INTEGRATING ACCLIMATED KINETIC ENVELOPES INTO SUSTAINABLE BUILDING DESIGN

A Dissertation

by

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ABSTRACT

The building envelope is one of the most important design parameters for determining how the indoor physical environment relates to thermal comfort, visual comfort, and even occupants' working productivity. Thus, the building envelope significantly affects the energy usage of a building. In an effort to simultaneously consider and satisfy all of the various indoor comfort requirements, changing climatic conditions can generate conflicting conditions. Acclimated Kinetic Envelope (AKE) is a notion proposed in this research to address these types of situations.

There have been a number of experimental designs and practices dealing with the potential benefits of AKE. However, there has yet to be a detailed comparison in terms of the various impacts on building energy, indoor comfort, and other human factors, especially in different climates. The general objective of this research was to evaluate AKE's performance on energy usage and human factors, and compare that information to CEE's in office buildings in four different climatic zones. The research methodology had two key elements: energy simulations and mockup surveys. With respect to energy use, the research employed a parametric simulation to assess building heating and cooling loads, the effects of envelope assemblies, and the overall building energy use related to the two types of envelopes (AKE and CEE). With respect to human factors, the research adopted mockup tests and surveys to evaluate the visual qualities and human responses of the two types of blind systems strategies (AKE and CEE).

This research determined the following: 1) Compared to the other referenced models, AKE technologies significantly reduced the heating and cooling loads and peak demands of buildings, even with regards to designs using highly-insulated glazing and walls, in the representative climates. 2) Kinetic windows played a more significant role in energy saving than other kinetic elements existing in the four representative climates; the savings were approximately twice as large as the savings from highly-insulated glazing. 3) Only cooling-dominated climate installations were able to obtain energy savings by setting up external movable blinds. 4) Mockup survey results showed that overall satisfaction with the visual quality created by external movable blinds was statistically higher than the satisfaction related to external static blinds. Similar trends were also found in the subjective responses to “Lighting Levels, Lighting Distributions, and Glare Sensation.”

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"I can do all things through Christ which strengthens me." (Philippians 4:13).

NOMENCLATURE

AEDG	Advanced Energy Design Guide
AKE	Acclimated Kinetic Envelopes
ANOVA	one-way analysis of variance
ANSI	American National Standards Institute
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BIPV	Building-integrated photovoltaic
BIM	Building Information Modeling
CAV	constant air volume
CBE	Center for the Built Environment
CBECS	Commercial Buildings Energy Consumption Survey
CDD	cooling degree days
CEE	Conventional Energy-efficient Envelopes
CGI	CIE Glare Index
DGI	Daylight Glare Index
DGP	Daylight Glare Probability
DGR	Daylight Glare Rating
DOAS	dedicated outdoor air system
DOE	Department of Energy
EC	electrochromic coatings

EMS	Energy Management Simulation
EPA	Environmental Protection Agency
Erl	*EnergyPlus* Runtime Language
EUI	energy use index
HDD	heating degree days
HDR	high dynamic range
HVAC	heating, ventilation, and air conditioning
IEQ	indoor environmental quality
IES/IESNA	Illuminating Engineering Society of North America
IRB	Institutional Review Board
LEED	Leadership in Energy and Environmental Design
LBNL	Lawrence Berkeley National Laboratory
LPD	lighting power density
NREL	National Renewable Energy Laboratory
PNNL	Pacific Northwest National Laboratory
PV	Photovoltaic
SEER	seasonal energy efficiency ratio
SHGC	solar heat gain coefficient
SWH	service water heating
TAMU	Texas A&M University
TSD	technical support document
UGR	Unified Glare Rating

USGBC	US Green Building Council
VAV	variable air volume
VCP	Visual Comfort Probability
VIP	vacuum insulation panels
VT	visible transmittance
WWR	window-to-wall ratio
ZEB	zero-energy building

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CHAPTER I

INTRODUCTION

1.1 Background

The use of mechanical devices may make highly conditioned buildings insensitive to the environment, uncoupling the building envelope from its role as an environmental moderator. However, this ignores the nature of sustainable buildings to acclimate (or climatically respond) to the environment and take full advantage of the positive influences found in nature. The building envelope is one of the most important design parameters for determining the indoor physical environment as it relates to thermal comfort, visual comfort, and even occupants' productivity; as a result, it radically affects a building's energy usage (Berkoz & Yilmaz, 1987; Lee et al., 2006; Oral & Yilmaz, 2003). In particular, the thermophysical and optical properties of building envelopes are the key factors defined by the material and geometry of building envelope components. As interest increases in net-zero energy buildings, even the current high performance envelopes fall short. Most available building envelopes are static, whereas climatological boundary conditions and user preferences are constantly changing. Some requirements, especially in response to changing climatic circumstances, can even create conflicting conditions (e.g., negative solar heat gains vs. desired sunlight, lower wall insulation vs. appropriate air temperature, etc., as shown in Table 1.1). As a result, envelope designs often provide less than optimal building performance within certain climatic situations.

Table 1.1. Conflicting conditions on climate and indoor requirements

Climatic variables	Conditions	Indoor temperature T_{in}		
		Over-low temperature ($T_{in}<T_{\lambda}$)	Comfortable range T_{λ}	Over-high temperature ($T_{in}>T_{\lambda}$)
Solar radiation		+	-	-
Air temperature	$T_{out}> T_{in}$	+	-	-
	$T_{out}= T_{in}$	/	/	/
	$T_{out}<T_{in}$	-	-	+
Natural light	/	+	+	+
Natural wind	$T_{out}> T_{in}$	+	-	-
	$T_{out}= T_{in}$	/	+	/
	$T_{out}<T_{in}$	-	-	+

Note: T_{λ} is the comfortable range of temperature; T_{out} is the outside temperature; T_{in} is the inside temperature. “+” refers to positive effects to indoor physical conditions, “-” refers to negative effects to indoor physical conditions, and “/” refers to neutral effects. Here, the symbols “+”, “-” and “/” are for general situations of buildings rather than all circumstances.

Over the last two decades, architectural solutions incorporating technology and material science have been explored to deal with some of these conflicting situations. Another way of improving building energy efficiency would be to develop kinetic building envelope systems that could alter their thermal and optical properties according to seasonal/daily climatic variations. These Acclimated Kinetic Envelopes (AKE) systems or modules range from a simple, automated blind for facilitating daylighting, to smart glazing, variable wall insulation, sliding walls, movable roofs, solar tracking building-integrated photovoltaics (BIPVs), and other active components. These kinetic properties are designed to resolve conflictive performance objectives in real time, as can be seen in Table 1.1. For example, solar heat gains are positive when the indoor environment is under heating conditions, but negative under cooling conditions. Some days may have both heating and cooling requirements, depending upon the indoor activities and other requirements. Integrating kinetic sunscreen systems or smart glazing technology may resolve such conflictive situations.

If we scan the literature related to the kinetic characteristics of buildings, it is easy to notice a number of closely associated terms such as dynamic, climate responsive, active, intelligent, climatic adaptive, smart, interactive, high performance, and so on. In order to avoid ambiguity, this research has adopted two terms: “acclimate” and “kinetic.” The term “acclimate” is from the field of biology and refers to a process whereby an individual organism adjusts to a gradual change in its environment (such as a change in temperature, humidity, etc.) through morphological, behavioral, and physical changes (Gatten, Echternautch, & Wilson, 1988). The term "kinetic," on the other hand, finds its origin in the Greek word κίνησις (kinesis), pertaining to or associated with motion; it indicates an organism’s response to a particular kind of stimulus in biology (Kendeigh, 1961). In 1970, Professor William Zuk (1970) described kinetic architecture as referring to building components or whole buildings with the capacity to adapt to changes through a use of kinetics in reversible, deformable, incremental, and/or mobile modes.

The Acclimated Kinetic Envelopes (AKE) discussed in this research are defined as envelopes responding to variable climatic environments and changing indoor performance requirements by means of their visible physical behaviors. Through these behaviors, building envelopes may affect the use of building energy and the experiences of the indoor occupants. Accordingly, the scope of this research was developed from the convergence of two key boundaries:

- The properties of building envelopes should be kinetic rather than static.
- Kinetic features should be related to climatic conditions and indoor environmental requirements rather than pure interactive aesthetics.

1.2 Problem Statement and Research Objectives

1.2.1 Problem Statement

There have been a considerable number of experimental designs and practices focused on the potential (e.g., possible energy savings, reduction of peak demands, indoor comfort levels, etc.) of AKE. However, AKE also introduces a new complexity in understanding and evaluating the impact of building envelopes on building energy and building occupants.

Researchers of Lawrence Berkeley National Laboratory (LBNL) Building Technologies Division have undertaken extensive efforts in studying two projects involving electrochromic glazing and automated blinds (e.g., Lee, et al., 1994; Lee & Selkowitz, 1998; Lee, et al., 2005; Lee et al., 2006; Lee & Tavil, 2007). On one hand, LBNL's simulation work for these projects did not deal specifically with any of the kinetic features of the opaque parts of building envelopes, but rather only window systems. On the other hand, LBNL's mockup surveys were mainly used to generate visual comfort mathematical models for different window systems, rather than comparisons between different kinetic and static window systems. Therefore, there are currently no comprehensive studies (including those on energy and/or human responses) that focus on comparative studies between AKE and CEE on building models across different climates.

Because of this lack of fundamental comparisons of AKE and CEE, some challenges, barriers, and even failures regarding design, technology, cost, and maintenance exist in the current applications of AKE (Hoffman & Henn, 2008; Moloney, 2009; Sullivan, 2006; Zerkin, 2006). All of these barriers can be traced back to the central issue of whether or not the bottom line incremental inputs (initial costs, operating and maintenance support, etc.) for AKE solutions can be justified on the basis of energy savings, increased occupant indoor comfort and performance, and the possible enhancement of amenities for a given building's application and climate. In other words, as compared to the Conventional Energy-Efficient Envelope (CEE) (defined as a conventional, energy-efficient design solution with static properties), the question is whether kinetic strategies of building envelopes can lead to better building performance across all climates, especially with regards to energy use and occupant experience.

The lack of comparative studies has led to a significant level of uncertainty regarding the benefits of such new building envelope technologies. Therefore, there is a real demand for a clearer and more fundamental understanding of AKE, as well as a comparative evaluation with regards to building performance (in terms of both the energy and non-energy aspects) for AKE and CEE solutions across different climatic conditions. However, few studies have attempted a detailed comparative study in terms of the impacts on building energy, indoor comfort, and other human factors, especially in different climates.

1.2.1 Research Objectives

The general purpose of this study was to evaluate AKE's performance with regards to energy usage and human factors, as compared to CEE in office buildings in four climatic zones. To achieve this general objective, the research aimed at addressing the following specific issues:

- Describing the typologies, features, and mechanisms of kinetic building envelopes responding to climates;
- Identifying the methods of modeling and simulating AKE's energy performance;
- Exploring the energy savings of kinetic envelope assemblies of AKE in different climates relative to CEE; and
- Analyzing the benefits of human factors beyond energy-centric performances of AKE, relative to CEE.

1.3 Conceptual Framework

More variables exist in AKE systems than CEE systems. Linked to the problem statement, a conceptual framework must be laid out to demonstrate all research variables and the relationships among these variables. All of the significant factors were considered and assembled according to the independent variables, mediate variables, moderator variables, and dependent variables, and in turn were organized into a conceptual framework (see Figure 1.1). As shown in Figure 1.1, the independent variables deal with building envelope characteristics (which may include both kinetic and static characteristics) and the dependent variables are the envelope-related performance variables, including energy consumption, occupant comfort, satisfaction, and acceptance. Building envelopes act as a mediator, which accounts for the relationships among the properties of building envelopes and the envelope-related performance. Thus, an analysis on the functions of AKE was central to this research. Site and climate variables play the role of moderator, affecting the relationships among the properties and functions of building envelopes.

By mapping the variables, we also were able to categorize them into three types of parameters regarding design, context, and performance (Rittel, 1973), as seen in Figure 1.2. This simpler categorization contributed to the case study, simulation, and evaluation process.

