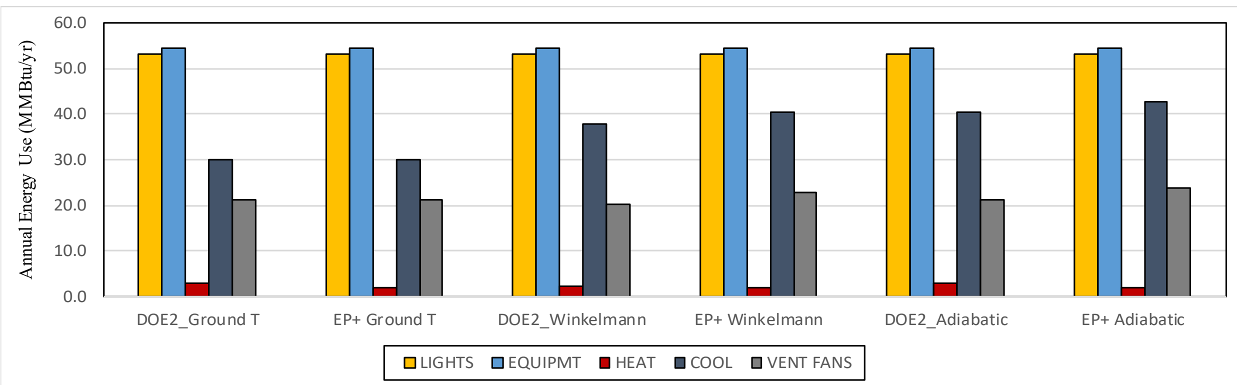


Figure G-2. Houston: Annual Energy Use of Ground Heat Transfer Calculations

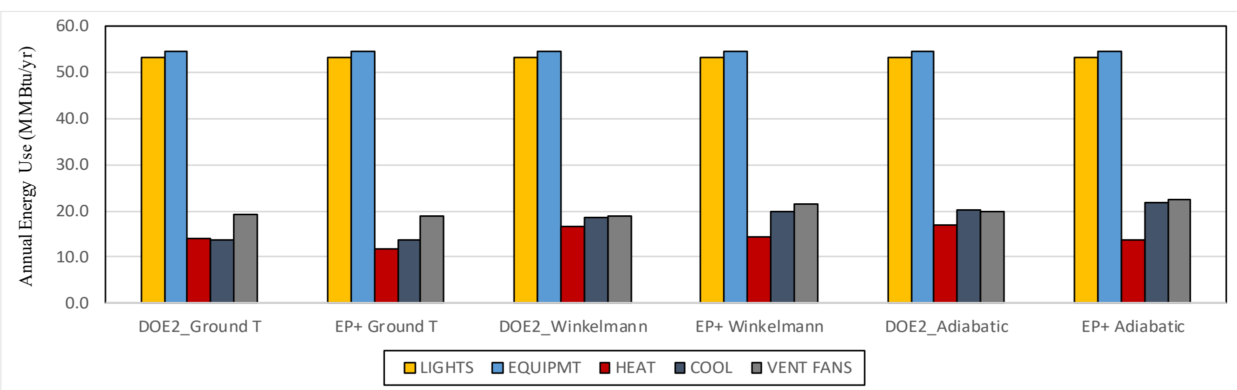


Figure G-3. Chicago: Annual Energy Use of Ground Heat Transfer Calculations

Table G-1. Houston: Annual Energy Use of Ground Heat Transfer Calculations

(MMBtu)	DOE2 (Base) Ground T	EP+ Ground T	DOE2 Winkelmann	EP+ Winkelmann	DOE2 Adiabatic	EP+ Adiabatic
Lights	53.2	53.1	53.2	53.1	53.2	53.1
Equipment	54.5	54.5	54.5	54.5	54.5	54.5
Heating	2.9	2.1	2.4	1.8	3.0	1.9
Cooling	29.9	29.9	37.7	40.4	40.3	42.9
Vent Fan	21.1	21.1	20.3	22.9	21.3	23.7
Total	161.6	160.7	168.1	172.7	172.3	176.1

Table G-2. Chicago: Annual Energy Use of Ground Heat Transfer Calculations

(MMBtu)	DOE2 (Base) Ground T	EP+ Ground T	DOE2 Winkelmann	EP+ Winkelmann	DOE2 Adiabatic	EP+ Adiabatic
Lights	53.2	53.1	53.2	53.1	53.2	53.1
Equipment	54.5	54.5	54.5	54.5	54.5	54.5
Heating	13.9	11.6	16.6	14.2	16.8	13.9
Cooling	13.7	13.6	18.4	19.8	20.1	21.7
Vent Fan	19.1	19.0	18.9	21.5	20.0	22.4
Total	154.4	151.8	161.6	163.2	164.6	165.6

The result of different ground floor calculations in small office models represented partial energy use differences of heating, cooling, and ventilation loads in the current PNNL prototype models compared to Winkelmann's methods and adiabatic floor. The ground-coupling affected heating, cooling, and ventilation energy use of the ground temperature models in DOE-2.1e and EnergyPlus. However, variations of energy use were different depending on weather stations, calculation methods, and load components.

APPENDIX H

PROPOSED OCCUPANCY-BASED CONTROL CREDITS: TOTAL BUILDING APPLICATIONS

Table H-1. Houston PSZ: Percentage-Based Energy Reduction Credits of Total Building Occupancy-Based Controls

	Reference PSZ															
	WWR 10%				WWR 21%				WWR 30%				WWR 40%			
	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%
Lights	0.0%	6.6%	33.0%	54.1%	0.0%	6.6%	33.0%	54.1%	0.0%	6.6%	33.0%	54.1%	0.0%	6.6%	33.0%	54.1%
Equipment	0.0%	6.4%	31.8%	50.9%	0.0%	6.4%	31.8%	50.9%	0.0%	6.4%	31.8%	50.9%	0.0%	6.4%	31.8%	50.9%
Heating	0.0%	-19.3%	-205.8%	-465.6%	0.0%	-15.6%	-132.2%	-386.1%	0.0%	-10.6%	-103.7%	-340.8%	0.0%	-10.5%	-99.2%	-329.7%
Cooling	0.0%	6.6%	34.3%	59.5%	0.0%	6.1%	31.6%	55.8%	0.0%	5.7%	29.9%	54.6%	0.0%	5.6%	28.4%	54.8%
Ventilation	0.0%	5.8%	29.2%	49.9%	0.0%	4.8%	24.1%	41.2%	0.0%	4.2%	21.2%	35.2%	0.0%	3.7%	18.6%	31.2%

	Raised Floor Lightweight PSZ															
	WWR 10%				WWR 21%				WWR 30%				WWR 40%			
	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%
Lights	0.0%	6.6%	33.0%	54.1%	0.0%	6.6%	33.0%	54.1%	0.0%	6.6%	33.0%	54.1%	0.0%	6.6%	33.0%	54.1%
Equipment	0.0%	6.4%	31.8%	50.9%	0.0%	6.4%	31.8%	50.9%	0.0%	6.4%	31.8%	50.9%	0.0%	6.4%	31.8%	50.9%
Heating	0.0%	-4.8%	-21.1%	-31.2%	0.0%	-2.6%	-10.0%	-12.4%	0.0%	-1.9%	-5.1%	-4.5%	0.0%	-1.9%	-3.7%	-2.0%
Cooling	0.0%	5.1%	25.3%	43.7%	0.0%	4.6%	23.0%	40.1%	0.0%	4.3%	21.7%	38.3%	0.0%	4.1%	20.7%	36.7%
Ventilation	0.0%	5.1%	25.3%	43.3%	0.0%	4.3%	21.4%	36.4%	0.0%	3.9%	19.5%	33.5%	0.0%	3.6%	18.0%	30.7%

	Heavyweight PSZ															
	WWR 10%				WWR 21%				WWR 30%				WWR 40%			
	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%
Lights	0.0%	6.6%	33.0%	54.1%	0.0%	6.6%	33.0%	54.1%	0.0%	6.6%	33.0%	54.1%	0.0%	6.6%	33.0%	54.1%
Equipment	0.0%	6.4%	31.8%	50.9%	0.0%	6.4%	31.8%	50.9%	0.0%	6.4%	31.8%	50.9%	0.0%	6.4%	31.8%	50.9%
Heating	0.0%	-19.3%	-205.8%	-465.6%	0.0%	-15.6%	-132.2%	-386.1%	0.0%	-10.6%	-103.7%	-340.8%	0.0%	-10.5%	-99.2%	-329.7%
Cooling	0.0%	6.6%	34.3%	59.5%	0.0%	6.1%	31.6%	55.8%	0.0%	5.7%	29.9%	54.6%	0.0%	5.6%	28.4%	54.8%
Ventilation	0.0%	5.8%	29.2%	49.9%	0.0%	4.8%	24.1%	41.2%	0.0%	4.2%	21.2%	35.2%	0.0%	3.7%	18.6%	31.2%

Table H-2. Houston PVAV: Percentage-Based Energy Reduction Credits of Total Building Occupancy-Based Controls

	Reference PVAV															
	WWR 10%				WWR 21%				WWR 30%				WWR 40%			
	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%
Lights	0.0%	6.6%	33.0%	54.1%	0.0%	6.6%	33.0%	54.1%	0.0%	6.6%	33.0%	54.1%	0.0%	6.6%	33.0%	54.1%
Equipment	0.0%	6.4%	31.8%	50.9%	0.0%	6.4%	31.8%	50.9%	0.0%	6.4%	31.8%	50.9%	0.0%	6.4%	31.8%	50.9%
Heating	0.0%	1.4%	10.8%	15.7%	0.0%	0.0%	3.1%	8.4%	0.0%	3.8%	-7.7%	-12.7%	0.0%	0.0%	0.0%	100.0%
Cooling	0.0%	6.2%	28.0%	43.5%	0.0%	5.6%	25.1%	40.4%	0.0%	5.2%	23.1%	38.2%	0.0%	4.8%	21.1%	36.3%
Ventilation	0.0%	6.9%	32.6%	51.1%	0.0%	6.1%	27.9%	43.1%	0.0%	5.4%	25.0%	38.4%	0.0%	4.8%	22.3%	34.4%

	Raised Floor Lightweight PVAV															
	WWR 10%				WWR 21%				WWR 30%				WWR 40%			
	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%
Lights	0.0%	6.6%	33.0%	54.1%	0.0%	6.6%	33.0%	54.1%	0.0%	6.6%	33.0%	54.1%	0.0%	6.6%	33.0%	54.1%
Equipment	0.0%	6.4%	31.8%	50.9%	0.0%	6.4%	31.8%	50.9%	0.0%	6.4%	31.8%	50.9%	0.0%	6.4%	31.8%	50.9%
Heating	0.0%	0.0%	-10.0%	2.3%	0.0%	2.1%	-6.4%	-24.7%	0.0%	0.0%	-2.3%	-33.2%	0.0%	-2.4%	-7.3%	-43.0%
Cooling	0.0%	5.2%	25.9%	42.8%	0.0%	4.9%	24.0%	39.4%	0.0%	4.6%	22.8%	37.4%	0.0%	4.5%	21.8%	35.6%
Ventilation	0.0%	6.4%	31.1%	49.7%	0.0%	5.8%	27.6%	44.3%	0.0%	5.3%	25.3%	41.0%	0.0%	4.9%	23.4%	38.1%