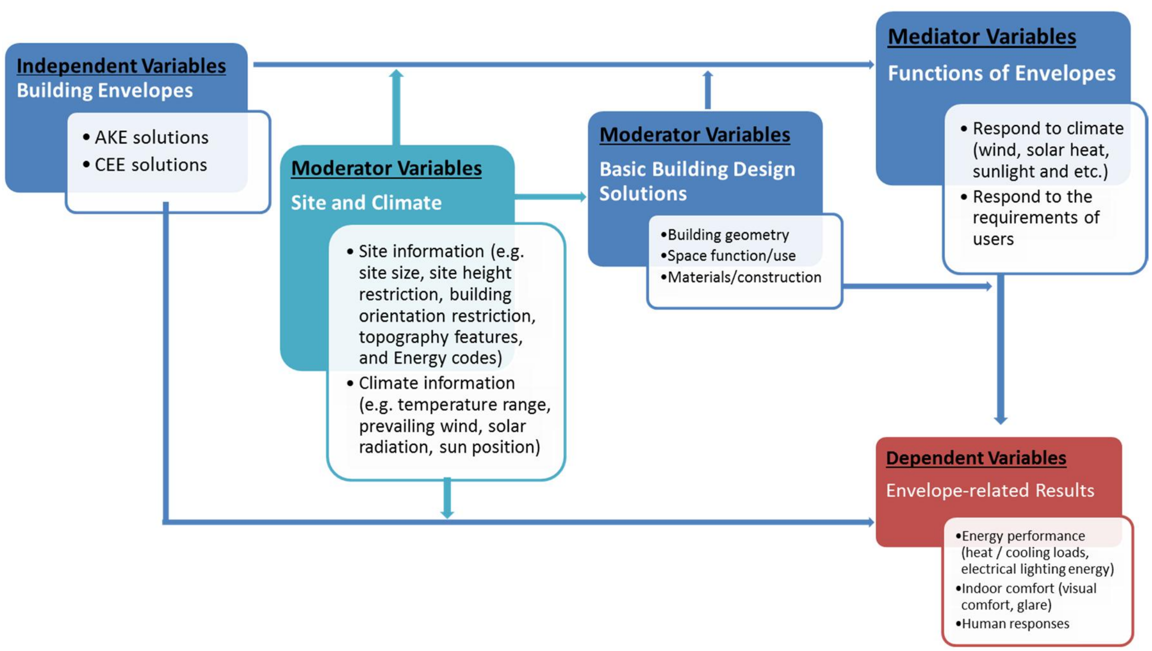


Figure 1.1. The conceptual framework for this study with dependent, independent, moderator, and mediator variables

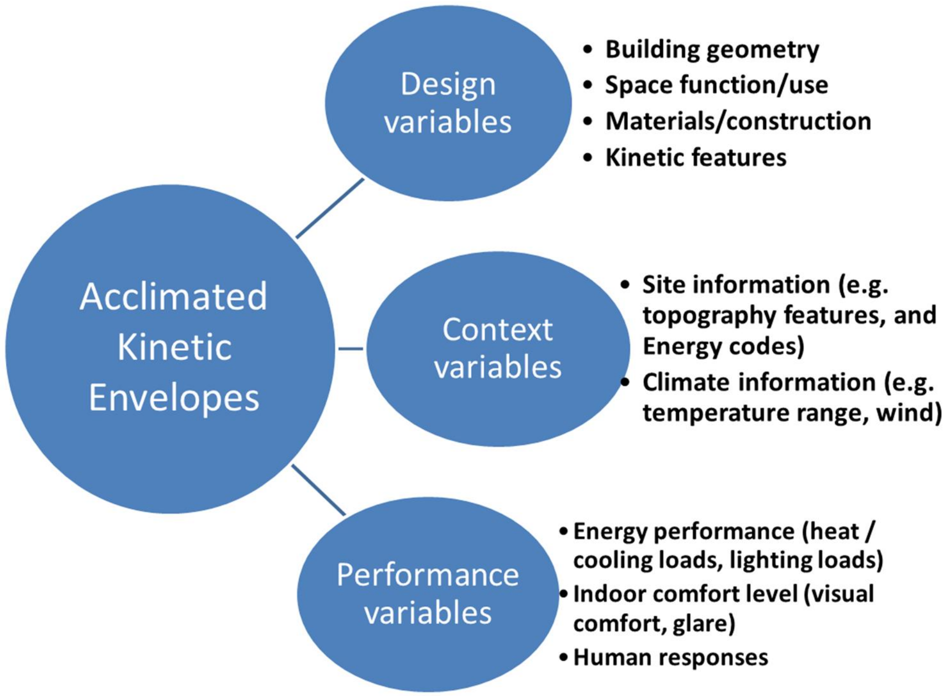


Figure 1.2. Rittel's variable categorization applied to AKE

The conceptual framework set the stage for our presentation of the specific variables and relationships related to this research. It also drove the research hypothesis, which was: under certain site and climate conditions, appropriated acclimated kinetic building skin solutions may enhance the building performance in terms of both building energy and indoor environmental comfort.

1.4 Research Methodology

In order to evaluate the above effects, the research methodology was divided into two aspects: an energy simulation and surveys. The entire procedure of the research plan is presented in Figure 1.3.

In terms of energy uses, this research utilized a parametric simulation to assess a building's heating and cooling loads, the effects of envelope assemblies, and the entire building's energy uses as they related to the two types (AKE and CEE) of envelopes' properties.

With regards to human factors, this research adopted mockup tests and surveys to assess the visual qualities and human responses to the two types (AKE and CEE) of blind systems.

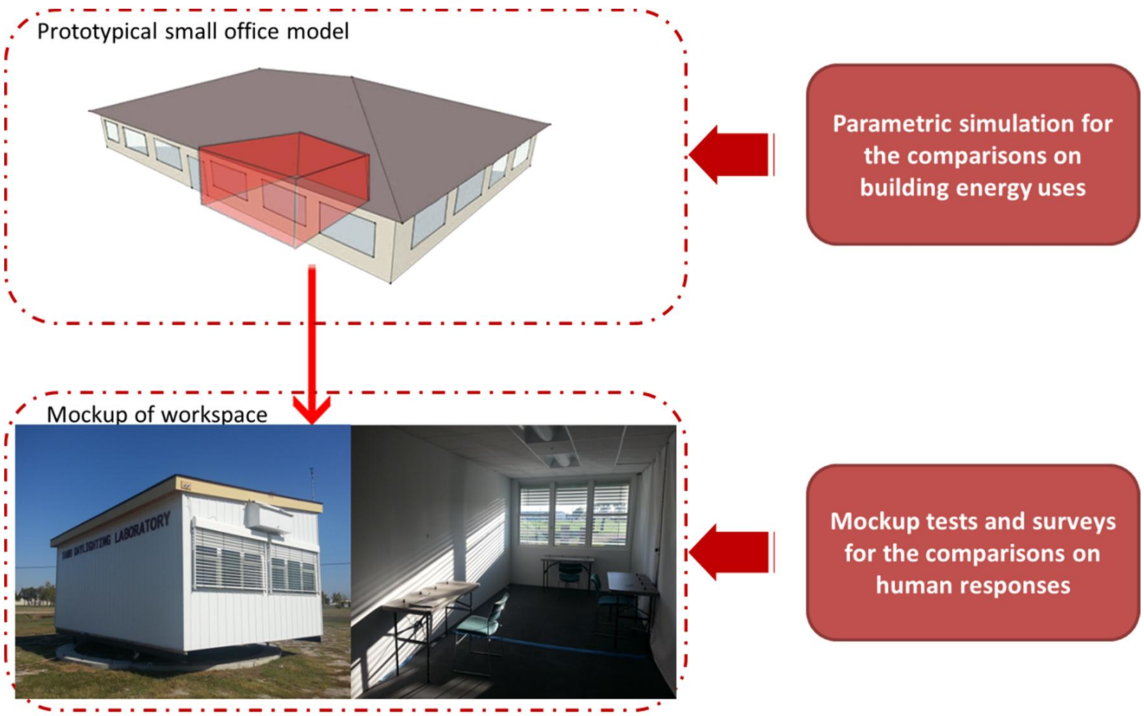


Figure 1.3. The two aspects of this research and the corresponding methods

1.4.1 Building Energy Simulation

In order to evaluate the potential energy savings of kinetic building envelopes, it was necessary to conduct a comparative simulation study. This study utilized a small office prototype model of 5,500 ft^2 developed by the Pacific Northwest National Laboratory (PNNL) in four selected cities. These cities represented a range of climates: Houston, TX (Climatic zone number 2A), San Francisco, CA (Climatic zone number 3C), Baltimore, MD (Climatic zone number 4B), and Chicago, IL (Climatic zone number 5A). The climatic zone numbers referred to the ASHRAE climatic zones (ASHRE, 2011).

The energy savings evaluation used the following energy simulation programs: *EnergyPlus* (DOE, 2013), *Energy Management System (EMS)* (Ellis, 2007) and *jEPlus* (Zhang, 2009). The particular methods used to produce the energy simulation and the modeling of the kinetic envelopes are shown in Table1.2.

Table 1.2. Programs used in simulation study

Models	**Components**	**Programs**
Reference Models	Building envelopes	*jEPlus* and *EnergyPlus*
Kinetic Models	Walls and roofs	Variable Thermal Conductivity of *EnergyPlus* and *jEPlus*
	Fenestration	EMS of *EnergyPlus*
	External Movable blinds	Built-in features of blinds

These modeling and simulation methods were adopted to evaluate the potential benefits of the Kinetic Models with kinetic envelope systems; additionally they were used to compare hypothetical future systems to the following three models: 1) Baseline Models with minimal compliance -- ASHRAE Standard 90.1-2010; 2) Advanced Models that use the recommendations in ASHRAE's Advanced Energy Design Guideline (AEDG) for small to medium office buildings, and Technical Support Documents (TSD) created by PNNL with 50% energy saving goals as compared to ASHRAE Standard 90.1-2010; and 3) Ultra[1] Models that may be the next generation of energy efficient technologies with "ultra" insulation, but with static properties rather than dynamic characteristics. In this comparative study, neither the kinetic envelope assemblies of the Kinetic Models nor the envelope properties of the Ultra Models were currently available, but they represented technologies that might realistically be developed in the next decade. The detailed research plan included the following steps:

1) Select Prototypical Small Office Models

The prototypical small office models examined in this study belonged to sixteen reference models developed by the U.S. Department of Energy (DOE) in conjunction with three of its national laboratories -- Pacific Northwest National Laboratory (PNNL), National Renewable Energy Laboratory (NREL), and Lawrence Berkeley National Laboratory (LBNL); the models formerly were known as commercial building benchmark models. This study selected the prototypical models specifically developed according to ASHRAE Standard 90.1-2010, which should have resulted in a 30% energy

[1] "Ultra" here means much higher levels of insulation of opaque materials and glazing than normal.

savings relative to 90.1-2004.

2) Create Baseline Models and Simulated Energy Performance

The baseline energy level was simulated in accordance with the standards provided by ASHRAE 90.1-2010.

3) Create Advanced Models and Simulated Energy Performance

Based on ASHRAE's AEDG and PNNL's TSD for 50% energy saving goals relative to ASHRAE Standard 90.1-2004, the envelope components of the advanced models were improved. Other parts (e.g., HVAC, internal loads, and schedules) kept the settings of the Baseline Models.

4) Create Ultra Models and Simulated Energy Performance

The third referenced model represented further improvements in envelope technologies, which likely are superior to most existing efficient envelopes. In particular, these models were defined to have super-insulated walls, roofs, and windows. Also, the windows' SHGC had two levels, according to different climates; one had high solar heat gains, and the other had low solar heat gains. However, all envelope properties in these models were static.

5) Create Kinetic Models and Simulated Energy Performance

We proposed kinetic envelope models that took certain characteristics of Ultra Models, and then added dynamic properties. The kinetic envelope components included: "Variable Insulation for Opaque Assemblies (walls and roofs)," "Dynamic Windows and Glazing," and "Movable Blinds." These simulation techniques for these models were combined built-in *EnergyPlus* functions and EMS which was used to set up the relationships among the dynamic properties and the external or internal environmental conditions. Also, *jEplus* was employed to identify the boundaries of the changes.

6) Evaluate Energy Savings in Four Climatic Conditions

This step compared the energy performance of the above four models in four selected cities; the cities were located in a heating-dominated climate, a cooling-dominated climate, and a mixed-climate.

7) Determine the Effects of the Kinetic Envelope Assemblies

In order to understand the energy benefits from each kinetic envelope element, a comparative energy performance analysis was conducted for each envelope component including walls, roofs, windows, and blinds in four selected cities.

1.4.2 Workspace Mock-up Tests and Surveys

In order to take non-energy benefits into account in the comparisons, this study selected a typical workspace of the aforementioned prototypical office model and focused on the study of human responses and indoor visual quality. The main methods utilized are described below:

1) Set up a Mockup with Two Workspaces

This study took place at the new TAMU Daylighting Laboratory which is a full scale mockup 360 degrees-rotating workspace structure built at the Riverside campus of Texas A&M University in Bryan, Texas (30°39′56″N 96°22′0″W). The daylighting lab was funded by a grant from the Environmental Protection Agency (EPA P3 program) (EPA, 2010). The structure is an elevated room over four casters that measured 30 ft. deep by 20 ft. wide and 10 ft. high. The space was designed to be divided into two identical rooms (10 ft. × 16 ft.), representing small open-plan offices. The two identical rooms had same-sized windows, glazing materials, and the same indoor setup of materials, desks, and chairs. The only difference between the two spaces was the windows' external blinds; one room was used external movable blinds, and the other was used external static blinds. Ideally, the movable blinds could be adjusted to fit the angles in order to accommodate various external lighting conditions and offer glare protection, while at the same time maintaining a limited view through the space between the blinds. Figure 1.4 shows the three desks (24 in. width, 48 in. length, and 29 in. height) that were placed in each room. One desk faced the window, and the other two desks faced the walls. The room had an air conditioning unit to maintain comfortable temperatures (70-75ºF) in the two rooms so that thermal conditions would not affect the subjects' responses to questions regarding visual quality.

Furthermore, the entire mockup structure could be rotated to satisfy the requirements of different orientations for measurements and surveys. The rotation enabled the mockup structure to be exposed to different solar positions and external lighting conditions.