	Heavyweight PVAV															
	WWR 10%				WWR 21%				WWR 30%				WWR 40%			
	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%
Lights	0.0%	6.6%	33.0%	54.1%	0.0%	6.6%	33.0%	54.1%	0.0%	6.6%	33.0%	54.1%	0.0%	6.6%	33.0%	54.1%
Equipment	0.0%	6.4%	31.8%	50.9%	0.0%	6.4%	31.8%	50.9%	0.0%	6.4%	31.8%	50.9%	0.0%	6.4%	31.8%	50.9%
Heating	0.0%	0.0%	9.1%	21.2%	0.0%	2.5%	9.8%	3.9%	0.0%	-1.6%	1.6%	7.0%	0.0%	0.0%	0.0%	-39.6%
Cooling	0.0%	6.6%	30.1%	45.8%	0.0%	6.0%	27.5%	42.7%	0.0%	5.6%	25.0%	40.0%	0.0%	5.1%	22.7%	38.0%
Ventilation	0.0%	7.7%	35.8%	55.3%	0.0%	6.7%	30.9%	47.7%	0.0%	5.8%	27.2%	41.5%	0.0%	5.1%	23.8%	36.5%

Table H-3. Chicago PSZ: Percentage-Based Energy Reduction Credits of Total Building Occupancy-Based Controls

	Reference PSZ															
	WWR 10%				WWR 21%				WWR 30%				WWR 40%			
	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%
Lights	0.0%	6.6%	33.0%	54.1%	0.0%	6.6%	33.0%	54.1%	0.0%	6.6%	33.0%	54.1%	0.0%	6.6%	33.0%	54.1%
Equipment	0.0%	6.4%	31.8%	50.9%	0.0%	6.4%	31.8%	50.9%	0.0%	6.4%	31.8%	50.9%	0.0%	6.4%	31.8%	50.9%
Heating	0.0%	-16.4%	-106.6%	-147.1%	0.0%	-17.2%	-120.6%	-152.4%	0.0%	-15.2%	-114.6%	-147.4%	0.0%	-14.8%	-108.7%	-146.0%
Cooling	0.0%	7.4%	37.0%	65.1%	0.0%	6.6%	32.9%	60.4%	0.0%	6.1%	30.6%	60.3%	0.0%	5.8%	29.0%	56.9%
Ventilation	0.0%	5.5%	27.1%	46.4%	0.0%	4.2%	21.0%	35.5%	0.0%	3.6%	18.1%	30.5%	0.0%	3.1%	15.6%	26.2%

	Raised Floor Lightweight PSZ															
	WWR 10%				WWR 21%				WWR 30%				WWR 40%			
	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%
Lights	0.0%	6.6%	33.0%	54.1%	0.0%	6.6%	33.0%	54.1%	0.0%	6.6%	33.0%	54.1%	0.0%	6.6%	33.0%	54.1%
Equipment	0.0%	6.4%	31.8%	50.9%	0.0%	6.4%	31.8%	50.9%	0.0%	6.4%	31.8%	50.9%	0.0%	6.4%	31.8%	50.9%
Heating	0.0%	-6.4%	-31.3%	-51.2%	0.0%	-3.5%	-22.1%	-37.3%	0.0%	-2.2%	-13.2%	-19.4%	0.0%	-0.9%	-6.4%	-8.0%
Cooling	0.0%	5.7%	28.7%	50.1%	0.0%	5.2%	25.5%	45.7%	0.0%	4.9%	23.8%	42.6%	0.0%	4.7%	22.6%	40.7%
Ventilation	0.0%	5.3%	26.4%	43.5%	0.0%	4.1%	20.3%	33.9%	0.0%	3.6%	17.9%	30.0%	0.0%	3.2%	16.0%	26.4%

	Heavyweight PSZ															
	WWR 10%				WWR 21%				WWR 30%				WWR 40%			
	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%
Lights	0.0%	6.6%	33.0%	54.1%	0.0%	6.6%	33.0%	54.1%	0.0%	6.6%	33.0%	54.1%	0.0%	6.6%	33.0%	54.1%
Equipment	0.0%	6.4%	31.8%	50.9%	0.0%	6.4%	31.8%	50.9%	0.0%	6.4%	31.8%	50.9%	0.0%	6.4%	31.8%	50.9%
Heating	0.0%	-20.1%	-101.6%	-135.1%	0.0%	-17.8%	-124.2%	-161.2%	0.0%	-17.2%	-118.8%	-159.4%	0.0%	-15.4%	-110.8%	-155.7%
Cooling	0.0%	7.5%	37.5%	65.8%	0.0%	6.6%	33.5%	63.1%	0.0%	6.1%	31.5%	62.4%	0.0%	5.4%	30.5%	60.0%
Ventilation	0.0%	5.8%	28.7%	48.3%	0.0%	4.4%	21.9%	37.4%	0.0%	3.7%	18.6%	31.6%	0.0%	3.2%	15.9%	27.0%

Table H-4. Chicago PVAV: Percentage-Based Energy Reduction Credits of Total Building Occupancy-Based Controls

	Reference PVAV															
	WWR 10%				**WWR 21%**				**WWR 30%**				**WWR 40%**			
	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%
Lights	0.0%	6.6%	33.0%	54.1%	0.0%	6.6%	33.0%	54.1%	0.0%	6.6%	33.0%	54.1%	0.0%	6.6%	33.0%	54.1%
Equipment	0.0%	6.4%	31.8%	50.9%	0.0%	6.4%	31.8%	50.9%	0.0%	6.4%	31.8%	50.9%	0.0%	6.4%	31.8%	50.9%
Heating	0.0%	0.6%	4.9%	9.2%	0.0%	-0.4%	-0.3%	2.1%	0.0%	-0.8%	-2.1%	-0.2%	0.0%	-2.3%	-10.8%	-11.3%
Cooling	0.0%	6.6%	31.6%	47.8%	0.0%	5.7%	27.5%	44.3%	0.0%	5.3%	25.0%	41.9%	0.0%	4.9%	22.8%	42.8%
Ventilation	0.0%	6.9%	31.2%	46.0%	0.0%	5.3%	24.3%	37.7%	0.0%	4.5%	20.7%	31.7%	0.0%	3.8%	17.7%	27.5%

	Raised Floor Lightweight PVAV															
	WWR 10%				**WWR 21%**				**WWR 30%**				**WWR 40%**			
	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%
Lights	0.0%	6.6%	33.0%	54.1%	0.0%	6.6%	33.0%	54.1%	0.0%	6.6%	33.0%	54.1%	0.0%	6.6%	33.0%	54.1%
Equipment	0.0%	6.4%	31.8%	50.9%	0.0%	6.4%	31.8%	50.9%	0.0%	6.4%	31.8%	50.9%	0.0%	6.4%	31.8%	50.9%
Heating	0.0%	-2.4%	-6.7%	39.4%	0.0%	-4.1%	-9.5%	-15.4%	0.0%	-2.1%	-11.4%	-19.4%	0.0%	-1.8%	-9.9%	-17.2%
Cooling	0.0%	5.7%	27.7%	15.1%	0.0%	5.5%	25.1%	40.3%	0.0%	4.8%	23.1%	37.4%	0.0%	4.3%	21.2%	34.4%
Ventilation	0.0%	6.3%	29.1%	-0.8%	0.0%	5.0%	23.7%	36.9%	0.0%	4.5%	21.2%	32.6%	0.0%	4.0%	19.0%	30.1%

	Heavyweight PVAV															
	WWR 10%				**WWR 21%**				**WWR 30%**				**WWR 40%**			
	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%
Lights	0.0%	6.6%	33.0%	54.1%	0.0%	6.6%	33.0%	54.1%	0.0%	6.6%	33.0%	54.1%	0.0%	6.6%	33.0%	54.1%
Equipment	0.0%	6.4%	31.8%	50.9%	0.0%	6.4%	31.8%	50.9%	0.0%	6.4%	31.8%	50.9%	0.0%	6.4%	31.8%	50.9%
Heating	0.0%	0.9%	5.7%	10.7%	0.0%	0.4%	0.3%	4.8%	0.0%	0.2%	0.4%	2.2%	0.0%	-0.6%	-4.8%	-10.5%
Cooling	0.0%	7.0%	33.3%	49.4%	0.0%	6.0%	28.7%	45.0%	0.0%	5.6%	26.0%	42.7%	0.0%	4.8%	23.3%	42.8%
Ventilation	0.0%	7.2%	31.7%	46.7%	0.0%	5.7%	25.3%	38.5%	0.0%	4.6%	21.3%	32.5%	0.0%	3.9%	18.0%	28.4%

APPENDIX I

PROPOSED OCCUPANCY-BASED CONTROL CREDITS: INDIVIDUAL ZONE APPLICATIONS

Table I-1. Houston PSZ: Percentage-Based Energy Reduction Credits of Space1-1 OBC on Total Loads

	Reference PSZ															
	WWR 10%				WWR 21%				WWR 30%				WWR 40%			
	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%
Lights	0.0%	1.4%	7.1%	11.3%	0.0%	1.4%	7.1%	11.3%	0.0%	1.4%	7.1%	11.3%	0.0%	1.4%	7.1%	11.3%
Equipment	0.0%	1.2%	5.7%	9.2%	0.0%	1.2%	5.7%	9.2%	0.0%	1.2%	5.7%	9.2%	0.0%	1.2%	5.7%	9.2%
Heating	0.0%	-0.9%	-6.8%	-14.8%	0.0%	-0.7%	-5.5%	-11.2%	0.0%	-0.8%	-5.4%	-9.6%	0.0%	-0.3%	-4.2%	-7.1%
Cooling	0.0%	1.3%	6.4%	10.5%	0.0%	1.1%	5.7%	9.2%	0.0%	1.0%	5.4%	8.6%	0.0%	1.0%	5.0%	8.0%
Ventilation	0.0%	0.9%	4.6%	7.4%	0.0%	0.8%	3.8%	6.1%	0.0%	0.7%	3.4%	5.4%	0.0%	0.6%	3.0%	4.7%

	Raised Floor Lightweight PSZ															
	WWR 10%				WWR 21%				WWR 30%				WWR 40%			
	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%
Lights	0.0%	1.4%	7.1%	11.6%	0.0%	1.4%	7.1%	11.6%	0.0%	1.4%	7.1%	11.6%	0.0%	1.4%	7.1%	11.6%
Equipment	0.0%	1.2%	5.7%	9.2%	0.0%	1.2%	5.7%	9.2%	0.0%	1.2%	5.7%	9.2%	0.0%	1.2%	5.7%	9.2%
Heating	0.0%	-0.4%	-2.4%	-4.9%	0.0%	-0.2%	-1.5%	-3.1%	0.0%	-0.1%	-1.1%	-2.3%	0.0%	-0.1%	-0.9%	-1.8%
Cooling	0.0%	1.0%	4.8%	8.3%	0.0%	0.9%	4.4%	7.6%	0.0%	0.8%	4.2%	7.2%	0.0%	0.8%	3.9%	6.9%
Ventilation	0.0%	0.8%	4.1%	6.9%	0.0%	0.7%	3.7%	6.3%	0.0%	0.7%	3.4%	5.8%	0.0%	0.6%	3.1%	5.3%

	Heavyweight PSZ															
	WWR 10%				WWR 21%				WWR 30%				WWR 40%			
	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%
Lights	0.0%	1.4%	7.1%	11.3%	0.0%	1.4%	7.1%	11.3%	0.0%	1.4%	7.1%	11.3%	0.0%	1.4%	7.1%	11.3%
Equipment	0.0%	1.2%	5.7%	9.2%	0.0%	1.2%	5.7%	9.2%	0.0%	1.2%	5.7%	9.2%	0.0%	1.2%	5.7%	9.2%
Heating	0.0%	-0.9%	-6.8%	-14.8%	0.0%	-0.7%	-5.5%	-11.2%	0.0%	-0.8%	-5.4%	-9.6%	0.0%	-0.3%	-4.2%	-7.1%
Cooling	0.0%	1.3%	6.4%	10.5%	0.0%	1.1%	5.7%	9.2%	0.0%	1.0%	5.4%	8.6%	0.0%	1.0%	5.0%	8.0%
Ventilation	0.0%	0.9%	4.6%	7.4%	0.0%	0.8%	3.8%	6.1%	0.0%	0.7%	3.4%	5.4%	0.0%	0.6%	3.0%	4.7%

Table I-2. Houston PVAV: Percentage-Based Energy Reduction Credits of Space1-1 OBC on Total Loads

	Reference PVAV															
	WWR 10%				**WWR 21%**				**WWR 30%**				**WWR 40%**			
	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%
Lights	0.0%	1.4%	7.1%	11.3%	0.0%	1.4%	7.1%	11.3%	0.0%	1.4%	7.1%	11.3%	0.0%	1.4%	7.1%	11.3%
Equipment	0.0%	1.2%	5.7%	9.2%	0.0%	1.2%	5.7%	9.2%	0.0%	1.2%	5.7%	9.2%	0.0%	1.2%	5.7%	9.2%
Heating	0.0%	0.0%	0.0%	0.9%	0.0%	0.0%	0.0%	0.5%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Cooling	0.0%	1.2%	5.9%	9.0%	0.0%	1.1%	5.3%	8.0%	0.0%	1.0%	4.9%	7.4%	0.0%	1.0%	4.5%	6.8%
Ventilation	0.0%	1.3%	6.4%	9.7%	0.0%	1.1%	5.2%	8.0%	0.0%	1.0%	4.6%	7.1%	0.0%	0.9%	4.0%	6.3%

	Raised Floor Lightweight PVAV															
	WWR 10%				**WWR 21%**				**WWR 30%**				**WWR 40%**			
	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%
Lights	0.0%	1.4%	7.1%	11.6%	0.0%	1.4%	7.1%	11.6%	0.0%	1.4%	7.1%	11.6%	0.0%	1.4%	7.1%	11.6%
Equipment	0.0%	1.2%	5.7%	9.2%	0.0%	1.2%	5.7%	9.2%	0.0%	1.2%	5.7%	9.2%	0.0%	1.2%	5.7%	9.2%
Heating	0.0%	0.6%	0.6%	0.0%	0.0%	-0.9%	-1.7%	-1.7%	0.0%	0.0%	0.0%	-1.1%	0.0%	-1.2%	-2.4%	-3.5%
Cooling	0.0%	1.0%	5.0%	8.3%	0.0%	0.9%	4.7%	7.7%	0.0%	0.9%	4.5%	7.2%	0.0%	0.9%	4.2%	6.8%
Ventilation	0.0%	1.3%	6.2%	10.0%	0.0%	1.0%	5.0%	8.0%	0.0%	0.9%	4.5%	7.3%	0.0%	0.8%	3.9%	6.5%

	Heavyweight PVAV															
	WWR 10%				**WWR 21%**				**WWR 30%**				**WWR 40%**			
	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%
Lights	0.0%	1.4%	7.1%	11.3%	0.0%	1.4%	7.1%	11.3%	0.0%	1.4%	7.1%	11.3%	0.0%	1.4%	7.1%	11.3%
Equipment	0.0%	1.2%	5.7%	9.2%	0.0%	1.2%	5.7%	9.2%	0.0%	1.2%	5.7%	9.2%	0.0%	1.2%	5.7%	9.2%
Heating	0.0%	-0.3%	0.8%	1.3%	0.0%	-0.3%	0.0%	0.9%	0.0%	0.0%	0.0%	0.5%	0.0%	0.0%	0.0%	-1.0%
Cooling	0.0%	1.3%	6.1%	9.2%	0.0%	1.2%	5.7%	8.7%	0.0%	1.1%	5.3%	8.0%	0.0%	1.0%	4.8%	7.2%
Ventilation	0.0%	1.5%	7.0%	10.5%	0.0%	1.2%	5.8%	8.8%	0.0%	1.0%	4.9%	7.6%	0.0%	0.9%	4.2%	6.5%

Table I-3. Houston PSZ: Percentage-Based Energy Reduction Credits of Space2-1 OBC on Total Loads

	Reference PSZ															
	WWR 10%				**WWR 21%**				**WWR 30%**				**WWR 40%**			
	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%
Lights	0.0%	0.8%	4.2%	6.7%	0.0%	0.8%	4.2%	6.7%	0.0%	0.8%	4.2%	6.7%	0.0%	0.8%	4.2%	6.7%
Equipment	0.0%	0.7%	3.3%	5.3%	0.0%	0.7%	3.3%	5.3%	0.0%	0.7%	3.3%	5.3%	0.0%	0.7%	3.3%	5.3%
Heating	0.0%	-0.5%	-3.0%	-6.0%	0.0%	-0.3%	-2.6%	-4.9%	0.0%	-0.4%	-2.5%	-4.7%	0.0%	-0.3%	-2.4%	-4.3%
Cooling	0.0%	0.7%	3.4%	5.4%	0.0%	0.6%	3.1%	4.9%	0.0%	0.6%	2.9%	4.6%	0.0%	0.6%	2.7%	4.3%
Ventilation	0.0%	0.4%	2.2%	3.5%	0.0%	0.4%	1.8%	2.9%	0.0%	0.3%	1.6%	2.6%	0.0%	0.3%	1.5%	2.4%

	Raised Floor Lightweight PSZ															
	WWR 10%				**WWR 21%**				**WWR 30%**				**WWR 40%**			
	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%
Lights	0.0%	0.8%	4.2%	6.9%	0.0%	0.8%	4.2%	6.9%	0.0%	0.8%	4.2%	6.9%	0.0%	0.8%	4.2%	6.9%
Equipment	0.0%	0.7%	3.3%	5.3%	0.0%	0.7%	3.3%	5.3%	0.0%	0.7%	3.3%	5.3%	0.0%	0.7%	3.3%	5.3%
Heating	0.0%	-0.3%	-1.7%	-3.4%	0.0%	-0.1%	-0.9%	-2.0%	0.0%	-0.1%	-0.7%	-1.5%	0.0%	-0.1%	-0.5%	-1.2%
Cooling	0.0%	0.5%	2.6%	4.5%	0.0%	0.5%	2.4%	4.1%	0.0%	0.4%	2.2%	3.8%	0.0%	0.4%	2.1%	3.6%
Ventilation	0.0%	0.4%	2.0%	3.4%	0.0%	0.4%	1.8%	3.2%	0.0%	0.3%	1.7%	2.9%	0.0%	0.3%	1.5%	2.7%

	Heavyweight PSZ															
	WWR 10%				**WWR 21%**				**WWR 30%**				**WWR 40%**			
	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%
Lights	0.0%	0.8%	4.2%	6.7%	0.0%	0.8%	4.2%	6.7%	0.0%	0.8%	4.2%	6.7%	0.0%	0.8%	4.2%	6.7%
Equipment	0.0%	0.7%	3.3%	5.3%	0.0%	0.7%	3.3%	5.3%	0.0%	0.7%	3.3%	5.3%	0.0%	0.7%	3.3%	5.3%
Heating	0.0%	-0.6%	-4.5%	-9.0%	0.0%	-0.6%	-3.7%	-7.4%	0.0%	-0.3%	-3.0%	-6.2%	0.0%	-0.4%	-2.8%	-5.1%
Cooling	0.0%	0.7%	3.7%	5.9%	0.0%	0.6%	3.2%	5.2%	0.0%	0.6%	3.0%	4.8%	0.0%	0.6%	2.8%	4.4%
Ventilation	0.0%	0.5%	2.5%	4.0%	0.0%	0.4%	2.1%	3.3%	0.0%	0.4%	1.8%	2.8%	0.0%	0.3%	1.6%	2.4%

Table I-4. Houston PVAV: Percentage-Based Energy Reduction Credits of Space2-1 OBC on Total Loads

	Reference PVAV															
	WWR 10%				**WWR 21%**				**WWR 30%**				**WWR 40%**			
	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%
Lights	0.0%	0.8%	4.2%	6.7%	0.0%	0.8%	4.2%	6.7%	0.0%	0.8%	4.2%	6.7%	0.0%	0.8%	4.2%	6.7%
Equipment	0.0%	0.7%	3.3%	5.3%	0.0%	0.7%	3.3%	5.3%	0.0%	0.7%	3.3%	5.3%	0.0%	0.7%	3.3%	5.3%
Heating	0.0%	0.0%	0.0%	0.3%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Cooling	0.0%	0.7%	3.2%	4.9%	0.0%	0.6%	2.9%	4.4%	0.0%	0.6%	2.6%	3.9%	0.0%	0.5%	2.4%	3.6%
Ventilation	0.0%	0.7%	3.4%	5.2%	0.0%	0.6%	2.8%	4.3%	0.0%	0.5%	2.4%	3.8%	0.0%	0.4%	2.2%	3.4%

	Raised Floor Lightweight PVAV															
	WWR 10%				**WWR 21%**				**WWR 30%**				**WWR 40%**			
	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%
Lights	0.0%	0.8%	4.2%	6.9%	0.0%	0.8%	4.2%	6.9%	0.0%	0.8%	4.2%	6.9%	0.0%	0.8%	4.2%	6.9%
Equipment	0.0%	0.7%	3.3%	5.3%	0.0%	0.7%	3.3%	5.3%	0.0%	0.7%	3.3%	5.3%	0.0%	0.7%	3.3%	5.3%
Heating	0.0%	0.0%	-0.5%	-0.5%	0.0%	0.0%	0.8%	0.0%	0.0%	0.0%	-1.0%	-1.0%	0.0%	0.0%	-1.2%	-1.2%
Cooling	0.0%	0.5%	2.6%	4.2%	0.0%	0.5%	2.5%	4.0%	0.0%	0.5%	2.3%	3.7%	0.0%	0.5%	2.3%	3.6%
Ventilation	0.0%	0.6%	3.1%	5.0%	0.0%	0.6%	2.8%	4.4%	0.0%	0.5%	2.5%	4.0%	0.0%	0.5%	2.3%	3.8%

	Heavyweight PVAV															
	WWR 10%				**WWR 21%**				**WWR 30%**				**WWR 40%**			
	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%
Lights	0.0%	0.8%	4.2%	6.7%	0.0%	0.8%	4.2%	6.7%	0.0%	0.8%	4.2%	6.7%	0.0%	0.8%	4.2%	6.7%
Equipment	0.0%	0.7%	3.3%	5.3%	0.0%	0.7%	3.3%	5.3%	0.0%	0.7%	3.3%	5.3%	0.0%	0.7%	3.3%	5.3%
Heating	0.0%	0.0%	0.5%	0.7%	0.0%	0.0%	0.3%	0.5%	0.0%	0.0%	0.4%	0.4%	0.0%	0.0%	0.0%	0.0%
Cooling	0.0%	0.7%	3.4%	5.2%	0.0%	0.7%	3.1%	4.7%	0.0%	0.6%	2.8%	4.3%	0.0%	0.5%	2.5%	3.8%
Ventilation	0.0%	0.8%	3.9%	6.0%	0.0%	0.6%	3.1%	4.8%	0.0%	0.6%	2.6%	4.0%	0.0%	0.5%	2.3%	3.5%

Table I-5. Houston PSZ: Percentage-Based Energy Reduction Credits of Space3-1 OBC on Total Loads