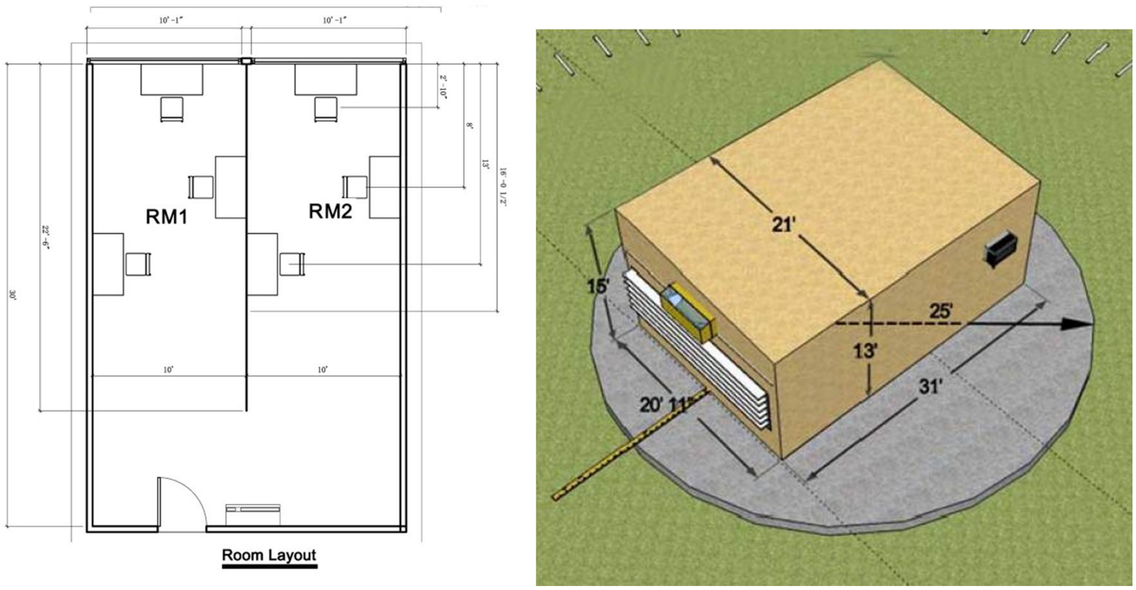


Figure 1.4. Rotatable daylighting lab

2) Set up Measurement Tools

The measurement tools in this study included 28 lighting sensors and one luminance meter. Regarding the illuminance data, 24 lighting sensors were horizontally placed on the desks, and connected to a CR1000 Campbell Scientific datalogger which was located in between the two workspaces. Also, there were two vertical illuminance sensors located at eye level (48 in.). In order to record the external lighting conditions, we installed two sensors on the roof of the lab to measure horizontal and vertical global illuminance.

3) Surveys on Occupants' Comfort, Satisfaction, and Acceptance

A subjective survey was carried out to assess the visual environment created by the external movable blinds (kinetic system). This survey study was of a two group, posttest-only, randomized experimental design. The study was carried out between the end of September and early October of 2013. Sixty subjects were selected for this mockup study (30 people were in the experimental group (RM2) and another 30 were in the control group (RM1)). Subjects were asked to fill out a 7-point rating scale questionnaire (see Appendix A) after spending about 30 minutes in one of the workspaces.

Subjects in the experimental group's room (RM2) were offered motorized external blinds which operated according to lighting sensors, an embedded computational system, and user preferences. Except for the operation mode of the blinds, all settings related to windows, glazing, blind geometry, furniture, room color, and other factors were identical to the control group's room (RM1). Subjects in the experimental group were not offered any controls for the blinds. People assigned to the control group, on the other hand, had external static blinds. No other aspects of the procedure for either group were controlled by the study protocol. Subjects were not told about the difference in blind types between the two rooms.

The data collected from questionnaires were used for conducting statistical analysis via SAS JMP 10.0. An independently paired sample *t-test* and a Chi-square test were used to compare the measures of the control and experimental groups. The confidence interval was 95%. A $p < 0.05$ was considered to be statistically significant.

1.4.3 Connection of Energy Simulations and Mockup Tests

On the one hand, the parametric energy simulation for kinetic properties aimed at an evaluation of the kinetic envelopes including opaque assemblies, windows, and blinds.

Thus, this aspect of the study explored the energy savings of kinetic envelopes. On the other hand, the mockup tests and surveys were only employed in one part of the kinetic envelopes, the element dealing with external movable blinds for visual quality. This was because the benefits with regards to human factors stemming from the kinetic envelopes had more to do with visual comfort and thermal comfort. However, thermal comfort studies of kinetic envelopes were not conducted in this research because integrating kinetic insulated envelopes (e.g., smart materials) into the mockup structure would have posed a significant challenge. Most existing kinetic insulated envelopes are expensive and/or difficult to maintain, and they only work with a limited range of changes for kinetic properties. For example, the visible transmittance (VT) and solar heat gain coefficient (SHGC) of existing thermochromic glazing materials were ranged 0.05~0.60 and 0.09~0.42, respectively (Lee et al., 2006). These two parameters were strongly correlated to each other. For mockup tests and surveys, therefore, it was difficult to find appropriate kinetic products with dynamic features similar to those proposed in this study. Movable blinds were adopted as a typical kinetic system in our human factor studies. The following four points show the links between the two key aspects (energy simulation and mockup surveys) in this study.

Firstly, each workspace in the mockup structure made up one unit of the building, and the geometry related to the space's width, depth, height, window size and other factors was in accordance with the energy simulation prototypical model. Also, the indoor visual characteristics related to the reflection of the walls, ceiling, and floors were identical for the energy models and the mockup workspaces.

Secondly, the reference point for using daylight and dimming lights in the energy simulation model was located at the same point (height and distance to the windows) in the real world mockup of the workspace.

Thirdly, regarding the blinds, the dimensions (slat width, spacing, and distance to the glazing) and properties (materials, rotation mechanisms, and controls) in the mockup structure were consistent with the energy simulation model.

Lastly, the entire mockup structure was rotatable a full 360 degrees. By using this rotation and selecting a particular time, we generally could obtain the solar conditions in different locations, including the four cities that were selected for conducting the energy simulations of the kinetic envelopes. Therefore, the results of the surveys in the mockup structure were able to reveal the features and the benefits of the kinetic envelopes in these selected locations.

1.5 Significance

By exploiting the comparison between AKE and CEE solutions, this research provides an understanding of the relationship among climatic variables and AKE’s kinetic properties. Accordingly, this dissertation provides a detailed technical demonstration for use in future discussions regarding the applicability of AKE technologies in particular climates. Moreover, by clarifying the comprehensive evaluation approach, this study seeks to take non-energy benefits into account with regards to AKE’s performance. Consequently, given the impacts of building envelopes on a building’s energy consumption and indoor physical environment, this research demonstrates that both energy efficiency and human wellbeing benefits can be achieved in particular buildings and certain climates.

1.6 Organization of the Dissertation

Figure 1.5 presents a summary of each chapter, including the topics covered in each. This dissertation has five chapters that are organized in the following way:

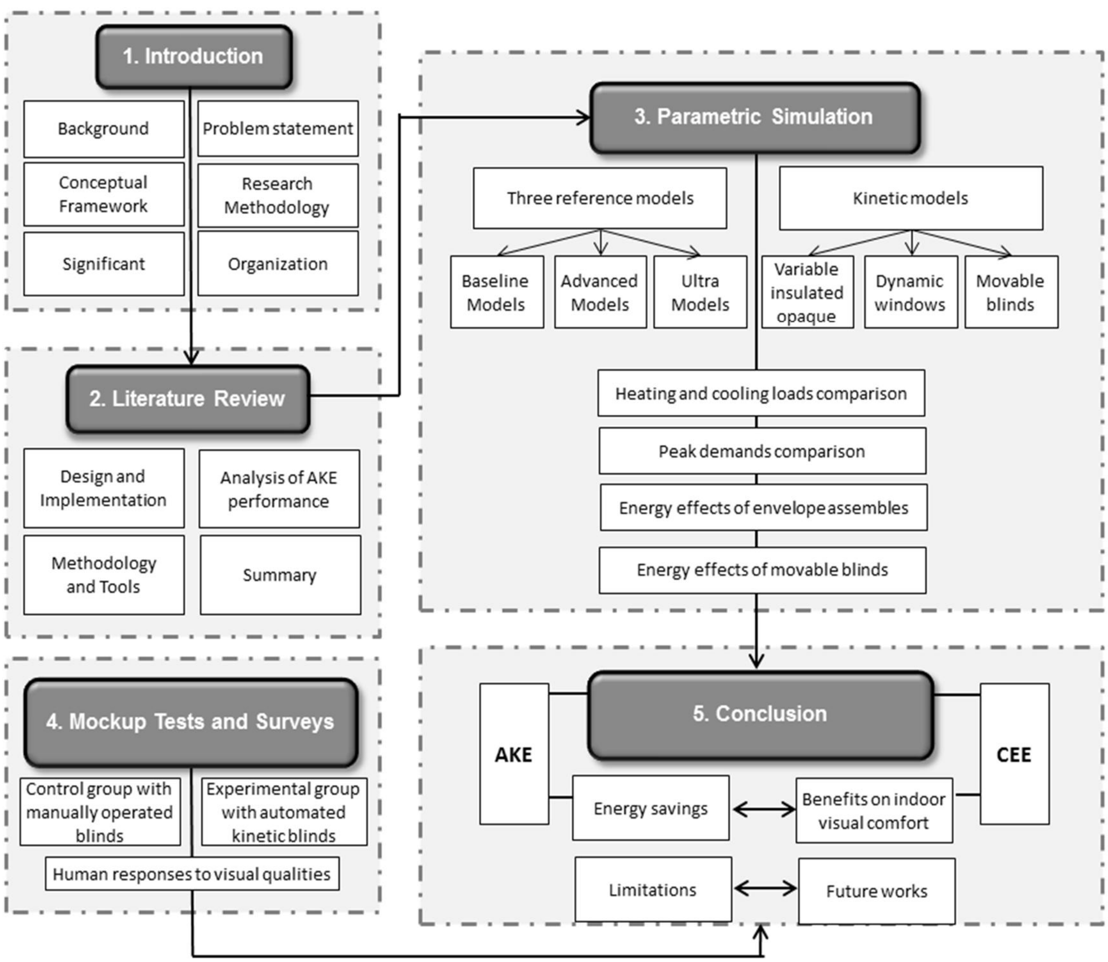


Figure 1.5. The research structure and organization

Chapter 1 – Introduction: This chapter defines the goals and purpose of this study, and presents the research objectives and methodology used to accomplish these objectives. Chapter 1 also explains the potential contributions of this study.

Chapter 2 – Literature Review: This chapter gives a general review of the fundamental knowledge currently available on kinetic architecture, current implementations and categorizations of acclimated kinetic envelopes, and identification of the critical issues with regards to surveys on indoor environmental comfort.

Chapter 3 – Parametric Energy Simulation for Kinetic Building Envelopes: This chapter is one of the two research topics central to this study. It describes and illustrates the modeling and simulation process for AKE and the associated reference models. This chapter also compares the effects of AKE and CEE in terms of heating and cooling loads, and the overall set of building energy uses. In addition, this section explores the different modeling and simulation approaches for kinetic properties.

Chapter 4 – Mockup Tests and Surveys for External Movable Blinds: This chapter discusses the other research topic central to this study, and illustrates an experimental design for assessing and comparing external movable and static blinds. This chapter also describes the mockup measurements of the visual environment by a set of instruments including lighting sensors, the datalogger, etc.

Chapter 5 – Conclusions: This chapter summarizes the main results from the energy simulations and the findings from the mockup tests and surveys, and draws conclusions based on these results. Chapter 5 also explains the limitations of this study. Lastly, this chapter proposes future research on the basis of the findings of this study.

The final part of this dissertation is a set of appendices that provide supporting materials for this study. The appendices include the questionnaires used in the mockup surveys, datalogger programming, and the lighting sensors' calibrations, as well as a list of the design and implementation cases of AKE.

CHAPTER II

LITERATURE REVIEW

A review of the existing literature is critical to understand several important aspects of acclimated kinetic buildings, as well as to locating the gaps in the current established body of knowledge. This chapter begins with some background on kinetic architecture and then reviews the primary literature in this realm, concluding with a synthesis of the surveyed literature. The research was grouped into three sub-categories: Design and Implementation, Analysis of AKE's Performance, and Methodology and Tools.

The fundamental concept of kinetic architecture can be traced back to the 1970s work *Kinetic Architecture*, by Zuk and Clark. They (1970) defined this genre of architecture as being adaptable to changing environmental conditions (not only solely to climate) and pragmatic needs. With the recent advances in embedded computation, and due to the technical development of smart materials, sensors, and actuators, there are now very few technological obstacles to making buildings and buildings' envelopes kinetic. These kinetic components can be as simple as automated blinds, or as complex as the façade system of the Institute du Monde Arab in Paris. Also, in the area of kinetic architecture, aesthetics and technology are beginning to converge. Nonetheless, the mainstream drivers behind kinetic architecture are sustainability, energy conservation, and occupant satisfaction (Sullivan, 2006).

2.1 Design and Implementation

As the development of building materials, environmental sensors and actuators, and construction technologies progresses, in recent years there have been an increasing number of examples of kinetic architecture in the real world. However, among the existing cases of kinetic architecture or envelopes, only a few can be classified as being climatically responsive. Thus, in order to clarify what AKE really is, an extensive review of AKE design and implementation cases had to be conducted. The cases of AKE discussed in this review either have already been built, or are in the experimental, research, design, or development stage.

Since AKEs are shaped strongly by climate, it makes sense to categorize them into distinct climate-responsive characteristics related to solar radiation, daylight, air flow, air temperature, and other climatic influences. These traits may exist separately in one single AKE module or be combined in some AKE systems and building design cases. Technically, an AKE can be analyzed at the system level and the building level. At the module level, the AKE mostly is designed to respond to a central climatic source, which generally refers to solar energy and air flow. Figure 2.1 shows the relationship among different modules relating to climatic sources. At the building level, there are few design cases suited to our focus on the building's environmental performance.

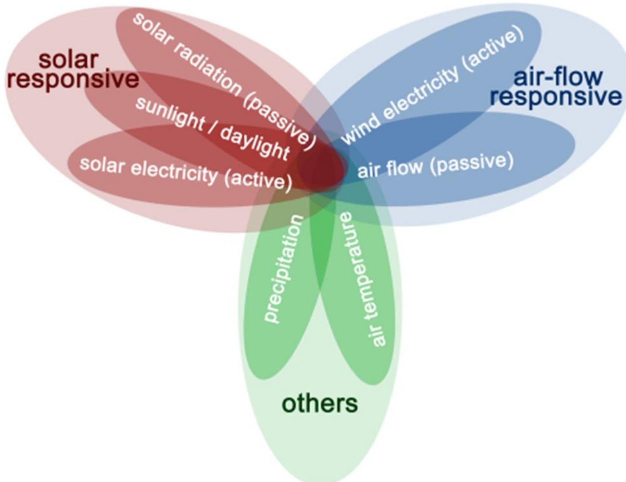


Figure 2.1. Relationships of the AKE types

2.1.1 Solar-responsive AKE

The solar conditions, including solar radiation and sunlight, form the solar-responsive AKE's kinetic behaviors; as a result, these modules fall into three basic types.

1) Solar Heat

The first type of solar-responsive AKE deals only with solar heat; it aims to maximize the acceptation of solar heat in winter and minimize solar gain in summer. The nature of this type of AKE is to alter the thermophysical properties of the module. A simple example is the Solar Barrel Wall (see Figure 2.2) designed in 1973 by Baer (2009). Functionally, the water-filled oil barrels are able to store solar heat during the day because the covered wall opens, thus subjecting the barrels to the sun. The barrels stop receiving heat when the covered wall is closed, which also diffuses the heat in the room (Knaack, Klein, Bilow, & Auer, 2007). Similarly, Jonathan Hommond's house (see Figure 2.3) uses water storage bags on the roof, and operable lids that can be opened or closed according to the needs presented by the level of external solar radiation (Anderson & Michal, 1978). On the visible scale, besides any movable components, this type of AKE also uses some smart materials. For example, thermochromic materials can change color due to temperature changes and can be designed for specific temperature ranges (Seeboth & Lotzsch, 2008). Some designs (see Figure 2.4) produced by Juergen H. Mayer use thermochromic materials to imprint the color shapes formed by human body temperature. One solution for climate design could be using the right materials on a building's surfaces to achieve the appropriate color and reflectance for responding to the outside temperature (Addington & Schtxiek, 2005). However, current available thermochromic paints for building exteriors may lose their color-changing features because of exposure to ultraviolet light (Addington & Schtxiek, 2005).

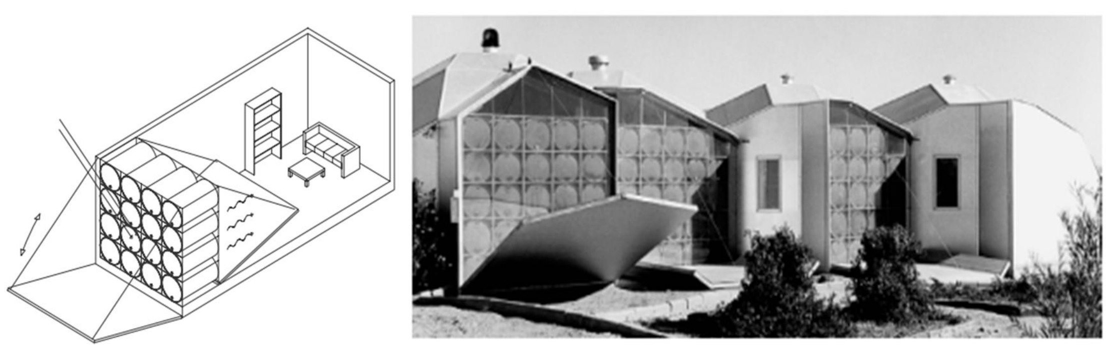


Figure 2.2. Solar barrel wall for solar heat absorption (Baer, 2009)

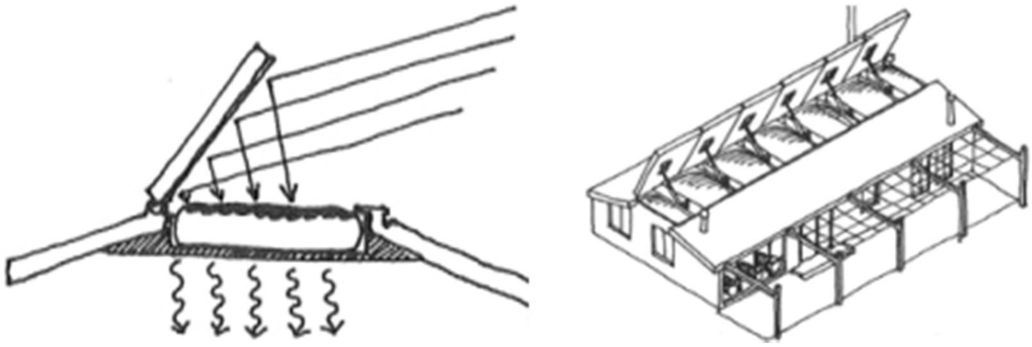


Figure 2.3. Water storage roof created by Jonathan Hommond (Anderson & Michal, 1978)

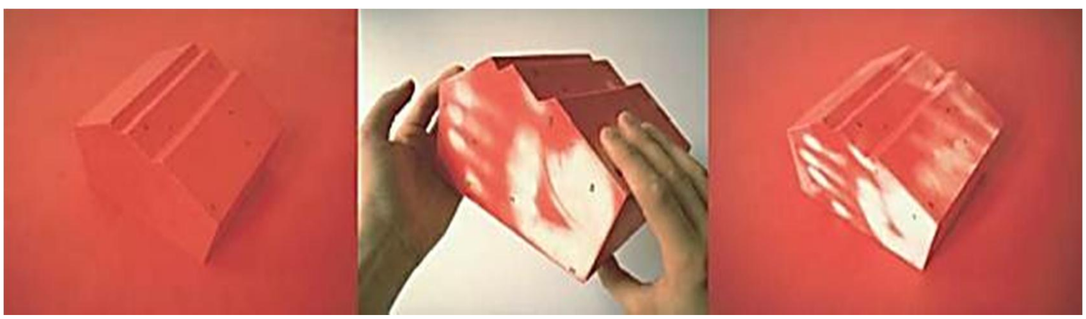


Figure 2.4. Thermochromic materials (Addington & Schtxiek, 2005)

In addition, some recent conceptual designs have combined solar-responsive AKE with bio-inspired designs. For instance, the Kinetic Honeycombed Canopy (see Figure 2.5) was designed by a BIM parametric method and was able to achieve certain kinetic features. The kinetic movements inspired by butterfly wings' honeycombed structure may maximize the acceptance of solar heat or minimize the same, based on the different seasons and solar radiation levels (Wang, 2011). Another example concerns designs inspired by the hair of mammals (see Figure 2.6), which translates the hair systems' behaviors related to temperature changes into the building surface. The adjustable system consists of water and porous materials that are able to inflate for thermal comfort (Lee, 2008).

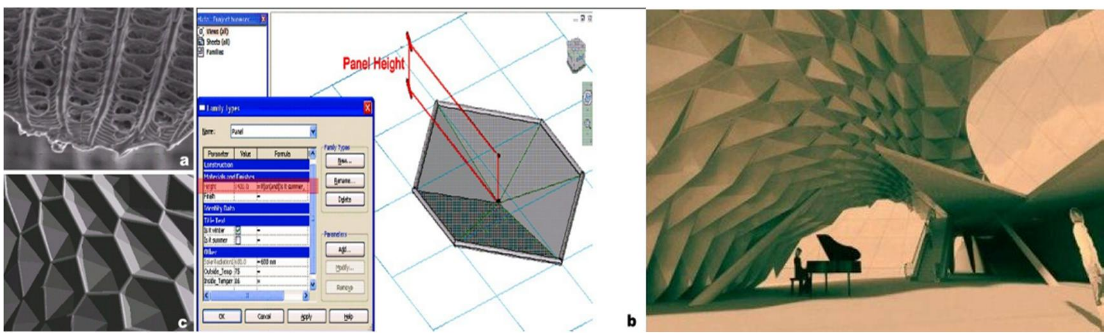


Figure 2.5. Bio-inspired kinetic honeycombed canopy (Wang, 2011)

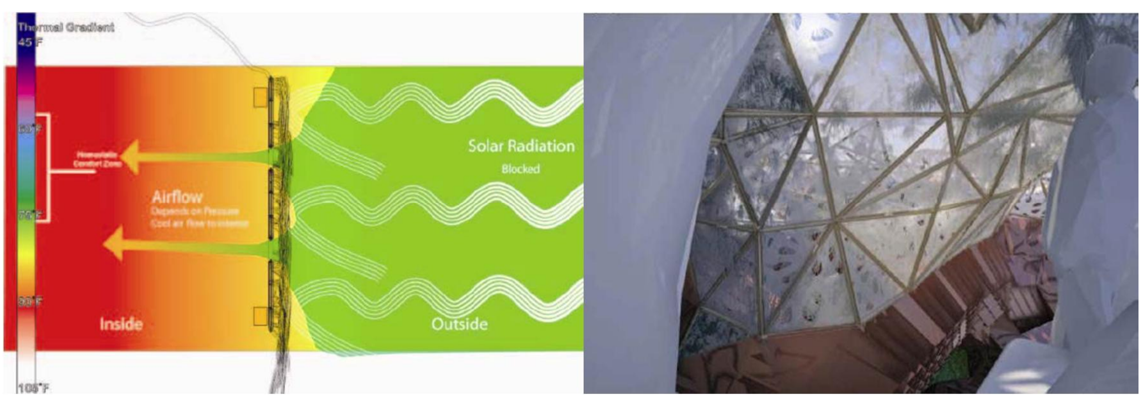


Figure 2.6. Porous inflatable water pillow (Lee, 2008)

2) Solar Light and Heat

The second type of solar-responsive AKE has more to do with daylight. These AKE systems control indoor illuminance levels, distributions, window views, and glare, particularly in museums and galleries; meanwhile, considerations concerning the control of heat from solar gain often must be taken into account (Laar & Grimme, 2002). Both the optical and the thermal properties of the AKE module are able to respond to outside lighting conditions to obtain appropriate daylighting and solar heat, and in turn may improve visual comfort, satisfaction, and productivity for occupants while minimizing their energy consumption for lighting and cooling. Currently, there is a wide array of AKE fenestration systems which are generally based on two kinetic mechanisms: mechanically driven devices and smart glazing (or translucent materials).

- Traditional Mechanical AKE

The characteristic example of traditional mechanical AKE is the venetian blind; this is a well-established technology used to control daylight and heat gain in front of, behind, or between windows (Lee & Selkowitz, 1998). Similar to motorized blinds, large scale horizontal shades were used in the Devonshire Building at the University of Newcastle. These external shades were able to rotate in a range of angles to track the amount of sunlight entering the windows, taking into account the time of day and the season.

Another representative design of kinetic shading is the double-skinned façade. It is difficult to categorize double skin envelopes because they have obvious integrated features dealing with solar radiation, daylight, and ventilation. However, most of the kinetic movement of double-skinned façades is incorporated into the shading and natural ventilation mechanisms (natural ventilation will be discussed in the next section). Motorized shades or blinds can work between double-skinned façades, as they do in the Eurotheum Building in Frankfurt (see Figure 2.7) (Hertzsch, 1998), or outside of the double-skinned façades as they do at GSW headquarters (Russell, 2000).

Figure 2.7. Eurotheum and the motorized blinds between the double skins (Hertzsch, 1998)

- Innovative Mechanical AKE

Recently, there have been many aesthetically pleasing design cases which incorporate more visible or dynamic mechanical fenestration systems and have more to do with making a visual impact on visitors and occupants. Although there have been problems with overly-involved maintenance needs and problems with functionality with Jean Nouvel’s design, it has continued to arouse the interests of architects because of its cultural symbolism and aesthetic expression. In recent years, more projects and experimental designs have incorporated visible and aesthetic AKE. The associated mechanical movements are rotational, retractable, sliding, and/or self-adjusting (Miao, Li, & Wang, 2011).

A recently completed project, Al Bahar Towers (see Figure 2.8), located in Abu Dhabi, presents an incredibly dynamic façade. The geometric patterns of the façade come from traditional Arabian culture and comprise a gigantic screen including over 1,000 movable elements. Each element can contract and expand to control glare and optimize natural light internally, depending upon the solar conditions (Cilento, 2013). Engineers on this project have stated that this kinetic sunscreen could potentially reduce the cooling load by over 20 percent, with commensurate savings in energy consumption and carbon emissions (Cilento, 2013).