	Reference PSZ															
	WWR 10%				WWR 21%				WWR 30%				WWR 40%			
	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%
Lights	0.0%	1.4%	7.1%	11.3%	0.0%	1.4%	7.1%	11.3%	0.0%	1.4%	7.1%	11.3%	0.0%	1.4%	7.1%	11.3%
Equipment	0.0%	1.2%	5.7%	9.2%	0.0%	1.2%	5.7%	9.2%	0.0%	1.2%	5.7%	9.2%	0.0%	1.2%	5.7%	9.2%
Heating	0.0%	-1.5%	-8.9%	-18.1%	0.0%	-1.1%	-7.5%	-15.4%	0.0%	-1.2%	-7.4%	-15.5%	0.0%	-1.7%	-8.1%	-15.9%
Cooling	0.0%	1.2%	5.9%	9.5%	0.0%	1.0%	5.3%	8.5%	0.0%	0.9%	4.9%	7.9%	0.0%	0.9%	4.6%	7.4%
Ventilation	0.0%	0.8%	4.1%	6.5%	0.0%	0.7%	3.4%	5.5%	0.0%	0.6%	3.1%	4.9%	0.0%	0.5%	2.7%	4.2%

	Raised Floor Lightweight PSZ															
	WWR 10%				WWR 21%				WWR 30%				WWR 40%			
	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%
Lights	0.0%	1.4%	7.1%	11.6%	0.0%	1.4%	7.1%	11.6%	0.0%	1.4%	7.1%	11.6%	0.0%	1.4%	7.1%	11.6%
Equipment	0.0%	1.2%	5.7%	9.2%	0.0%	1.2%	5.7%	9.2%	0.0%	1.2%	5.7%	9.2%	0.0%	1.2%	5.7%	9.2%
Heating	0.0%	-0.7%	-3.7%	-7.3%	0.0%	-0.4%	-2.0%	-3.8%	0.0%	-0.3%	-1.4%	-2.9%	0.0%	-0.2%	-1.1%	-2.2%
Cooling	0.0%	1.0%	4.6%	7.8%	0.0%	0.8%	4.1%	7.0%	0.0%	0.8%	3.8%	6.5%	0.0%	0.7%	3.6%	6.1%
Ventilation	0.0%	0.8%	4.0%	6.8%	0.0%	0.7%	3.6%	6.1%	0.0%	0.6%	3.2%	5.6%	0.0%	0.6%	3.0%	5.1%

	Heavyweight PSZ															
	WWR 10%				WWR 21%				WWR 30%				WWR 40%			
	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%
Lights	0.0%	1.4%	7.1%	11.3%	0.0%	1.4%	7.1%	11.3%	0.0%	1.4%	7.1%	11.3%	0.0%	1.4%	7.1%	11.3%
Equipment	0.0%	1.2%	5.7%	9.2%	0.0%	1.2%	5.7%	9.2%	0.0%	1.2%	5.7%	9.2%	0.0%	1.2%	5.7%	9.2%
Heating	0.0%	-1.2%	-10.9%	-23.5%	0.0%	-1.2%	-9.1%	-19.5%	0.0%	-1.3%	-8.8%	-18.1%	0.0%	-1.5%	-8.6%	-17.7%
Cooling	0.0%	1.2%	6.4%	10.4%	0.0%	1.1%	5.8%	9.3%	0.0%	1.0%	5.2%	8.5%	0.0%	0.9%	4.8%	7.7%
Ventilation	0.0%	0.9%	4.6%	7.4%	0.0%	0.8%	3.8%	6.0%	0.0%	0.7%	3.3%	5.2%	0.0%	0.6%	2.9%	4.4%

Table I-6. Houston PVAV: Percentage-Based Energy Reduction Credits of Space3-1 OBC on Total Loads

	Reference PVAV															
	WWR 10%				**WWR 21%**				**WWR 30%**				**WWR 40%**			
	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%
Lights	0.0%	1.4%	7.1%	11.3%	0.0%	1.4%	7.1%	11.3%	0.0%	1.4%	7.1%	11.3%	0.0%	1.4%	7.1%	11.3%
Equipment	0.0%	1.2%	5.7%	9.2%	0.0%	1.2%	5.7%	9.2%	0.0%	1.2%	5.7%	9.2%	0.0%	1.2%	5.7%	9.2%
Heating	0.0%	0.3%	0.3%	0.6%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.6%	0.6%	0.0%	0.0%	-1.2%	-1.2%
Cooling	0.0%	1.1%	5.2%	7.8%	0.0%	1.0%	4.6%	6.8%	0.0%	0.9%	4.0%	6.0%	0.0%	0.8%	3.6%	5.4%
Ventilation	0.0%	1.3%	5.9%	9.0%	0.0%	1.1%	5.0%	7.6%	0.0%	0.9%	4.4%	6.7%	0.0%	0.9%	3.9%	5.9%

	Raised Floor Lightweight PVAV															
	WWR 10%				**WWR 21%**				**WWR 30%**				**WWR 40%**			
	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%
Lights	0.0%	1.4%	7.1%	11.6%	0.0%	1.4%	7.1%	11.6%	0.0%	1.4%	7.1%	11.6%	0.0%	1.4%	7.1%	14.2%
Equipment	0.0%	1.2%	5.7%	9.2%	0.0%	1.2%	5.7%	9.2%	0.0%	1.2%	5.7%	9.2%	0.0%	1.2%	5.7%	9.2%
Heating	0.0%	0.0%	-0.5%	-0.5%	0.0%	0.0%	-0.8%	-1.6%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	-1.0%	-1.0%
Cooling	0.0%	0.9%	4.4%	6.9%	0.0%	0.8%	4.0%	6.1%	0.0%	0.8%	3.7%	5.6%	0.0%	0.7%	3.5%	5.5%
Ventilation	0.0%	1.1%	5.2%	8.3%	0.0%	1.0%	4.8%	7.4%	0.0%	0.9%	4.4%	6.8%	0.0%	0.8%	4.1%	6.7%

	Heavyweight PVAV															
	WWR 10%				**WWR 21%**				**WWR 30%**				**WWR 40%**			
	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%
Lights	0.0%	1.4%	7.1%	11.3%	0.0%	1.4%	7.1%	11.3%	0.0%	1.4%	7.1%	11.3%	0.0%	1.4%	7.1%	11.3%
Equipment	0.0%	1.2%	5.7%	9.2%	0.0%	1.2%	5.7%	9.2%	0.0%	1.2%	5.7%	9.2%	0.0%	1.2%	5.7%	9.2%
Heating	0.0%	0.3%	1.3%	1.8%	0.0%	0.0%	0.6%	0.9%	0.0%	0.0%	-0.4%	-0.9%	0.0%	0.0%	0.0%	0.0%
Cooling	0.0%	1.2%	5.8%	8.8%	0.0%	1.1%	5.1%	7.7%	0.0%	1.0%	4.5%	6.8%	0.0%	0.9%	4.0%	5.9%
Ventilation	0.0%	1.4%	6.7%	10.2%	0.0%	1.2%	5.7%	8.6%	0.0%	1.1%	4.9%	7.5%	0.0%	0.9%	4.3%	6.4%

Table I-7. Houston PSZ: Percentage-Based Energy Reduction Credits of Space4-1 OBC on Total Loads

	Reference PSZ															
	WWR 10%				WWR 21%				WWR 30%				WWR 40%			
	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%
Lights	0.0%	0.8%	4.2%	6.7%	0.0%	0.8%	4.2%	6.7%	0.0%	0.8%	4.2%	6.7%	0.0%	0.8%	4.2%	6.7%
Equipment	0.0%	0.7%	3.3%	5.3%	0.0%	0.7%	3.3%	5.3%	0.0%	0.7%	3.3%	5.3%	0.0%	0.7%	3.3%	5.3%
Heating	0.0%	-0.5%	-3.5%	-6.9%	0.0%	-0.6%	-3.6%	-6.5%	0.0%	-0.5%	-3.0%	-5.8%	0.0%	-0.6%	-3.1%	-5.5%
Cooling	0.0%	0.7%	3.4%	5.5%	0.0%	0.7%	3.1%	5.0%	0.0%	0.6%	2.9%	4.7%	0.0%	0.6%	2.8%	4.4%
Ventilation	0.0%	0.5%	2.4%	3.8%	0.0%	0.4%	2.0%	3.3%	0.0%	0.4%	1.8%	2.9%	0.0%	0.3%	1.6%	2.6%

	Raised Floor Lightweight PSZ															
	WWR 10%				WWR 21%				WWR 30%				WWR 40%			
	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%
Lights	0.0%	0.8%	4.2%	6.9%	0.0%	0.8%	4.2%	6.9%	0.0%	0.8%	4.2%	6.9%	0.0%	0.8%	4.2%	6.9%
Equipment	0.0%	0.7%	3.3%	5.3%	0.0%	0.7%	3.3%	5.3%	0.0%	0.7%	3.3%	5.3%	0.0%	0.7%	3.3%	5.3%
Heating	0.0%	-0.3%	-2.3%	-4.6%	0.0%	-0.2%	-1.3%	-2.6%	0.0%	-0.2%	-1.0%	-1.9%	0.0%	-0.1%	-0.7%	-1.4%
Cooling	0.0%	0.5%	2.8%	4.7%	0.0%	0.5%	2.5%	4.3%	0.0%	0.5%	2.3%	4.0%	0.0%	0.4%	2.2%	3.8%
Ventilation	0.0%	0.5%	2.3%	3.9%	0.0%	0.4%	2.1%	3.6%	0.0%	0.4%	1.9%	3.3%	0.0%	0.4%	1.8%	3.0%

	Heavyweight PSZ															
	WWR 10%				WWR 21%				WWR 30%				WWR 40%			
	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%
Lights	0.0%	0.8%	4.2%	6.7%	0.0%	0.8%	4.2%	6.7%	0.0%	0.8%	4.2%	6.7%	0.0%	0.8%	4.2%	6.7%
Equipment	0.0%	0.7%	3.3%	5.3%	0.0%	0.7%	3.3%	5.3%	0.0%	0.7%	3.3%	5.3%	0.0%	0.9%	3.3%	5.3%
Heating	0.0%	-0.6%	-5.2%	-10.2%	0.0%	-0.5%	-3.8%	-7.7%	0.0%	-0.4%	-3.4%	-6.7%	0.0%	-0.5%	-3.3%	-6.0%
Cooling	0.0%	0.7%	3.7%	6.0%	0.0%	0.6%	3.3%	5.3%	0.0%	0.6%	3.0%	4.8%	0.0%	0.6%	2.8%	4.5%
Ventilation	0.0%	0.5%	2.7%	4.3%	0.0%	0.4%	2.2%	3.6%	0.0%	0.4%	2.0%	3.1%	0.0%	0.3%	1.7%	2.7%

Table I-8. Houston PVAV: Percentage-Based Energy Reduction Credits of Space4-1 OBC on Total Loads

	Reference PVAV															
	WWR 10%				WWR 21%				WWR 30%				WWR 40%			
	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%
Lights	0.0%	0.8%	4.2%	6.7%	0.0%	0.8%	4.2%	6.7%	0.0%	0.8%	4.2%	6.7%	0.0%	0.8%	4.2%	6.7%
Equipment	0.0%	0.7%	3.3%	5.3%	0.0%	0.7%	3.3%	5.3%	0.0%	0.7%	3.3%	5.3%	0.0%	0.7%	3.3%	5.3%
Heating	0.0%	0.3%	0.6%	0.8%	0.0%	0.0%	0.4%	0.4%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	-1.3%
Cooling	0.0%	0.7%	3.3%	5.1%	0.0%	0.6%	2.9%	4.5%	0.0%	0.6%	2.7%	4.1%	0.0%	0.5%	2.4%	3.7%
Ventilation	0.0%	0.7%	3.2%	5.0%	0.0%	0.5%	2.7%	4.3%	0.0%	0.5%	2.4%	3.9%	0.0%	0.4%	2.2%	3.5%