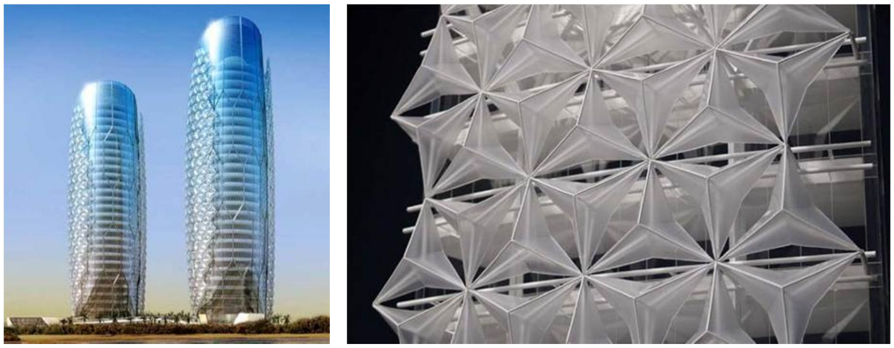


Figure 2.8. Al Bahar Towers and the kinetic sunscreen (Cilento, 2013)

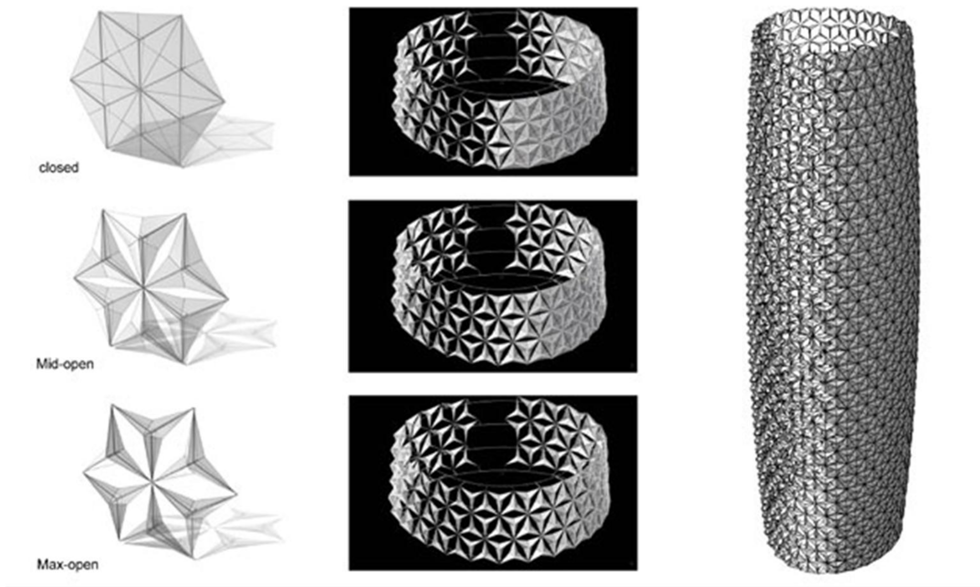


Figure 2.9. Al Bahar Towers and the kinetic sunscreen (Cilento, 2013)

Regarding sliding cases, the Sliding House project (see Figure 2.9) designed by dRMM architects, offers a creative kinetic design concept. The entire enclosure, including walls, windows, and roofs, can slide on two tracks; as a result, the house is able to adjust its thermal and visual properties according to the seasons, weather conditions, or for other aesthetic reasons (Basulto, 2009). Another sliding case is the Showroom project in Kiefer. This is a promising design and a typical case of sliding movement in that it integrates external sliding shades to form a dynamic façade sculpture for each day and hour (Vinnitskaya, 2010). An example of a retractable design is Madrid's City of Justice (see Figure 2.10) designed by Foster + Partners. The design creates a 2-D retractable hexagonal shading unit which occupies the central circular atrium and atria, and can extend to cover the roof or disappear into the structural profiles of the roof (Foster + Partners, 2012). On balance, these creative buildings and design concepts work in close conjunction with the climate and take full advantage of positive natural factors. However, currently there is little documentation of their energy performance and physical environmental comfort.

Figure 2.10. Sliding movements of the Sliding House envelope (Basulto, 2009)

Figure 2.11. Retractable roof of the High Court of Justice and Supreme Court (Foster+Partners, 2012)

- Smart Glazing or Translucent Materials

There has been extensive study of many of the switchable smart glazing or translucent materials; these materials have been developed around the world for several decades, and have had a dramatic effect on AKE and overall architectural design. As seen in Figure 2.11, these exciting optical materials (e.g., thermochromic, photochromic, electrochromic materials, etc.), used in windows, are able to change the windows' optical properties (absorptivity, reflectivity, and transmission within various wavelength ranges), lighting direction (diffraction, reflection, and refraction), visual appearance (opacity, color, and transparency) and thermophysical properties (thermal conductivity and SHGC). Among these smart materials, electrically-activated glazing for building façades has gained commercial viability and remains the most visible indicator for smart materials in a building (Addington & Schtxiek, 2005).

Figure 2.12. Examples of electrochromic glazing by LBNL (Lee, DiBartolomeo, & Selkowitz, 2000)

3) Solar Electricity

A third type of solar-responsive AKE is involved with solar electricity, which often is deemed a kind of active solar energy technique. According to this research's boundaries, this review focused on Building Integrated Photovoltaics (BIPVs) with the ability to be kinetic, rather than separated movable PV panels on buildings. The most typical type of kinetic movement is sliding or rotation, enabling panels to track a maximum amount of solar energy; this is often also called a heliotropic sun-tracking system. For instance, with the EWE Arena (see Figure 2.12) (Byabato & Müller, 2007) in Oldenburg and the Gemini Haus in Weiz, the floating shading or curtain walls are mounted PV modules that can rotate on their tracks around the building to capture a maximum amount of solar energy and, hence, maximize the electrical output. Another advantage is that PV walls also can provide shading and better daylighting performances for the interior. Similar technologies are combined with building roofs in the Sündreyer project in Treia, Germany and the B&W House.

At the module level, the Photovoltaic Leave (see Figure 2.12) offers an impressive design case. Designed by SMIT (Sustainably Minded Interactive Technology), the Photovoltaic Leave consists of a layer of thin film material on top of polyethylene, with a piezoelectric generator attached to each leaf. The light-sourcing leaves can move around and catch the solar energy to generate electrical power via both the sun and the wind. A 4×7 foot strip of this material can generate 85 Watts of solar power (SMIT, 2012).

Figure 2.13. Kinetic solar electricity design cases (Byabato & Müller, 2007; SMIT, 2012)

2.1.2 Air-flow-responsive AKE

The modules that interact with air flow are termed airflow-responsive AKE and incorporate two types: natural ventilation and wind electricity. For the former, the kinetic behavior is influenced by the air exchange and circulation for indoor thermal comfort and air quality. The latter refers to the envelopes' kinetic process that can convert wind energy into electricity. Consequently, the airflow-responsive AKE may have the ability to impact the lighting environment and the overall aesthetic sense of the space.

1) Natural Ventilation

The kinetic process correlated to natural ventilation is used to introduce proper outside air while controlling for temperature, moisture, dust, odor, and other variables in indoor rooms. In contrast with mechanical fans or ventilation systems, these AKE systems are still considered to be natural ventilation (though some systems are motorized). This type of system serves to improve thermal comfort and the acceptable level of indoor air quality, and in some cases promote better daylighting performance.

The Kinetic Roof House (see Figure 2.13) (Kawi, 2001) was first proposed in a design competition in 2001. The kinetic roof structure of this design can be opened to the sun, allowing direct sunlight into a room during daytime in the winter; it can then be closed to keep the heat inside at night. In summer, the roof can move to a particular degree to allow natural ventilation, but at the same time block out direct sunlight; at night it can be fully opened to allow for a cooler air temperature.

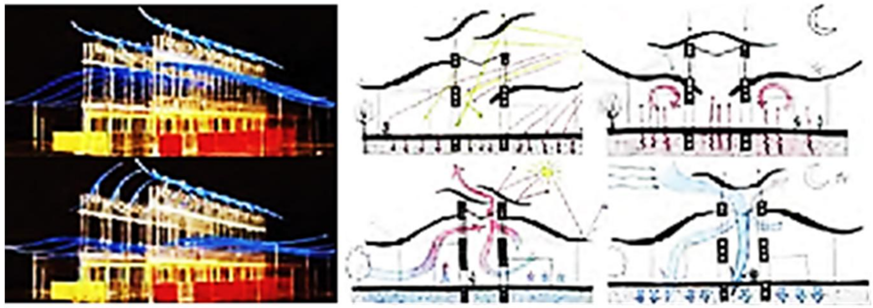


Figure 2.14. Kinetic roofs promoting natural ventilation (Kawi, 2001)

From the above analysis of double-skinned façades, it can be seen that certain kinetic movements can work toward natural ventilation, promoting air circulation within the building envelope and/or indoor rooms, and hence achieving better indoor comfort (Kolokotroni, 2011; Martin & Fletcher, 1996). A typical project of this type is the new San Francisco Federal Building (see Figure 2.14). The local climate provided architects an opportunity to take advantage of the area's natural air flow. On the building’s southeast side, external panels of double-skinned façades flip up to a 90-degree angle, allowing fresh air directly into the building (based on wind speed and direction) (Morphosis, 2011).

Figure 2.15. The double skins of the San Francisco Federal Building (Morphosis, 2011)

2) Wind Electricity

Similar to BIPVs, small scale wind turbines integrated into buildings can also be defined as forms of micro-energy generation (AS & PAB, 2006). This research focused on integrated wind turbines rather than standalone wind energy systems such as rooftop wind turbines. One of the most interesting kinetic building designs that involve wind turbines is the Dynamic Tower planned by David Fisher. Wind turbines were fitted horizontally between each floor and then used to produce electricity (Fisher, 2012).

Other well-integrated AKE cases with wind electricity include the COR Building in Miami and the Greenway Self-park Garage in Chicago (see Figure 2.15). Economic and regulatory issues aside (Bussel & Mertens, 2005), the use of existing wind turbine technologies may be problematic due to severe noise issues and difficulties in matching the structural and aesthetical integrity of existing buildings (Ayhana & Sağlamb, 2012).

Figure 2.16. Examples of the kinetic envelopes for generating wind electricity (Cilento, 2010; Minner, 2010)

2.1.3 Trends and Challenges

Current energy-efficient design strategies and technologies of building envelopes have led to significant building energy savings. However, for most climates, conventional building envelopes with static properties may not offer an optimal solution. The aforementioned representative cases and studies have manifested a growing interest in kinetic envelope technologies proposed for improving energy performance, indoor comfort (especially visual quality), and occupancy interactions with buildings. Appendix C includes a comprehensive table that shows a number of application cases and their characteristics.

Based on the review of the representative examples, the following conclusions were made: (i) because solar energy (solar radiation and daylight) tends to be climate specific and has certain conflicting circumstances for buildings, most design cases are of the solar-responsive AKE type; and (ii) as seen in the most recent examples, in order to maximize the benefits of kinetic properties, AKE systems tend to be more complex and integrate solar heat, daylight, airflow features, and other potential kinetic features.

There also are certain challenges to AKE technology development. Most AKE systems consume energy, due to the use of mechanical devices. The question, then, is whether there are still significant energy benefits that can be gained from these technologies, as compared with the conventional energy-efficient envelope design in the four climates studied here. Furthermore, similar to other new high tech systems, expensive initial costs and maintenance inputs for AKE systems may cause failures even though there are some energy savings. Actually, AKE systems are usually designed not only for energy performance but also for visual comfort and human factors. However, researchers are still undecided about how to evaluate the benefits of these new technologies from multiple dimensions, beyond the current energy-centric evaluation approaches. Future studies should establish a comprehensive evaluation approach which could assess the AKE's contributions to occupancy satisfaction including indoor comfort, acoustical performance, and access to fresh air.

2.2 Analysis on AKE's Performance

2.2.1 Evaluate Smart Windows and Affiliated Units

1) Mockup Studies on Electrochromic Glazing

LBNL's Building Technologies researchers have undertaken extensive efforts to study two projects - electrochromic glazing and automated blinds windows (e.g., Lee et al., 1994; Lee & Selkowitz, 1998; Lee & Selkowitz, 2006; Lee et al., 2006; Lee & Tavil, 2007) - which are typical commercialized technologies in the area of AKE. They utilized simulation, mockup tests, and field facility tests to analyze the performances of these particular products in integrated whole buildings.

In order to identify and quantify the overall benefits, costs, and risks of certain advanced facade and window systems, LBNL research groups focused on electrochromic (EC) windows under realistic building operating conditions in a full scale Windows Testbed Facility (see Figure 2.16) in Berkeley, California, for two and a half years. The tested EC products had a VT range of 0.60–0.05 and SHGC range of 0.42–0.09 (Lee et al., 2006). The outcomes of this research included information regarding energy performance, peak demand performance, occupant comfort, satisfaction, and acceptance. Compared to the reference model which was defined by ASHRAE 90.1-2005 and which used matte-white Venetian blinds, well-tuned daylighting control systems and low-e windows, EC windows were shown to achieve a 10+15% savings of energy use for daily lighting (Lee et al., 2006). Additionally, EC windows reduced the average daily cooling loads related to solar heat gain (Lee et al., 2006). The maximum cooling peak demand reduction due to reduced solar heat gain was 19% (Lee et al., 2006). Also, complaints regarding problems with glare were reduced over 12.3% when utilizing the EC windows (Lee et al., 2006). The researchers found that EC windows were able to deliver adequate control of window glare and keep the luminance ratios within the recommended limits; however, the reference model's luminance ratio of 6.4 exceeded the requirements (Lee et al., 2006).