	Raised Floor Lightweight PVAV															
	WWR 10%				WWR 21%				WWR 30%				WWR 40%			
	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%
Lights	0.0%	0.8%	4.2%	6.9%	0.0%	0.8%	4.2%	6.9%	0.0%	0.8%	4.2%	6.9%	0.0%	0.8%	4.2%	6.9%
Equipment	0.0%	0.7%	3.3%	5.3%	0.0%	0.7%	3.3%	5.3%	0.0%	0.7%	3.3%	5.3%	0.0%	0.7%	3.3%	5.3%
Heating	0.0%	-0.5%	-0.5%	-1.0%	0.0%	0.0%	0.0%	-0.8%	0.0%	-1.0%	-2.0%	-2.0%	0.0%	0.0%	-1.1%	-2.3%
Cooling	0.0%	0.6%	2.9%	4.6%	0.0%	0.5%	2.6%	4.1%	0.0%	0.5%	2.4%	3.8%	0.0%	0.5%	2.3%	3.7%
Ventilation	0.0%	0.6%	3.0%	4.9%	0.0%	0.6%	2.7%	4.4%	0.0%	0.5%	2.4%	4.0%	0.0%	0.5%	2.2%	3.7%

	Heavyweight PVAV															
	WWR 10%				WWR 21%				WWR 30%				WWR 40%			
	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%
Lights	0.0%	0.8%	4.2%	6.7%	0.0%	0.8%	4.2%	6.7%	0.0%	0.8%	4.2%	6.7%	0.0%	0.8%	4.2%	6.7%
Equipment	0.0%	0.7%	3.3%	5.3%	0.0%	0.7%	3.3%	5.3%	0.0%	0.7%	3.3%	5.3%	0.0%	0.7%	3.3%	5.3%
Heating	0.0%	0.2%	0.7%	1.0%	0.0%	0.3%	0.5%	0.5%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	-0.7%	0.0%
Cooling	0.0%	0.7%	3.5%	5.4%	0.0%	0.7%	3.2%	4.9%	0.0%	0.6%	2.9%	4.4%	0.0%	0.6%	2.6%	4.0%
Ventilation	0.0%	0.7%	3.7%	5.6%	0.0%	0.6%	3.0%	4.7%	0.0%	0.5%	2.6%	4.1%	0.0%	0.4%	2.3%	3.6%

Table I-9. Houston PSZ: Percentage-Based Energy Reduction Credits of Space5-1 OBC on Total Loads

	Reference PSZ															
	WWR 10%				**WWR 21%**				**WWR 30%**				**WWR 40%**			
	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%
Lights	0.0%	1.9%	9.4%	15.0%	0.0%	1.9%	9.4%	15.0%	0.0%	1.9%	9.4%	15.0%	0.0%	1.9%	9.4%	15.0%
Equipment	0.0%	1.5%	7.7%	12.3%	0.0%	1.5%	7.7%	12.3%	0.0%	1.5%	7.7%	12.3%	0.0%	1.5%	7.7%	12.3%
Heating	0.0%	-1.4%	-6.8%	-18.1%	0.0%	-0.7%	-6.2%	-15.1%	0.0%	-0.7%	-5.2%	-12.9%	0.0%	-0.5%	-3.8%	-10.3%
Cooling	0.0%	1.6%	8.3%	13.9%	0.0%	1.5%	7.7%	12.9%	0.0%	1.4%	7.4%	12.3%	0.0%	1.3%	6.9%	11.6%
Ventilation	0.0%	1.1%	5.4%	8.6%	0.0%	0.9%	4.5%	7.2%	0.0%	0.8%	4.0%	6.5%	0.0%	0.7%	3.6%	5.8%

	Raised Floor Lightweight PSZ															
	WWR 10%				**WWR 21%**				**WWR 30%**				**WWR 40%**			
	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%
Lights	0.0%	1.9%	9.4%	15.4%	0.0%	1.9%	9.4%	15.4%	0.0%	1.9%	9.4%	15.4%	0.0%	1.9%	9.4%	15.4%
Equipment	0.0%	1.5%	7.7%	12.3%	0.0%	1.5%	7.7%	12.3%	0.0%	1.5%	7.7%	12.3%	0.0%	1.5%	7.7%	12.3%
Heating	0.0%	-0.4%	-5.0%	-15.7%	0.0%	-0.4%	-4.2%	-13.2%	0.0%	-0.3%	-3.7%	-11.6%	0.0%	-0.3%	-3.5%	-10.7%
Cooling	0.0%	1.5%	7.8%	13.4%	0.0%	1.5%	7.5%	12.9%	0.0%	1.4%	7.3%	12.5%	0.0%	1.4%	7.1%	12.2%
Ventilation	0.0%	1.1%	5.3%	9.1%	0.0%	1.0%	4.8%	8.3%	0.0%	0.9%	4.4%	7.5%	0.0%	0.8%	4.1%	6.9%

	Heavyweight PSZ															
	WWR 10%				**WWR 21%**				**WWR 30%**				**WWR 40%**			
	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%
Lights	0.0%	1.9%	9.4%	15.0%	0.0%	1.9%	9.4%	15.0%	0.0%	1.9%	9.4%	15.0%	0.0%	1.9%	9.4%	15.0%
Equipment	0.0%	1.5%	7.7%	12.3%	0.0%	1.5%	7.7%	12.3%	0.0%	1.5%	7.7%	12.3%	0.0%	1.5%	7.7%	12.3%
Heating	0.0%	-0.9%	-9.7%	-24.4%	0.0%	-0.9%	-8.0%	-20.5%	0.0%	-0.7%	-6.9%	-16.0%	0.0%	-0.7%	-5.2%	-12.6%
Cooling	0.0%	1.8%	8.9%	14.9%	0.0%	1.6%	8.2%	13.7%	0.0%	1.5%	7.7%	13.0%	0.0%	1.4%	7.3%	12.1%
Ventilation	0.0%	1.2%	6.1%	9.8%	0.0%	1.0%	5.0%	8.0%	0.0%	0.9%	4.4%	7.0%	0.0%	0.8%	3.8%	6.1%

Table I-10. Houston PVAV: Percentage-Based Energy Reduction Credits of Space5-1 OBC on Total Loads

	Reference PVAV															
	WWR 10%				WWR 21%				WWR 30%				WWR 40%			
	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%
Lights	0.0%	1.9%	9.4%	15.0%	0.0%	1.9%	9.4%	15.0%	0.0%	1.9%	9.4%	15.0%	0.0%	1.9%	9.4%	15.0%
Equipment	0.0%	1.5%	7.7%	12.3%	0.0%	1.5%	7.7%	12.3%	0.0%	1.5%	7.7%	12.3%	0.0%	1.5%	7.7%	12.3%
Heating	0.0%	0.0%	0.9%	1.5%	0.0%	0.5%	1.9%	2.9%	0.0%	0.8%	4.2%	7.6%	0.0%	1.3%	6.6%	10.5%
Cooling	0.0%	1.6%	7.3%	10.9%	0.0%	1.4%	6.7%	9.9%	0.0%	1.3%	6.2%	9.2%	0.0%	1.3%	5.7%	8.4%
Ventilation	0.0%	1.7%	7.8%	10.9%	0.0%	1.5%	6.8%	9.4%	0.0%	1.3%	6.1%	8.5%	0.0%	1.2%	5.5%	7.6%

	Raised Floor Lightweight PVAV															
	WWR 10%				WWR 21%				WWR 30%				WWR 40%			
	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%
Lights	0.0%	1.9%	9.4%	15.4%	0.0%	1.9%	9.4%	15.4%	0.0%	1.9%	9.4%	15.4%	0.0%	1.9%	9.4%	15.4%
Equipment	0.0%	1.5%	7.7%	12.3%	0.0%	1.5%	7.7%	12.3%	0.0%	1.5%	7.7%	12.3%	0.0%	1.5%	7.7%	12.3%
Heating	0.0%	-0.6%	-3.1%	-0.6%	0.0%	-0.8%	-4.8%	-0.8%	0.0%	-1.9%	-5.7%	-0.9%	0.0%	-1.0%	-5.7%	-1.0%
Cooling	0.0%	1.3%	6.7%	11.9%	0.0%	1.2%	6.3%	11.1%	0.0%	1.2%	6.0%	10.7%	0.0%	1.1%	5.8%	10.3%
Ventilation	0.0%	1.7%	8.4%	13.0%	0.0%	1.6%	7.7%	12.0%	0.0%	1.5%	7.3%	11.3%	0.0%	1.4%	7.0%	10.8%

	Heavyweight PVAV															
	WWR 10%				WWR 21%				WWR 30%				WWR 40%			
	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%
Lights	0.0%	1.9%	9.4%	15.0%	0.0%	1.9%	9.4%	15.0%	0.0%	1.9%	9.4%	15.0%	0.0%	1.9%	9.4%	15.0%
Equipment	0.0%	1.5%	7.7%	12.3%	0.0%	1.5%	7.7%	12.3%	0.0%	1.5%	7.7%	12.3%	0.0%	1.5%	7.7%	12.3%
Heating	0.0%	0.3%	0.8%	1.9%	0.0%	-0.3%	0.3%	1.2%	0.0%	0.5%	2.3%	2.8%	0.0%	0.9%	4.7%	7.5%
Cooling	0.0%	1.7%	7.9%	11.7%	0.0%	1.5%	7.2%	10.6%	0.0%	1.4%	6.7%	9.8%	0.0%	1.3%	6.0%	8.9%
Ventilation	0.0%	1.9%	8.6%	12.0%	0.0%	1.6%	7.4%	10.3%	0.0%	1.5%	6.7%	9.2%	0.0%	1.3%	5.9%	8.1%

Table I-11. Chicago PSZ: Percentage-Based Energy Reduction Credits of Space1-1 OBC on Total Loads

	Reference PSZ															
	WWR 10%				WWR 21%				WWR 30%				WWR 40%			
	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%
Lights	0.0%	1.4%	7.1%	11.3%	0.0%	1.4%	7.1%	11.3%	0.0%	1.4%	7.1%	11.3%	0.0%	1.4%	7.1%	11.3%
Equipment	0.0%	1.2%	5.7%	9.2%	0.0%	1.2%	5.7%	9.2%	0.0%	1.2%	5.7%	9.2%	0.0%	1.2%	5.7%	9.2%
Heating	0.0%	-1.4%	-6.6%	-10.9%	0.0%	-1.1%	-5.0%	-8.1%	0.0%	-1.0%	-4.4%	-7.0%	0.0%	-0.8%	-4.1%	-6.4%
Cooling	0.0%	1.4%	7.2%	11.5%	0.0%	1.4%	6.6%	10.4%	0.0%	1.2%	6.1%	9.6%	0.0%	1.2%	5.7%	8.9%
Ventilation	0.0%	1.0%	5.0%	7.9%	0.0%	0.8%	3.8%	6.1%	0.0%	0.6%	3.2%	5.2%	0.0%	0.5%	2.8%	4.4%

	Raised Floor Lightweight PSZ															
	WWR 10%				WWR 21%				WWR 30%				WWR 40%			
	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%
Lights	0.0%	1.4%	7.1%	11.6%	0.0%	1.4%	7.1%	11.6%	0.0%	1.4%	7.1%	11.6%	0.0%	1.4%	7.1%	11.6%
Equipment	0.0%	1.2%	5.7%	9.2%	0.0%	1.2%	5.7%	9.2%	0.0%	1.2%	5.7%	9.2%	0.0%	1.2%	5.7%	9.2%
Heating	0.0%	-0.9%	-4.7%	-8.8%	0.0%	-0.6%	-3.3%	-5.8%	0.0%	-0.4%	-2.6%	-4.6%	0.0%	-0.3%	-2.1%	-3.8%
Cooling	0.0%	1.1%	5.4%	9.1%	0.0%	1.1%	4.9%	8.5%	0.0%	0.9%	4.5%	7.8%	0.0%	0.8%	4.2%	7.3%
Ventilation	0.0%	0.9%	4.6%	7.4%	0.0%	0.7%	3.6%	6.0%	0.0%	0.6%	3.2%	5.3%	0.0%	0.6%	2.9%	4.7%

	Heavyweight PSZ															
	WWR 10%				WWR 21%				WWR 30%				WWR 40%			
	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%
Lights	0.0%	1.4%	7.1%	11.3%	0.0%	1.4%	7.1%	11.3%	0.0%	1.4%	7.1%	11.3%	0.0%	1.4%	7.1%	11.3%
Equipment	0.0%	1.2%	5.7%	9.2%	0.0%	1.2%	5.7%	9.2%	0.0%	1.2%	5.7%	9.2%	0.0%	1.2%	5.7%	9.2%
Heating	0.0%	-1.4%	-6.6%	-10.9%	0.0%	-1.1%	-5.0%	-8.1%	0.0%	-1.0%	-4.4%	-7.0%	0.0%	-0.8%	-4.1%	-6.4%
Cooling	0.0%	1.4%	7.2%	11.5%	0.0%	1.4%	6.6%	10.4%	0.0%	1.2%	6.1%	9.6%	0.0%	1.2%	5.7%	8.9%
Ventilation	0.0%	1.0%	5.0%	7.9%	0.0%	0.8%	3.8%	6.1%	0.0%	0.6%	3.2%	5.2%	0.0%	0.5%	2.8%	4.4%

Table I-12. Chicago PVAV: Percentage-Based Energy Reduction Credits of Space1-1 OBC on Total Loads

	Reference PVAV															
	WWR 10%				WWR 21%				WWR 30%				WWR 40%			
	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%
Lights	0.0%	1.4%	7.1%	11.3%	0.0%	1.4%	7.1%	11.3%	0.0%	1.4%	7.1%	11.3%	0.0%	1.4%	7.1%	11.3%
Equipment	0.0%	1.2%	5.7%	9.2%	0.0%	1.2%	5.7%	9.2%	0.0%	1.2%	5.7%	9.2%	0.0%	1.2%	5.7%	9.2%
Heating	0.0%	-0.2%	0.3%	1.0%	0.0%	-0.1%	-0.3%	-0.2%	0.0%	0.1%	0.0%	-0.1%	0.0%	0.0%	-0.1%	-0.2%
Cooling	0.0%	1.3%	6.6%	10.2%	0.0%	1.2%	6.1%	9.3%	0.0%	1.1%	5.5%	8.4%	0.0%	1.0%	4.8%	7.4%
Ventilation	0.0%	1.3%	6.0%	9.0%	0.0%	1.0%	4.6%	7.1%	0.0%	0.8%	3.9%	6.1%	0.0%	0.7%	3.3%	5.3%

	Raised Floor Lightweight PVAV															
	WWR 10%				WWR 21%				WWR 30%				WWR 40%			
	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%
Lights	0.0%	1.4%	7.1%	11.6%	0.0%	1.4%	7.1%	11.6%	0.0%	1.4%	7.1%	11.6%	0.0%	1.4%	7.1%	11.6%
Equipment	0.0%	1.2%	5.7%	9.2%	0.0%	1.2%	5.7%	9.2%	0.0%	1.2%	5.7%	9.2%	0.0%	1.2%	5.7%	9.2%
Heating	0.0%	-0.3%	-0.8%	-1.2%	0.0%	-0.1%	-1.0%	-2.0%	0.0%	-0.2%	-1.3%	-2.5%	0.0%	-0.2%	-0.8%	-2.1%
Cooling	0.0%	1.1%	5.5%	9.0%	0.0%	1.1%	5.2%	8.8%	0.0%	1.0%	4.8%	8.0%	0.0%	0.9%	4.5%	7.5%
Ventilation	0.0%	1.2%	5.7%	8.8%	0.0%	0.9%	4.4%	7.3%	0.0%	0.8%	3.9%	6.3%	0.0%	0.7%	3.4%	5.6%

	Heavyweight PVAV															
	WWR 10%				WWR 21%				WWR 30%				WWR 40%			
	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%
Lights	0.0%	1.4%	7.1%	11.3%	0.0%	1.4%	7.1%	11.3%	0.0%	1.4%	7.1%	11.3%	0.0%	1.4%	7.1%	11.3%
Equipment	0.0%	1.2%	5.7%	9.2%	0.0%	1.2%	5.7%	9.2%	0.0%	1.2%	5.7%	9.2%	0.0%	1.2%	5.7%	9.2%
Heating	0.0%	-0.1%	0.6%	1.2%	0.0%	-0.2%	-0.7%	-0.4%	0.0%	0.0%	-0.1%	-0.1%	0.0%	-0.3%	-0.3%	-0.3%
Cooling	0.0%	1.4%	6.7%	10.3%	0.0%	1.3%	6.4%	9.7%	0.0%	1.2%	5.7%	8.7%	0.0%	1.1%	5.0%	7.6%
Ventilation	0.0%	1.3%	6.2%	9.2%	0.0%	1.0%	4.7%	7.4%	0.0%	0.8%	4.0%	6.3%	0.0%	0.7%	3.4%	5.3%

Table I-13. Chicago PSZ: Percentage-Based Energy Reduction Credits of Space2-1 OBC on Total Loads

	Reference PSZ															
	WWR 10%				**WWR 21%**				**WWR 30%**				**WWR 40%**			
	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%
Lights	0.0%	0.8%	4.2%	6.7%	0.0%	0.8%	4.2%	6.7%	0.0%	0.8%	4.2%	6.7%	0.0%	0.8%	4.2%	6.7%
Equipment	0.0%	0.7%	3.3%	5.3%	0.0%	0.7%	3.3%	5.3%	0.0%	0.7%	3.3%	5.3%	0.0%	0.7%	3.3%	5.3%
Heating	0.0%	-0.9%	-3.7%	-5.9%	0.0%	-0.9%	-3.8%	-5.6%	0.0%	-0.8%	-3.4%	-5.2%	0.0%	-0.7%	-3.3%	-5.0%
Cooling	0.0%	0.8%	4.0%	6.3%	0.0%	0.7%	3.6%	5.6%	0.0%	0.7%	3.3%	5.1%	0.0%	0.6%	3.0%	4.7%
Ventilation	0.0%	0.5%	2.3%	3.5%	0.0%	0.3%	1.7%	2.7%	0.0%	0.3%	1.4%	2.3%	0.0%	0.2%	1.2%	2.0%

	Raised Floor Lightweight PSZ															
	WWR 10%				**WWR 21%**				**WWR 30%**				**WWR 40%**			
	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%
Lights	0.0%	0.8%	4.2%	6.9%	0.0%	0.8%	4.2%	6.9%	0.0%	0.8%	4.2%	6.9%	0.0%	0.8%	4.2%	6.9%
Equipment	0.0%	0.7%	3.3%	5.3%	0.0%	0.7%	3.3%	5.3%	0.0%	0.7%	3.3%	5.3%	0.0%	0.7%	3.3%	5.3%
Heating	0.0%	-0.6%	-2.8%	-5.2%	0.0%	-0.4%	-2.1%	-3.7%	0.0%	-0.3%	-1.8%	-2.9%	0.0%	-0.3%	-1.5%	-2.5%
Cooling	0.0%	0.6%	2.9%	4.9%	0.0%	0.5%	2.4%	4.2%	0.0%	0.4%	2.2%	3.9%	0.0%	0.4%	2.1%	3.6%
Ventilation	0.0%	0.4%	2.0%	3.3%	0.0%	0.3%	1.5%	2.6%	0.0%	0.3%	1.3%	2.3%	0.0%	0.2%	1.2%	2.0%

	Heavyweight PSZ															
	WWR 10%				**WWR 21%**				**WWR 30%**				**WWR 40%**			
	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%
Lights	0.0%	0.8%	4.2%	6.7%	0.0%	0.8%	4.2%	6.7%	0.0%	0.8%	4.2%	6.7%	0.0%	0.8%	4.2%	6.7%
Equipment	0.0%	0.7%	3.3%	5.3%	0.0%	0.7%	3.3%	5.3%	0.0%	0.7%	3.3%	5.3%	0.0%	0.7%	3.3%	5.3%
Heating	0.0%	-0.6%	-3.0%	-5.3%	0.0%	-0.8%	-3.7%	-5.6%	0.0%	-0.9%	-3.6%	-5.4%	0.0%	-0.8%	-3.5%	-5.4%
Cooling	0.0%	0.7%	2.6%	3.8%	0.0%	0.8%	3.6%	5.9%	0.0%	0.7%	3.3%	5.2%	0.0%	0.6%	3.0%	4.7%
Ventilation	0.0%	0.5%	2.4%	3.8%	0.0%	0.4%	1.8%	2.9%	0.0%	0.3%	1.6%	2.5%	0.0%	0.3%	1.3%	2.2%

Table I-14. Chicago PVAV: Percentage-Based Energy Reduction Credits of Space2-1 OBC on Total Loads

	Reference PVAV															
	WWR 10%				**WWR 21%**				**WWR 30%**				**WWR 40%**			
	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%
Lights	0.0%	0.8%	4.2%	6.7%	0.0%	0.8%	4.2%	6.7%	0.0%	0.8%	4.2%	6.7%	0.0%	0.8%	4.2%	6.7%
Equipment	0.0%	0.7%	3.3%	5.3%	0.0%	0.7%	3.3%	5.3%	0.0%	0.7%	3.3%	5.3%	0.0%	0.7%	3.3%	5.3%
Heating	0.0%	0.1%	0.5%	0.8%	0.0%	0.0%	0.4%	0.7%	0.0%	0.1%	0.4%	0.6%	0.0%	0.1%	0.3%	0.5%
Cooling	0.0%	0.8%	3.7%	5.7%	0.0%	0.6%	3.2%	4.8%	0.0%	0.6%	2.9%	4.3%	0.0%	0.5%	2.5%	3.8%
Ventilation	0.0%	0.7%	3.1%	4.6%	0.0%	0.5%	2.2%	3.5%	0.0%	0.4%	1.9%	2.9%	0.0%	0.3%	1.6%	2.5%

	Raised Floor Lightweight PVAV															
	WWR 10%				**WWR 21%**				**WWR 30%**				**WWR 40%**			
	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%
Lights	0.0%	0.8%	4.2%	6.9%	0.0%	0.8%	4.2%	6.9%	0.0%	0.8%	4.2%	6.9%	0.0%	0.8%	4.2%	6.9%
Equipment	0.0%	0.7%	3.3%	5.3%	0.0%	0.7%	3.3%	5.3%	0.0%	0.7%	3.3%	5.3%	0.0%	0.7%	3.3%	5.3%
Heating	0.0%	-0.1%	-0.7%	-1.3%	0.0%	-0.1%	-0.7%	-1.6%	0.0%	-0.2%	-0.8%	-1.9%	0.0%	-0.1%	-0.9%	-1.8%
Cooling	0.0%	0.6%	2.9%	4.8%	0.0%	0.5%	2.6%	4.3%	0.0%	0.5%	2.5%	4.1%	0.0%	0.4%	2.3%	3.7%
Ventilation	0.0%	0.6%	2.7%	4.2%	0.0%	0.5%	2.2%	3.4%	0.0%	0.4%	1.8%	3.0%	0.0%	0.4%	1.6%	2.7%