Figure 2.17. Test facility for EC windows by LBNL (Lee et al., 2006)

With respect to price, according to LBNL's study (Lee et al., 2006) the cost of producing EC windows is expected to be reduced significantly in the next few years. From 2000 to 2010, the price of EC windows decreased approximately 56.7% per square foot. However, given the final product cost (adding the necessary wiring, sensors, controls, connections to the building's energy management system, and maintenance design and engineering services), the costs related to EC windows are still much higher than for regular low-e windows. In order to analyze the economic justification, LBNL conducted a study in the 1990s and found that EC windows would pay for themselves in as little as four years in a medium sized office building (100,000 square feet with 60% windows on building surfaces) (Warner, Reilly, Selkowitz, Arasteh, & Ander, 1992). Furthermore, the adoption of this type of dynamic glazing solution should not only be motivated by energy savings; these technologies also offer impressive benefits for occupants' comfort and satisfaction.

The outcomes of this research were primarily centered on the products' performances as they related to energy and peak demand performance, as well as occupant comfort and satisfaction. One significant contribution was that the study compared AKE products to available energy-efficient technologies (low-e windows, passive blinds, etc.) on the same building case and in the same climate condition, and demonstrated that the EC windows or automated blind windows could provide energy and visual comfort benefits year round.

2) Automated Venetian Blinds

Substantial research, especially from LBNL, has been devoted to this area. Simulations, laboratory tests, and scale field tests have all been performed to demonstrate that advancements in visual comfort and energy efficiency can be associated with these kinetic systems (e.g., interior automated venetian blind full-scale tests (Lee & Selkowitz, 1998), automated venetian blinds between panes controlled by temperature and solar positions, etc. (Rheault & Bilgen, 1990).

Full-scale tests and monitored records showed, as compared to static blind systems with daylighting controls, that similar automated venetian blind/lighting systems obtained an average of 35% daily lighting energy savings on average in winter, and ranged from 40% to 75% savings in summer in Oakland (Lee & Selkowitz, 1998). Also, DOE-2 simulations showed that kinetic blind systems offered a 16% to 26% annual energy savings in Los Angeles for all directions except north, as compared to an advanced spectrally-selective window system (Lee & Selkowitz, 1998). Similarly, LBNL set up a mockup and conducted field tests for an automated roller shading system planned for use at the New York Times headquarters (see Figure 2.17). They found that the automated roller shading system provided better uniform lighting distribution, sun penetration depth, and glare control while simultaneously offering a lower cost (Lee et al., 2005). Another significant effect was on human factor issues. Kinetic window systems often are reported to increase occupant satisfaction, and they have the potential to promote work efficiency (Lee, DiBartolomeo, Vine, & Selkowitz, 1998). However, efficient mechanical daylighting systems are more closely related to automatic one-axis tracking systems.

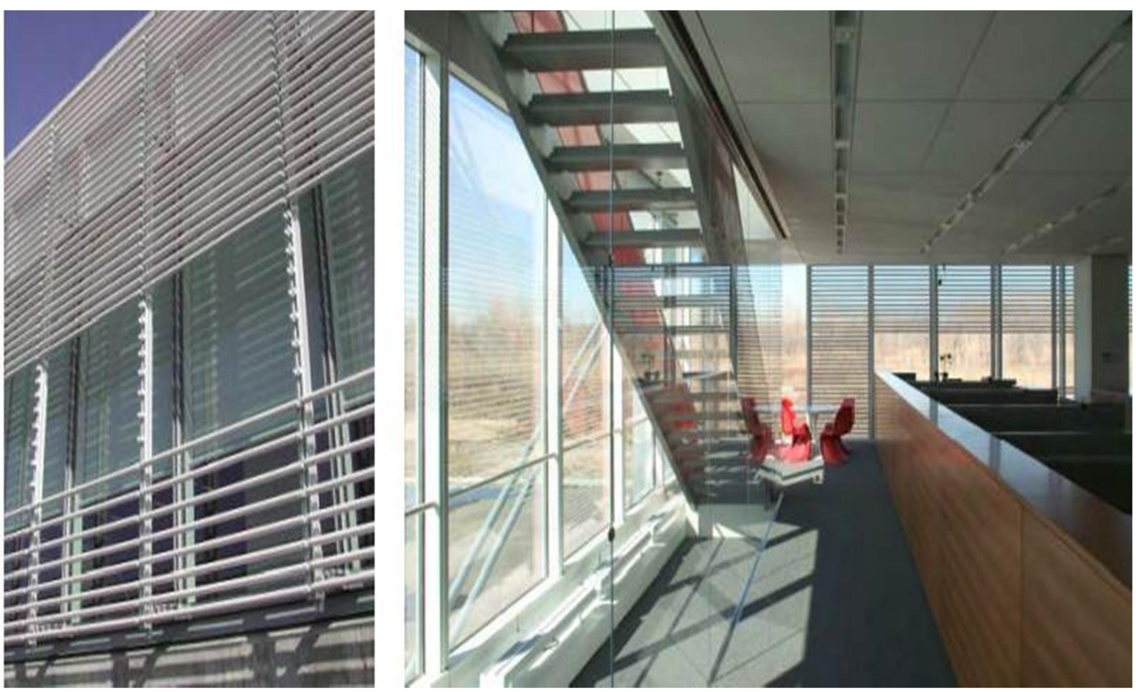


Figure 2.18. New York Times headquarters mockup (Lee et al., 2005)

Similarly, there are considerable simulation studies with or without experimental tests on windows' kinetic features including automated window shades, blinds or sunscreens, and smart glazing, mostly through simulation methods (e.g., Jonsson & Roos, 2010; Karlsson, 2001; Koo, Yeo, & Kim, 2010; Tenner & Zonneveldt, 2002). These simulation studies also noted that the use of dynamic features dramatically improved the quality of daylight available compared to the fixed solar shading, as well as generated total and peak energy savings, and lighting energy reductions as well. Additionally, most of analyzed cases are from available market products.

2.2.2 Evaluate Opaque Parts of Envelopes

Regarding the kinetic envelopes' other parts such as operable roofs, switchable walls, and variable insulation walls, there are only a few studies. The representative project was conducted by Zupančič, Škrjanc et al. (2006), and the simulator was developed in a MATLAB-Simulink environment rather than in any of the current computational programs in architecture. Focusing on total energy under different conditions, the research evaluated kinetic solutions using variable wall insulations, window insulations, movable shading systems and rotating objects, but some solutions did not exist in practical implementation forms.

2.2.3 Relevant Research to Other Kinetic Features

Building envelopes have been an important area of study for energy efficiency and indoor comfort for several decades. There are also many technical tests and simulation studies, such as double-skinned envelopes (e.g., Charron & Athienitis, 2006, Goia, Perino, Serra, & Zanghirella, 2010; Zanghirella, Perino, & Serra, 2011), high performance façades with operable nature ventilation (e.g., Conahey, Haves, & Christ, 2002; Wang, 2008), solar-tracking BIPVs (e.g., Tan, Green, & Hernandez-Aramburo, 2007), and smart materials (Ritter, 2007; Addington & Schodek, 2005). Nevertheless, the above studies focused on one or two particular elements of building envelopes, and as a result the findings cannot offer sufficient evaluation of the impacts of the entire kinetic building envelope.

2.3 Methodology and Tools

2.3.1 Simulation Approaches

Historically, it has not been easy to explore the possible kinetic compositions and shapes by using regular computational modeling methods. However, in recent years this design process has been substantially transformed by the introduction of parametric design. There have been many studies using computational tools such as Maya, Rhino and Grasshopper, Processing, CATIA, and Solid Works for the parametric control of model geometry. Parametric design allows for quick responses to design rules or constraints without having to recreate the entire model for each design iteration. The rules and constraints usually consist of mathematical formulas, physical equations, and values or data for exploring, representing, or optimizing geometry, forms, or size.

However, most existing programs have more to do with geometry and basic building information. Users can connect some popular parametric design programs to a certain range of environmental analysis: for example, DIVA for Rhino. Also, the accuracy of the analysis is another controversial issue. In recent years, Building Information Modeling (BIM), which has 3D knowledge-rich parameters including construction, materials, cost, and user-defined parameters, has been developed for parametric modeling and simulation (Lee, Sacks, & Eastman, 2006). Consider, for instance, Autodesk Revit API combined with C# programming that can be used to define the kinetic modes and regulations, as well as the user interfaces of new plug-ins. Some researchers (Welle, Haymaker, & Rogers, 2011; Azhar, Brown, & Farooqui, 2009) have further developed specific environmental analysis (e.g., thermal analysis, acoustic analysis, lighting analysis, etc.) connections to the BIM models. Although the BIM-based design approach can offer a way of exploring the kinetic building components and conducting some energy analyses, the complexity of kinetic envelopes and the overall evaluation accuracy are still limited in these programs.

In addition, *EnergyPlus* offers some options for users hoping to conduct studies of the dynamic properties of building envelopes, such as those involving phase change materials, variable thermal conductivity, thermochromic glazing, etc. However, the controls for the built-in functions in *EnergyPlus* are for specific materials, which may react in response to only one or two types of parameters.

2.3.2 Surveys on User Experiences in Sustainable Buildings

In the field of sustainable buildings, design strategies, HVAC systems, and other sustainable solutions have been proposed to offer comfortable indoor environments; meanwhile, they also manifest some energy-efficient features such as daylighting, green roofs, and others. Therefore, indoor physical environmental quality is the most important aspect for sustainable buildings. Moreover, the level of indoor environmental quality greatly impacts the occupants of these buildings. The indoor building physical environment relates to air quality, thermal comfort, visual quality, and acoustic quality. The LEED rating system also names these aspects collectively as Indoor Environmental Quality (IEQ) (USGBC, 2012). In order to understand how sustainable buildings perform from the perspective of their occupants, survey instruments should be developed and implemented.

Surveys of occupant experiences in buildings allow designers, developers, owners, operators, and tenants to objectively gauge how well sustainable design features are working and whether employee productivity, effectiveness and well-being can be improved (Abbaszadeh, Zagreus, Lehrer, & Huizenga, 2006). There are a considerable number of survey studies on building physical environmental quality in terms of sustainable design. According to the stated purposes of these surveys, the studies can be categorized by specific environmental quality and comprehensive environmental performance.

1) Surveys on Specific Environmental Quality

In order to understand the relationships among occupants' experiences and sustainable buildings' environmental performances, many survey studies have been conducted on individual environmental factors, especially with regards to thermal comfort and visual comfort.

Regarding thermal comfort, Rijal (2007) proposed a detailed survey method that combined a cross-sectional model (using transverse surveys) and a longitudinal model. On the one hand, the cross-sectional survey included objective information regarding building information, space features, occupants' clothing, activity, and other details, and included subjective responses to the thermal environment at the time of the survey. The longitudinal survey, on the other hand, was conducted at the same time as the cross-sectional questionnaires and recorded data for periods of up to three months. During this period of time, users were asked to fill out a questionnaire four times a day (early morning, late morning, early afternoon and late afternoon) to record their thermal satisfaction, clothing, activity and their uses of the building controls. Simple Temptrak dataloggers were placed in the working environment close to the respondents during the examined period of time. In addition to this integrated survey method, most studies utilized mail-out or web-based questionnaires based on a cross-sectional type of survey (e.g., Nasrollahi, Knight, & Jones, 2008)..

Regarding visual comfort, the most detailed survey was conducted by LBNL's Window and Daylighting Group. In order to understand the differences between new windows technologies and conventional types, the survey (Lee et al., 2006) started from an initial pilot test. The pilot test was designed to test the survey process and the questionnaires. There were forty-three subjects who experienced the lighting environment in the different room lighting configurations. For the analysis, the one-way analysis of variance (ANOVA) test and the "Tukey test" were utilized to analyze the significant differences and multiple comparisons, respectively (Zar, 1984).

2) Surveys on Comprehensive Environmental Performance

Although there has been considerable survey research on specific environmental quality, there is far less survey data on comprehensive environmental performance for occupants. To address this problem, there have been several survey methods adopted for overall access to environmental performance, or IEQ. A popular survey method was proposed by the Center for the Built Environment (CBE) at the University of California, Berkeley. The survey was an invite-style web-based mode with anonymous self-reported information in nine IEQ categories, based on questionnaires (Zagreus, Huizenga, Arens, & Lehrer, 2004). This online survey measured two types of variables (objective and subjective). Objective variables include gender, age, office type and other descriptive building environmental information like window blinds. Subjective variables are about occupant satisfaction and self-reported productivity, according to IEQ categories such as office layout, office furnishings, thermal comfort, air quality, lighting, acoustics, cleaning and maintenance, overall satisfaction with the building, and overall satisfaction with the workspace. Regarding these users' subjective data, the survey method utilized a 7-point semantic differential scale with endpoints of "very dissatisfied" and "very satisfied" (Abbaszadeh, Zagreus, Lehrer, & Huizenga, 2006). The respondents were then taken to a follow up page with questions on detailed information regarding dissatisfaction and any open ended comments. In a given building, the overall satisfaction value was derived from the mean of all of the respondents' answers to the satisfaction questionnaires. Moreover, the CBE survey database had some information and data from certain LEED-rated buildings. Thus, these data offered a comparative analysis between users' buildings and LEED buildings.

Similarly, researchers conducted surveys and field studies on IEQ issues in terms of occupant acceptability (e.g., Wong, Mui, & Hui, 2008), accuracy in task performance (Shaughnessy, Haverinen-Shaughnessy, Nevalainen, & Moschandreas, 2006), and users' perceptions of indoor quality (Wargocki, Wyon, Baik, Clausen, & Fanger, 1999). The survey method generally was in the form of self-administered questionnaires that were either mailed out or transferred the user to a website. The satisfaction of the users in the questionnaires was measured at both the overall level and the level of individual environmental factors such as noise, sunlight, and air ventilation (Zagreus, Huizenga, Arens, & Lehrer, 2004). To avoid confusion in the questions, some surveys were incorporated with certain answer examples (e.g., Wong, Lai, Ho, Chau, Lam, & Ng, 2009).