	Heavyweight PVAV															
	WWR 10%				**WWR 21%**				**WWR 30%**				**WWR 40%**			
	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%
Lights	0.0%	0.8%	4.2%	6.7%	0.0%	0.8%	4.2%	6.7%	0.0%	0.8%	4.2%	6.7%	0.0%	0.8%	4.2%	6.7%
Equipment	0.0%	0.7%	3.3%	5.3%	0.0%	0.7%	3.3%	5.3%	0.0%	0.7%	3.3%	5.3%	0.0%	0.7%	3.3%	5.3%
Heating	0.0%	0.1%	0.5%	0.8%	0.0%	0.0%	0.6%	1.0%	0.0%	-0.1%	0.3%	0.6%	0.0%	0.0%	0.2%	0.4%
Cooling	0.0%	0.8%	3.8%	5.7%	0.0%	0.7%	3.4%	5.1%	0.0%	0.6%	3.0%	4.5%	0.0%	0.5%	2.6%	3.9%
Ventilation	0.0%	0.7%	3.1%	4.7%	0.0%	0.5%	2.3%	3.6%	0.0%	0.4%	1.9%	3.0%	0.0%	0.3%	1.7%	2.6%

Table I-15. Chicago PSZ: Percentage-Based Energy Reduction Credits of Space3-1 OBC on Total Loads

	Reference PSZ															
	WWR 10%				WWR 21%				WWR 30%				WWR 40%			
	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%
Lights	0.0%	1.4%	7.1%	11.3%	0.0%	1.4%	7.1%	11.3%	0.0%	1.4%	7.1%	11.3%	0.0%	1.4%	7.1%	11.3%
Equipment	0.0%	1.2%	5.7%	9.2%	0.0%	1.2%	5.7%	9.2%	0.0%	1.2%	5.7%	9.2%	0.0%	1.2%	5.7%	9.2%
Heating	0.0%	-1.5%	-9.0%	-22.5%	0.0%	-1.6%	-8.3%	-18.3%	0.0%	-1.2%	-7.2%	-14.7%	0.0%	-1.2%	-6.4%	-12.3%
Cooling	0.0%	1.4%	6.8%	10.9%	0.0%	1.1%	5.9%	9.6%	0.0%	1.1%	5.5%	8.6%	0.0%	1.0%	4.9%	7.8%
Ventilation	0.0%	0.9%	4.7%	7.4%	0.0%	0.7%	3.6%	5.7%	0.0%	0.6%	3.0%	4.9%	0.0%	0.5%	2.6%	4.2%

	Raised Floor Lightweight PSZ															
	WWR 10%				WWR 21%				WWR 30%				WWR 40%			
	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%
Lights	0.0%	1.4%	7.1%	11.6%	0.0%	1.4%	7.1%	11.6%	0.0%	1.4%	7.1%	11.6%	0.0%	1.4%	7.1%	11.6%
Equipment	0.0%	1.2%	5.7%	9.2%	0.0%	1.2%	5.7%	9.2%	0.0%	1.2%	5.7%	9.2%	0.0%	1.2%	5.7%	9.2%
Heating	0.0%	-1.2%	-6.3%	-12.9%	0.0%	-0.9%	-5.2%	-11.2%	0.0%	-0.7%	-4.1%	-8.7%	0.0%	-0.6%	-3.4%	-7.2%
Cooling	0.0%	1.0%	5.0%	8.4%	0.0%	0.8%	4.2%	7.1%	0.0%	0.7%	3.7%	6.3%	0.0%	0.7%	3.3%	5.7%
Ventilation	0.0%	0.9%	4.6%	7.8%	0.0%	0.7%	3.5%	6.0%	0.0%	0.6%	3.0%	5.2%	0.0%	0.5%	2.7%	4.6%

	Heavyweight PSZ															
	WWR 10%				WWR 21%				WWR 30%				WWR 40%			
	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%
Lights	0.0%	1.4%	7.1%	11.3%	0.0%	1.4%	7.1%	11.3%	0.0%	1.4%	7.1%	11.3%	0.0%	1.4%	7.1%	11.3%
Equipment	0.0%	1.2%	5.7%	9.2%	0.0%	1.2%	5.7%	9.2%	0.0%	1.2%	5.7%	9.2%	0.0%	1.2%	5.7%	9.2%
Heating	0.0%	-1.0%	-5.7%	-11.8%	0.0%	-1.3%	-7.8%	-19.1%	0.0%	-1.3%	-7.0%	-15.0%	0.0%	-1.2%	-6.1%	-12.2%
Cooling	0.0%	0.9%	4.2%	6.2%	0.0%	1.2%	6.1%	9.7%	0.0%	1.0%	5.3%	8.6%	0.0%	1.0%	4.9%	8.1%
Ventilation	0.0%	1.0%	4.9%	7.9%	0.0%	0.7%	3.7%	5.9%	0.0%	0.6%	3.1%	5.0%	0.0%	0.5%	2.6%	4.2%

Table I-16. Chicago PVAV: Percentage-Based Energy Reduction Credits of Space3-1 OBC on Total Loads

	Reference PVAV															
	WWR 10%				**WWR 21%**				**WWR 30%**				**WWR 40%**			
	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%
Lights	0.0%	1.4%	5.7%	11.3%	0.0%	1.4%	7.1%	11.3%	0.0%	1.4%	7.1%	11.3%	0.0%	1.4%	7.1%	11.3%
Equipment	0.0%	1.2%	4.6%	9.2%	0.0%	1.2%	5.7%	9.2%	0.0%	1.2%	5.7%	9.8%	0.0%	1.2%	5.7%	9.2%
Heating	0.0%	0.1%	0.6%	1.2%	0.0%	0.1%	0.6%	0.8%	0.0%	0.1%	0.2%	0.3%	0.0%	0.0%	0.0%	-0.1%
Cooling	0.0%	1.2%	4.8%	8.1%	0.0%	1.0%	4.7%	6.9%	0.0%	1.0%	4.3%	6.2%	0.0%	0.9%	3.7%	5.5%
Ventilation	0.0%	1.1%	4.2%	6.9%	0.0%	0.8%	3.8%	5.2%	0.0%	0.8%	3.2%	4.3%	0.0%	0.6%	2.6%	3.5%

	Raised Floor Lightweight PVAV															
	WWR 10%				**WWR 21%**				**WWR 30%**				**WWR 40%**			
	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%
Lights	0.0%	1.4%	7.1%	11.6%	0.0%	1.4%	7.1%	11.6%	0.0%	1.4%	7.1%	11.6%	0.0%	1.4%	7.1%	11.6%
Equipment	0.0%	1.2%	5.7%	9.2%	0.0%	1.2%	5.7%	9.2%	0.0%	1.2%	5.7%	9.2%	0.0%	1.2%	5.7%	9.2%
Heating	0.0%	-0.1%	-0.7%	-1.2%	0.0%	-0.2%	-0.9%	-1.7%	0.0%	-0.3%	-1.5%	-2.4%	0.0%	-0.2%	-1.4%	-2.4%
Cooling	0.0%	1.1%	4.9%	7.1%	0.0%	1.0%	4.0%	6.2%	0.0%	0.8%	3.6%	5.6%	0.0%	0.7%	3.3%	5.1%
Ventilation	0.0%	1.0%	4.0%	4.2%	0.0%	0.8%	3.3%	3.8%	0.0%	0.7%	2.9%	3.6%	0.0%	0.6%	2.6%	3.3%

	Heavyweight PVAV															
	WWR 10%				**WWR 21%**				**WWR 30%**				**WWR 40%**			
	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%
Lights	0.0%	1.4%	7.1%	11.3%	0.0%	1.4%	7.1%	11.3%	0.0%	1.4%	7.1%	11.3%	0.0%	1.4%	7.1%	11.3%
Equipment	0.0%	1.2%	5.7%	9.2%	0.0%	1.2%	5.7%	9.2%	0.0%	1.2%	5.7%	9.2%	0.0%	1.2%	5.7%	9.2%
Heating	0.0%	0.1%	0.8%	1.2%	0.0%	0.1%	0.3%	0.7%	0.0%	0.1%	0.4%	0.6%	0.0%	0.1%	-0.1%	0.0%
Cooling	0.0%	1.3%	6.3%	8.5%	0.0%	1.2%	5.1%	7.2%	0.0%	1.0%	4.4%	6.4%	0.0%	1.0%	3.9%	5.6%
Ventilation	0.0%	1.1%	5.1%	6.5%	0.0%	0.9%	4.0%	5.2%	0.0%	0.7%	3.3%	4.2%	0.0%	0.6%	2.6%	3.4%

Table I-17. Chicago PSZ: Percentage-Based Energy Reduction of Space4-1 OBC on Total Loads

	Reference PSZ															
	WWR 10%				WWR 21%				WWR 30%				WWR 40%			
	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%
Lights	0.0%	0.8%	4.2%	6.7%	0.0%	0.8%	4.2%	6.7%	0.0%	0.8%	4.2%	6.7%	0.0%	0.8%	4.2%	6.7%
Equipment	0.0%	0.7%	3.3%	5.3%	0.0%	0.7%	3.3%	5.3%	0.0%	0.7%	3.3%	5.3%	0.0%	0.7%	3.3%	5.3%
Heating	0.0%	-0.8%	-3.8%	-6.1%	0.0%	-0.8%	-3.3%	-5.4%	0.0%	-0.8%	-3.4%	-5.1%	0.0%	-0.8%	-3.1%	-4.7%
Cooling	0.0%	0.8%	4.0%	6.5%	0.0%	0.7%	3.6%	5.6%	0.0%	0.6%	3.1%	5.2%	0.0%	0.6%	3.0%	4.8%
Ventilation	0.0%	0.5%	2.8%	4.4%	0.0%	0.4%	2.1%	3.4%	0.0%	0.4%	1.9%	3.0%	0.0%	0.3%	1.6%	2.5%

	Raised Floor Lightweight PSZ															
	WWR 10%				WWR 21%				WWR 30%				WWR 40%			
	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%
Lights	0.0%	0.8%	4.2%	6.9%	0.0%	0.8%	4.2%	6.9%	0.0%	0.8%	4.2%	6.9%	0.0%	0.8%	4.2%	6.9%
Equipment	0.0%	0.7%	3.3%	5.3%	0.0%	0.7%	3.3%	5.3%	0.0%	0.7%	3.3%	5.3%	0.0%	0.7%	3.3%	5.3%
Heating	0.0%	-0.6%	-3.1%	-5.7%	0.0%	-0.5%	-2.3%	-4.3%	0.0%	-0.4%	-1.9%	-3.4%	0.0%	-0.3%	-1.6%	-2.8%
Cooling	0.0%	0.6%	3.0%	5.2%	0.0%	0.5%	2.6%	4.5%	0.0%	0.5%	2.3%	4.0%	0.0%	0.4%	2.1%	3.6%
Ventilation	0.0%	0.5%	2.7%	4.6%	0.0%	0.4%	2.1%	3.6%	0.0%	0.4%	1.8%	3.1%	0.0%	0.3%	1.6%	2.8%

	Heavyweight PSZ															
	WWR 10%				WWR 21%				WWR 30%				WWR 40%			
	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%
Lights	0.0%	0.8%	4.2%	6.7%	0.0%	0.8%	4.2%	6.7%	0.0%	0.8%	4.2%	6.7%	0.0%	0.8%	4.2%	6.7%
Equipment	0.0%	0.7%	3.3%	5.3%	0.0%	0.7%	3.3%	5.3%	0.0%	0.7%	3.3%	5.3%	0.0%	0.7%	3.3%	5.3%
Heating	0.0%	-0.7%	-4.0%	-5.9%	0.0%	-0.9%	-3.6%	-5.7%	0.0%	-0.9%	-3.5%	-5.2%	0.0%	-0.7%	-3.3%	-5.0%
Cooling	0.0%	0.6%	2.9%	4.0%	0.0%	0.7%	3.7%	5.8%	0.0%	0.7%	3.4%	5.3%	0.0%	0.6%	3.0%	4.7%
Ventilation	0.0%	0.6%	2.9%	4.6%	0.0%	0.4%	2.2%	3.6%	0.0%	0.4%	1.9%	3.0%	0.0%	0.3%	1.6%	2.6%

Table I-18. Chicago PVAV: Percentage-Based Energy Reduction of Space4-1 OBC on Total Loads

	Reference PVAV															
	WWR 10%				WWR 21%				WWR 30%				WWR 40%			
	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%
Lights	0.0%	0.8%	4.2%	6.7%	0.0%	0.8%	4.2%	6.7%	0.0%	0.8%	4.2%	6.7%	0.0%	0.8%	4.2%	6.7%
Equipment	0.0%	0.7%	3.3%	5.3%	0.0%	0.7%	3.3%	5.3%	0.0%	0.7%	3.3%	5.3%	0.0%	0.7%	3.3%	5.3%
Heating	0.0%	0.1%	0.6%	1.0%	0.0%	0.1%	0.6%	0.9%	0.0%	0.1%	0.3%	0.3%	0.0%	0.1%	0.0%	-0.2%
Cooling	0.0%	0.8%	3.9%	6.0%	0.0%	0.7%	3.3%	5.1%	0.0%	0.6%	3.0%	4.7%	0.0%	0.6%	2.7%	4.1%
Ventilation	0.0%	0.7%	3.3%	5.2%	0.0%	0.5%	2.6%	4.1%	0.0%	0.4%	2.2%	3.5%	0.0%	0.4%	1.9%	3.0%

	Raised Floor Lightweight PVAV															
	WWR 10%				WWR 21%				WWR 30%				WWR 40%			
	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%
Lights	0.0%	0.8%	4.2%	6.9%	0.0%	0.8%	4.2%	6.9%	0.0%	0.8%	4.2%	6.9%	0.0%	0.8%	4.2%	6.9%
Equipment	0.0%	0.7%	3.3%	5.3%	0.0%	0.7%	3.3%	5.3%	0.0%	0.7%	3.3%	5.3%	0.0%	0.7%	3.3%	5.3%
Heating	0.0%	-0.1%	-0.5%	-1.4%	0.0%	-0.1%	-0.8%	-1.7%	0.0%	-0.3%	-1.5%	-2.7%	0.0%	-0.3%	-1.6%	-2.7%
Cooling	0.0%	0.7%	3.2%	5.4%	0.0%	0.6%	2.9%	4.9%	0.0%	0.6%	2.7%	4.5%	0.0%	0.5%	2.5%	4.1%
Ventilation	0.0%	0.6%	3.1%	5.0%	0.0%	0.6%	2.5%	4.2%	0.0%	0.4%	2.2%	3.7%	0.0%	0.4%	2.0%	3.4%

	Heavyweight PVAV															
	WWR 10%				WWR 21%				WWR 30%				WWR 40%			
	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%
Lights	0.0%	0.8%	4.2%	6.7%	0.0%	0.8%	4.2%	6.7%	0.0%	0.8%	4.2%	6.7%	0.0%	0.8%	4.2%	6.7%
Equipment	0.0%	0.7%	3.3%	5.3%	0.0%	0.7%	3.3%	5.3%	0.0%	0.7%	3.3%	5.3%	0.0%	0.7%	3.3%	5.3%
Heating	0.0%	0.1%	0.6%	1.0%	0.0%	0.1%	0.6%	1.1%	0.0%	0.1%	0.2%	0.3%	0.0%	-0.1%	-0.2%	-0.2%
Cooling	0.0%	0.8%	3.9%	5.9%	0.0%	0.7%	3.5%	5.3%	0.0%	0.7%	3.2%	4.8%	0.0%	0.6%	2.8%	4.2%
Ventilation	0.0%	0.7%	3.5%	5.4%	0.0%	0.6%	2.7%	4.3%	0.0%	0.5%	2.3%	3.6%	0.0%	0.4%	1.9%	3.1%

Table I-19. Chicago PSZ: Percentage-Based Energy Reduction of Space5-1 OBC on Total Loads

	Reference PSZ															
	WWR 10%				WWR 21%				WWR 30%				WWR 40%			
	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%
Lights	0.0%	1.9%	9.4%	15.0%	0.0%	1.9%	9.4%	15.0%	0.0%	1.9%	9.4%	15.0%	0.0%	1.9%	9.4%	15.0%
Equipment	0.0%	1.5%	7.7%	12.3%	0.0%	1.5%	7.7%	12.3%	0.0%	1.5%	7.7%	12.3%	0.0%	1.5%	7.7%	12.3%
Heating	0.0%	-2.4%	-11.9%	-30.4%	0.0%	-1.9%	-10.6%	-27.6%	0.0%	-1.6%	-9.3%	-24.2%	0.0%	-1.5%	-8.3%	-21.3%
Cooling	0.0%	1.9%	9.6%	15.7%	0.0%	1.9%	8.8%	14.1%	0.0%	1.5%	8.2%	13.0%	0.0%	1.5%	7.5%	11.8%
Ventilation	0.0%	1.2%	6.1%	9.8%	0.0%	1.0%	4.7%	7.6%	0.0%	0.8%	4.1%	6.5%	0.0%	0.7%	3.5%	5.6%

	Raised Floor Lightweight PSZ															
	WWR 10%				WWR 21%				WWR 30%				WWR 40%			
	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%
Lights	0.0%	1.9%	9.4%	15.4%	0.0%	1.9%	9.4%	15.4%	0.0%	1.9%	9.4%	15.4%	0.0%	1.9%	9.4%	15.4%
Equipment	0.0%	1.5%	7.7%	12.3%	0.0%	1.5%	7.7%	12.3%	0.0%	1.5%	7.7%	12.3%	0.0%	1.5%	7.7%	12.3%
Heating	0.0%	-1.7%	-10.5%	-22.5%	0.0%	-1.7%	-11.3%	-24.9%	0.0%	-1.6%	-10.6%	-23.4%	0.0%	-1.5%	-10.1%	-22.4%
Cooling	0.0%	1.9%	9.6%	15.7%	0.0%	1.7%	8.7%	13.8%	0.0%	1.7%	8.2%	13.1%	0.0%	1.6%	7.8%	12.4%
Ventilation	0.0%	1.2%	6.1%	9.7%	0.0%	0.9%	4.7%	7.4%	0.0%	0.8%	4.1%	6.5%	0.0%	0.7%	3.6%	5.8%

	Heavyweight PSZ															
	WWR 10%				WWR 21%				WWR 30%				WWR 40%			
	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%
Lights	0.0%	1.9%	9.4%	15.0%	0.0%	1.9%	9.4%	15.0%	0.0%	1.9%	9.4%	15.0%	0.0%	1.9%	9.4%	15.0%
Equipment	0.0%	1.5%	7.7%	12.3%	0.0%	1.5%	7.7%	12.3%	0.0%	1.5%	7.7%	12.3%	0.0%	1.5%	7.7%	12.3%
Heating	0.0%	-1.3%	-10.9%	-29.5%	0.0%	-2.0%	-10.6%	-27.9%	0.0%	-2.1%	-9.9%	-25.3%	0.0%	-1.6%	-8.5%	-22.0%
Cooling	0.0%	1.0%	4.5%	7.2%	0.0%	1.8%	9.1%	14.5%	0.0%	1.6%	8.3%	13.4%	0.0%	1.4%	7.5%	12.0%
Ventilation	0.0%	1.3%	6.5%	10.4%	0.0%	1.0%	4.9%	7.8%	0.0%	0.8%	4.1%	6.6%	0.0%	0.7%	3.5%	5.6%

Table I-20. Chicago PVAV: Percentage-Based Energy Reduction of Space5-1 OBC on Total Loads

	Reference PVAV															
	WWR 10%				WWR 21%				WWR 30%				WWR 40%			
	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%
Lights	0.0%	1.9%	9.4%	15.0%	0.0%	1.9%	9.4%	15.0%	0.0%	1.9%	9.4%	15.0%	0.0%	1.9%	9.4%	15.0%
Equipment	0.0%	1.5%	7.7%	12.3%	0.0%	1.5%	7.7%	12.3%	0.0%	1.5%	7.7%	12.3%	0.0%	1.5%	7.7%	12.3%
Heating	0.0%	0.1%	1.1%	2.3%	0.0%	0.2%	2.0%	3.9%	0.0%	0.6%	3.5%	6.1%	0.0%	0.9%	4.8%	8.4%
Cooling	0.0%	1.7%	8.1%	11.6%	0.0%	1.4%	6.8%	9.7%	0.0%	1.2%	5.7%	8.1%	0.0%	1.0%	4.8%	6.8%
Ventilation	0.0%	1.6%	7.4%	9.1%	0.0%	1.3%	5.8%	7.0%	0.0%	1.1%	5.0%	6.0%	0.0%	0.9%	4.3%	5.0%

	Raised Floor Lightweight PVAV															
	WWR 10%				WWR 21%				WWR 30%				WWR 40%			
	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%
Lights	0.0%	1.9%	9.4%	15.4%	0.0%	1.9%	9.4%	15.4%	0.0%	1.9%	9.4%	15.4%	0.0%	1.9%	9.4%	15.4%
Equipment	0.0%	1.5%	7.7%	12.3%	0.0%	1.5%	7.7%	12.3%	0.0%	1.5%	7.7%	12.3%	0.0%	1.5%	7.7%	12.3%
Heating	0.0%	-2.8%	-2.8%	0.4%	0.0%	-3.5%	-3.7%	-0.4%	0.0%	-3.9%	-4.3%	-0.5%	0.0%	-4.1%	-4.4%	-0.4%
Cooling	0.0%	1.4%	7.3%	11.9%	0.0%	1.1%	5.8%	9.1%	0.0%	1.0%	5.2%	8.2%	0.0%	0.9%	4.8%	7.5%
Ventilation	0.0%	1.7%	7.9%	10.1%	0.0%	1.4%	6.5%	8.4%	0.0%	1.3%	5.9%	7.6%	0.0%	1.2%	5.3%	6.9%

	Heavyweight PVAV															
	WWR 10%				WWR 21%				WWR 30%				WWR 40%			
	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%	OBC 100%	OBC 90%	OBC 50%	OBC 0%
Lights	0.0%	1.9%	9.4%	15.0%	0.0%	1.9%	9.4%	15.0%	0.0%	1.9%	9.4%	15.0%	0.0%	1.9%	9.4%	15.0%
Equipment	0.0%	1.5%	7.7%	12.3%	0.0%	1.5%	7.7%	12.3%	0.0%	1.5%	7.7%	12.3%	0.0%	1.5%	7.7%	12.3%
Heating	0.0%	0.2%	1.3%	2.7%	0.0%	0.2%	1.9%	3.7%	0.0%	0.7%	3.1%	5.9%	0.0%	0.7%	4.3%	7.9%
Cooling	0.0%	1.8%	8.9%	12.5%	0.0%	1.5%	7.2%	10.2%	0.0%	1.3%	6.0%	8.6%	0.0%	1.1%	5.0%	7.1%
Ventilation	0.0%	1.6%	7.5%	8.9%	0.0%	1.4%	6.1%	7.3%	0.0%	1.1%	5.2%	6.1%	0.0%	1.0%	4.3%	5.1%