2.3.3 Summary

As more studies related to AKE performance have emerged, AKE has become increasingly likely as a means of defining the optimal climatic responses and heightening indoor comfort. Research has examined certain particular commercial products, especially with regards to glazing and blinds or sunscreens, in terms of their impacts on energy and occupants. The existing modeling and simulation programs (Autodesk Revit, COMFEN, etc.) have also been able to offer some means of evaluating AKE performance. However, a specific comparative study between AKE and CEE in different climatic conditions has not been conducted.

In addition, existing survey studies on environmental performance may provide appropriate methods and test procedures, especially with regards to mockup tests, for AKE performance survey research.

CHAPTER III

PARAMETRIC ENERGY SIMULATION FOR KINETIC ENVELOPES

3.1 Objective of Parametric Simulation

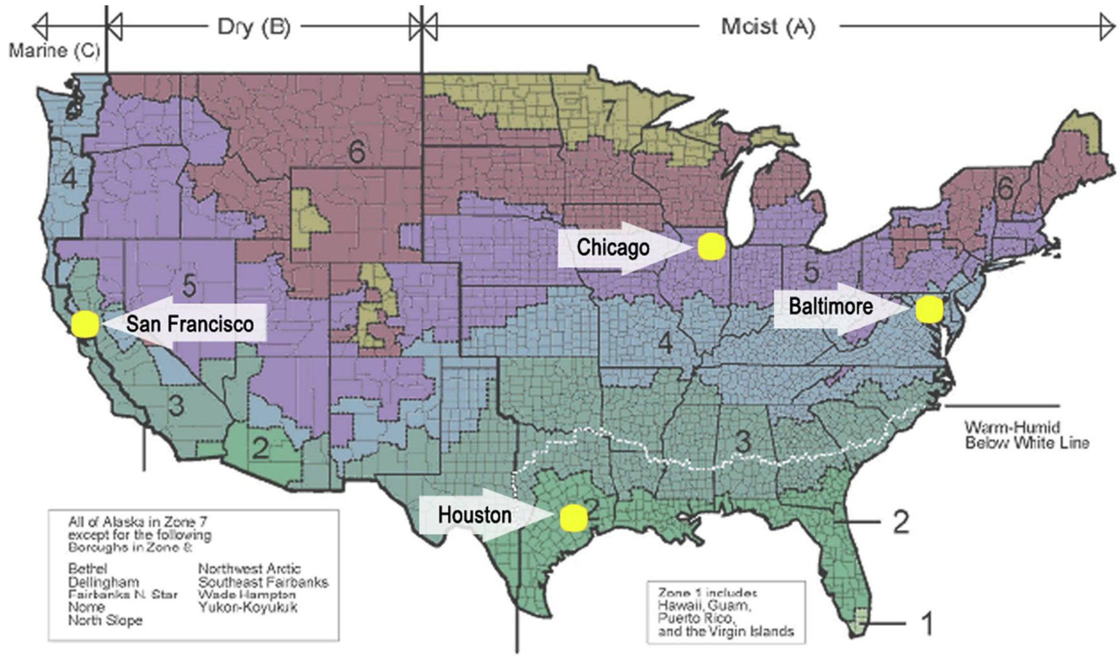
In order to evaluate the potential energy savings of kinetic building envelopes, it is important to conduct a comparative simulation study. This study utilized a small office prototype model developed by the Pacific Northwest National Laboratory (PNNL). The energy savings' evaluation used the energy simulation program, *EnergyPlus*, to evaluate the potential benefits of **Kinetic Models** with kinetic envelope systems and compared these hypothetical future systems to three models: 1) **Baseline Models** with minimally code compliant -- ASHRAE Standard 90.1-2010 (ANSI/ASHRAE/IES, 2010); 2) **Advanced Models** that used the recommendations in AEDG developed by ASHRAE and TSD created by PNNL with 50% energy saving goals compared to ASHRAE Standard 90.1-2010; and 3) **Ultra Models** that might be the next generation of energy-efficient technologies with "ultra" insulation but "static" properties rather than dynamic features.

In this comparative analysis, neither the kinetic envelope assemblies of Kinetic Models nor the envelope properties in Ultra Models are currently available, but they represent technologies that can be realistically developed in a real world in the next decade.

3.2 Simulation Design and Energy Analysis Methodology

3.2.1 Evaluation Approach

For this study, the energy performance was simulated by using *EnergyPlus* v8.0 (released in Apr. 2013) and utilized the small office prototype model with 5,500 ft^2 developed by PNNL for the study on *30% AEDG for Small Office Buildings* (Jarnagin et. al. 2006). The selected four cities (see Table 3.1) represented a range of climates: Houston, TX (Climatic zone number 2A), San Francisco, CA (Climatic zone number 3C), Baltimore, MD (Climatic zone number 4B), and Chicago, IL (Climatic zone number 5A). Although Baltimore was categorized into the mixed-climate in Figure 3.1, our energy simulation results based on ASHRAE Standard 90.1-2010 showed that the annual heating loads were 50.5% higher than annual cooling loads. Thus, in this study, I grouped Baltimore and Chicago into the heating-dominated climate. Houston was in the cooling-dominated climate, and San Francisco was related to the mixed-climate. The purpose of this simulation was to explore energy saving potentials of kinetic envelopes for different climatic zones relative to Baseline Models and the other two models with enhanced envelope characteristics. A series of steps were taken to reach this aim, and the whole process is illustrated in the following section.



Climate Zone Number	Name	Thermal Criteria*
1A and 1B	Very Hot–Humid (1A) Dry (1B)	9000 < CDD50°F
2A and 2B	Hot–Humid (2A) Dry (2B)	6300 < CDD50°F ≤ 9000
3A and 3B	Warm–Humid (3A) Dry (3B)	4500 < CDD50°F ≤ 6300
3C	Warm–Marine (3C)	CDD50°F ≤ 4500 AND HDD65°F ≤ 3600
4A and 4B	Mixed–Humid (4A) Dry (4B)	CDD50°F ≤ 4500 AND 3600 < HDD65°F ≤ 5400
4C	Mixed–Marine (4C)	3600 < HDD65°F ≤ 5400
5A, 5B, and 5C	Cool–Humid (5A) Dry (5B) Marine (5C)	5400 < HDD65°F ≤ 7200
6A and 6B	Cold–Humid (6A) Dry (6B)	7200 < HDD65°F ≤ 9000
7	Very Cold	9000 < HDD65°F ≤ 12600
8	Subarctic	12600 < HDD65°F

*CDD = cooling degree-day, HDD = heating degree-day.

Figure 3.1. US climatic zones and their characteristics (ASHRAE, 2011)

Table 3.1. The selected cities and climatic zones

A: Moist	**B: Dry**	**C: Marine**
2A: Houston, TX	4B: Baltimore, MD	3C: San Francisco, CA
5A: Chicago, IL		

1) Selected Prototypical Small Office Models

Prototypical small office models in this study belonged to sixteen reference models developed by the U.S. Department of Energy (DOE), in conjunction with three of its national laboratories, formerly known as commercial building benchmark models (Thorton et al., 2011). As DOE claimed, these prototypical buildings represent 80% (Thorton et al., 2011) of the U.S. commercial building floor area and over 70% of the energy consumed in U.S. commercial buildings (Thorton et al., 2011). This study selected the prototypical models specifically developed according to ASHRAE Standard 90.1-2010 (ANSI/ASHRAE/IES, 2010), which should result in 30% energy savings relative to 90.1-2004.

2) Created Baseline Models and Simulated Energy Performance

The baseline energy level was simulated in accordance with the standard of ASHRAE 90.1-2010. The baseline model inputs for the four climates are described in Section 3.2.

3) Created Advanced Models and Simulated Energy Performance

Based on the PNNL's final recommendations of TSD for 50% energy saving goals relative to ASHRAE Standard 90.1-2004, this study adopted the recommended properties for the envelope components and kept the same settings of Baseline Models on the other parts, e.g., HVAC, internal loads, schedules, etc. Section 3.3 documented these model inputs and assumptions for Advanced Models.

4) Created Ultra Models and Simulated Energy Performance

The third referenced model represented further improvements in envelope technologies, which may be superior than most existing efficient envelopes. In particular, these models were defined to have super insulated walls, roofs, and windows. Also, the window's SHGC had two levels according to different climates: one had high-gain ultra-windows, and another one had low-gain ultra-window. However, all envelope properties in these models were static.

5) Created Kinetic Models and Simulated Energy Performance

We proposed kinetic envelope models that took the characteristics of Ultra Models and added dynamic properties. The kinetic envelope components referred to "Variable Insulation for Opaque Assemblies (walls and roofs)", "Dynamic Windows and Glazing", and "Movable Blinds". The simulation methods for these models were unique to the others since some dynamic properties of envelopes were not typical to energy simulation. Section 4.1 documented the process of modeling and simulation by using some specific functions and EMS of *EnergyPlus*.

6) Evaluate Energy Savings for Four Climatic Conditions

This step was to compare the energy performance of above four models in four selected cities. The summary of energy simulation results was described in Section 5.

7) Effects of the Kinetic Envelope Assemblies

In order to understand the energy benefits from each kinetic envelope component, we conducted a comparative energy performance analysis for each envelope component in the four selected cities.

3.2.2 Simulation Tool Description

This simulation study adopted the *EnergyPlus* version 8.0 to assess energy performances for the four selected cities. *EnergyPlus* has been developed by DOE based on the most popular features and capabilities of BLAST and DOE-2 since 1996 (DOE, 2013). It is a complex building energy simulation program for modeling building heating, cooling, lighting, ventilation, and the other energy flows in buildings.

Furthermore, *jEPlus* version 1.4 (released in Jul 2013) was used to create and manage parametric simulation jobs while conducting simulation of the three reference models for the four cities. *jEPlus* works with the *EnergyPlus* engine (the relations are shown in Figure 3.2) and was developed by Prof. Zhang, De Montfort University, United Kingdom. The program aims to explore multiple design options simultaneously. This program may save repeated simulation workloads, particularly with similar building models. On one hand, this program was used to conduct modeling and simulation for the reference models that had similar basecase models but with different envelopes' properties (see Section 3.3.5). On the other hand, since the changes of the dynamic properties in Kinetic Models were related to the boundaries of temperature, it was necessary to find the best relations for minimizing the building energy. Therefore, *jEPlus* was used to input a few temperature boundaries and then provide the energy results of each input. All results could be automatically sent to one excel table and the "best" solution was selected after comparisons. As seen in Figure 3.3, basically, the process of simulation by *jEplus* is parametric.

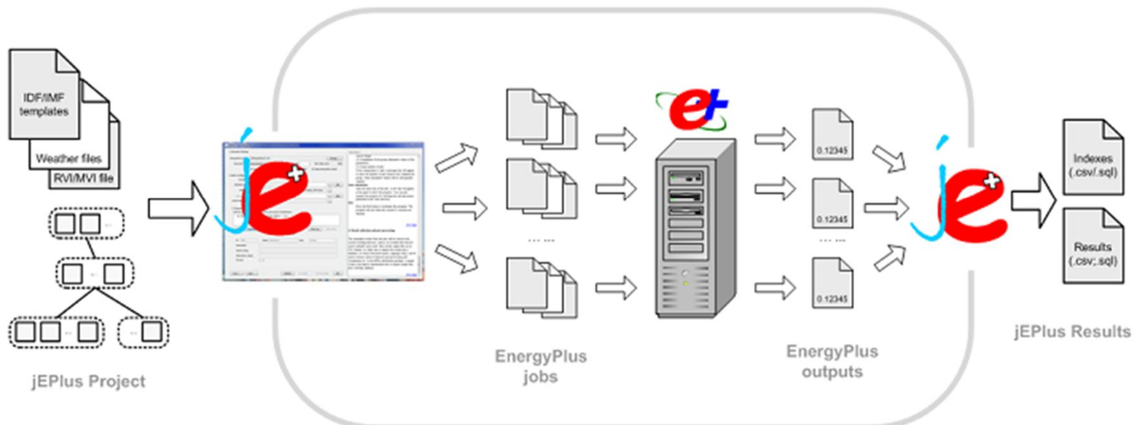


Figure 3.2. How *jEPlus* works (Zhang, 2009)

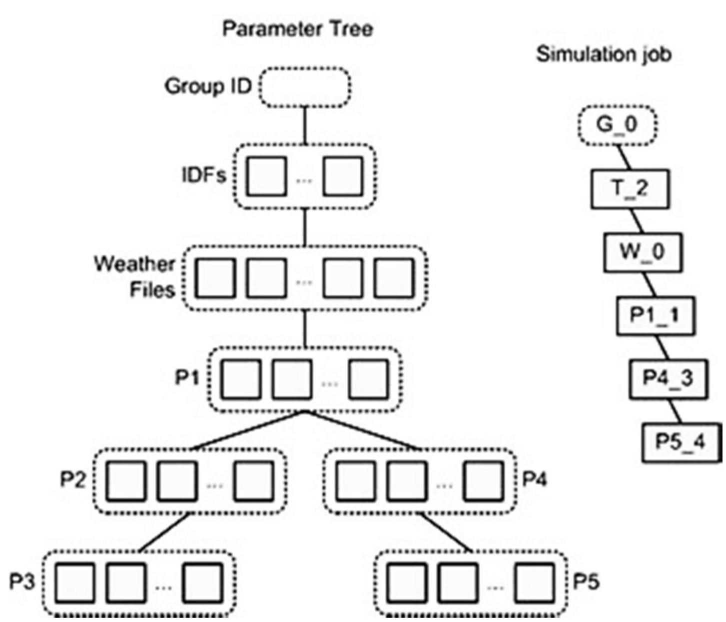


Figure 3.3. Parameter tree of *jEPlus* parametric simulation (Zhang, 2009)

3.3 Modeling and Simulation of Reference Models

3.3.1 Building Shape and Basic Information of Prototype

This one-floor prototypical small office building (see Figure 3.4) was developed by DOE. The building model was a rectangular form (90.8 ft. × 60.5 ft. × 10 ft.) with an attic roof. The gross floor area is 5,500 sq. ft. The windows were evenly distributed over the four façades of the model. Table 3.2 presents more information of the models.

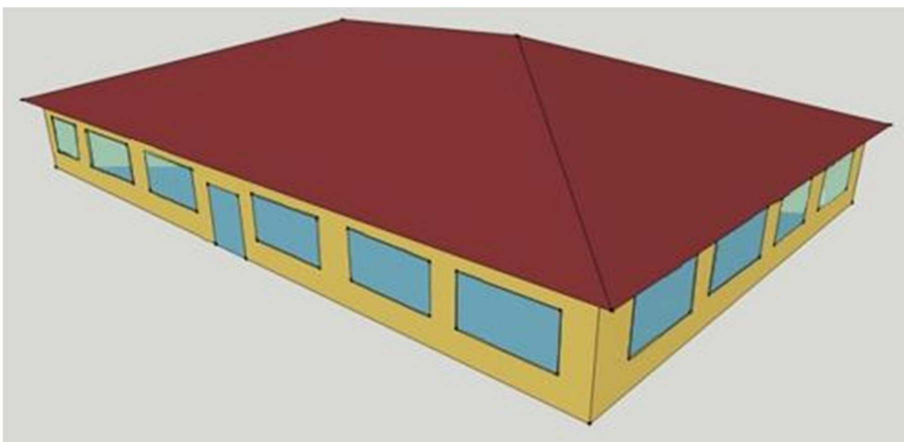


Figure 3.4. The prototypical office model based on DOE models (Thorton et al., 2011)

Table 3.2. The basic geometric information of the prototypical models

Total Floor Area (sq. ft.)	5500 (90.8 ft. x 60.5ft)
Aspect Ratio	1.5
Number of Floors	1

Table 3.2. Continued

Window Fraction (Window-to-Wall Ratio)	24.4% for South and 19.8% for the other three orientations (Window Dimensions: 9.0 ft. x 5.0 ft. punch windows for all façades) Data source: 2003 CBECS Data and PNNL's CBECS Study 2007
Azimuth	non-directional
Floor to floor height (feet)	10
Floor to ceiling height (feet)	10
Glazing sill height (feet)	3 (top of the window is 8 ft. high with 5 ft. high glass)

3.3.2 Baseline Models

1) Schedule

In the simulation of *EnergyPlus*, how to operate buildings is defined as schedules. They greatly affect the building energy usage. The schedule part in *EnergyPlus* includes the fraction of lights that are on, whether HVAC systems are on or off, thermostat settings, etc. Moreover, these values vary by day of the week and time of year based on users' plan. Figures 3.5 and 3.6 show the heating and cooling setpoints in weekdays and weekends.

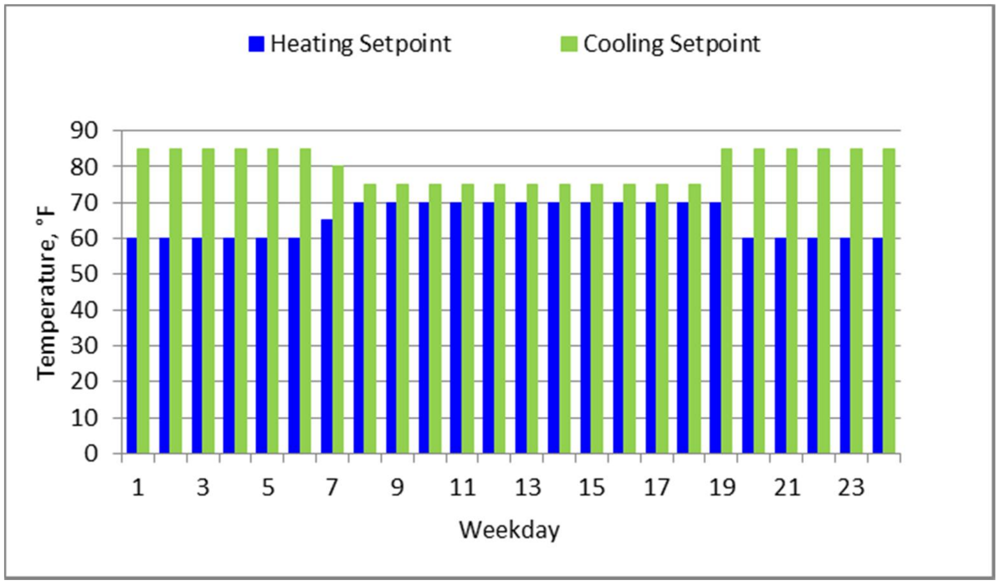


Figure 3.5. The heating and cooling setpoints in weekdays (Thorton et al., 2011)

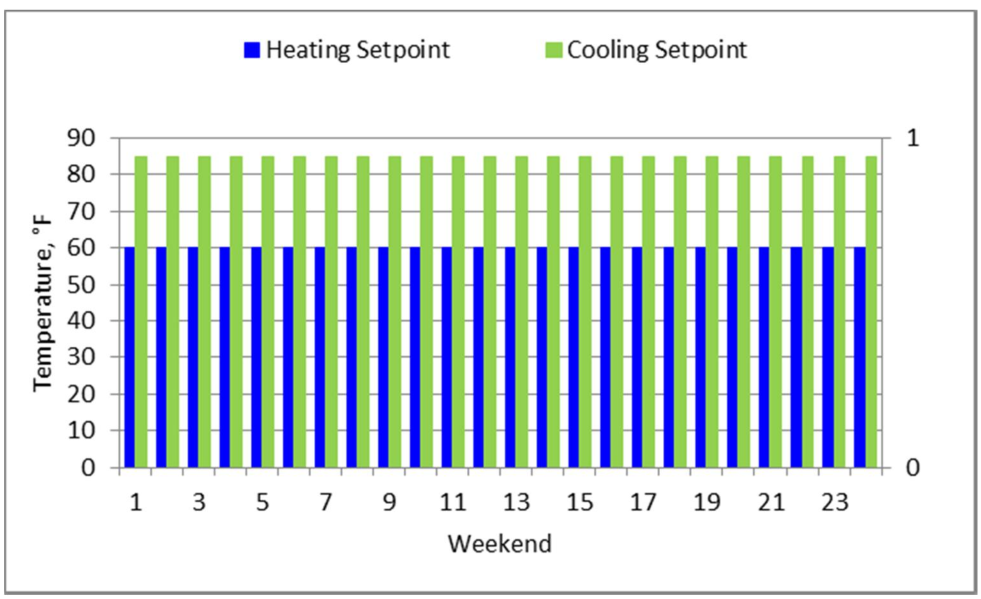


Figure 3.6. The heating and cooling setpoints in weekends (Thorton et al., 2011)

2) Thermal Zoning

As seen in Figure 3.7, the building model has five thermal zones including four perimeter zones (depth 16.4 ft.) and one core zone (there was an attic zone in this model). Tables 3.3 and 3.4 show a summary of areas, lighting power density, people density, etc. used in this model. The perimeter zones were 70% of floor area and the core zone was 30%.

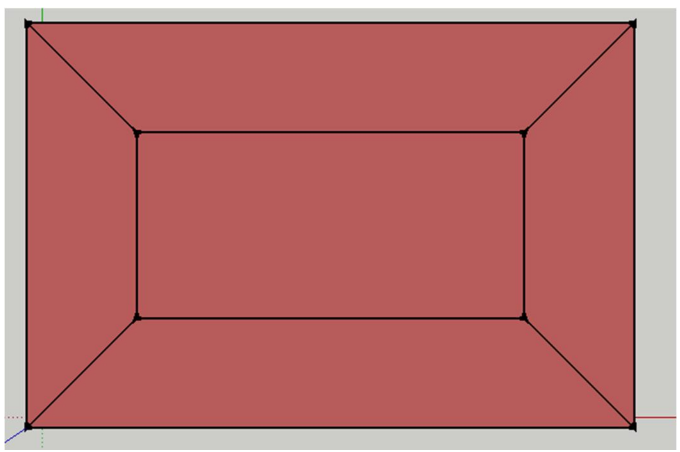


Figure 3.7. Thermal zones of the prototypical small office model (Thorton et al., 2011)

Table 3.3. The zone summary I

Zone	Area [ft^2]	Conditioned [Y/N]	Volume [ft^3]	Gross Wall Area [ft^2]
CORE_ZN	1,611	Yes	16,122	0
PERIMETER_ZN_1	1,221	Yes	12,221	909

Table 3.3. Continued

Zone	Area [ft²]	Conditioned [Y/N]	Volume [ft³]	Gross Wall Area [ft²]
PERIMETER_ZN_2	724	Yes	7,250	606
PERIMETER_ZN_3	1,221	Yes	12,221	909
PERIMETER_ZN_4	724	Yes	7,250	606
ATTIC	6,114	No	25,437	0
TOTAL[1]	5,503		80,502	3,030

Table 3.4. The zone summary II

Zone	Window Glass Area [ft²]	Lighting [W/ft²]	People [ft²/person]	Numbe r of People	Plug and Process [W/ft²]
CORE_ZN	0	1.00	179	9	0.63
PERIMETER_ZN_1	222	1.00	179	7	0.63
PERIMETER_ZN_2	120	1.00	179	4	0.63
PERIMETER_ZN_3	180	1.00	179	7	0.63
PERIMETER_ZN_4	120	1.00	179	4	0.63
ATTIC	0	0.00	-	0	0.00
TOTAL[1]	643			31	

3) Building Envelopes

Thermal and optical properties of building envelopes play a very important role in building energy performance. Further, in this research, the specific differences among

Baseline Models, Advanced Models, Ultra Models, and Kinetic Models were related to the envelope properties. This baseline model was created in accordance with ASHRAE Standard 90.1-2010, which provided prescriptive requirements for building envelopes' thermal performance and other characteristics. The requirement values vary with different climatic zones. The following describes the requirements of the key envelope assemblies for the selected cities.

- Exterior Walls

The exterior walls of the small office prototype were a type of wood-frame. The exterior walls included the following layers: 1 in. stucco, 5/8 in. gypsum board, wall insulation, and 5/8 in. gypsum board.

The Baseline Model's wall R-values were created according to ASHRAE Standard 90.1-2010 and met the maximum U-factors for the selected cities. The assembly U-factors (IP and metric units) and equivalent R-values of the baseline models are shown in Table 3.5.

Table 3.5. Thermal properties of walls in Baseline Models

Climate Zone		**Assembly U-factor**		**Equivalent R-value in ASHRAE Standard 2010**
		Btu/h · ft² · °F	W/m² · K	h · ft² · °F/Btu
Houston, TX	2A	0.089	0.505	R-13
San Francisco, CA	3C	0.089	0.505	R-13
Baltimore, MD	4B	0.089	0.505	R-13
Chicago, IL	5A	0.064	0.363	R-13 + R-3.8c.i.

- Roof

The small office prototype had an attic roof with wooden joists. It consisted of roof insulation and 5/8 in. gypsum board. The insulation R-values were set to match the maximum roof U-factor requirements for different climate zones in accordance with ASHRAE Standard 90.1-2010. The assembly U-factors in the baseline models and the equivalent R-values of ASHRAE Standard 90.1-2010 are shown in Table 3.6.

Table 3.6. Thermal properties of roofs in Baseline Models

Climate Zone		**Assembly U-factor**		**Equivalent R-value in ASHRAE Standard 2010**
-		Btu/h · ft² · °F	W/m² · K	h · ft² · °F/Btu
Houston, TX	2A	0.027	0.153	R-38
San Francisco, CA	3C	0.027	0.153	R-38
Baltimore, MD	4B	0.027	0.153	R-38
Chicago, IL	5A	0.027	0.153	R-38

- Fenestration

The prototypical model generally had 24.4% window-to-wall ratios for South façade and window-to-wall ratios 19.8% for the other three orientations, which was according to the CBECS 2003 data (CBECS, 2003). Eight windows with the same dimension - 5 ft. by 9 ft. wide - were distributed evenly on each wall of the building model. Except for these windows, the model did not have any other type of daylighting systems.

In order to match the requirements of U-factors and solar heat gain coefficient (SHGC) of ASHRAE Standard 90.1-2010, NREL developed a series of hypothetical glazing materials for *EnergyPlus*. Baseline Models also had lighting controls for daylight harvesting, so visible transmittance of glazing directly impacted lightings, which also brought internal heat gains and then affected space heating and cooling loads. The baseline U-factors, SHGC, and VT are shown in Table 3.7.

Table 3.7. Thermal properties of windows in Baseline Models

Climate Zone		**Assembly U-factor**		**Assembly SHGC**	**VT**
-		$Btu/h \cdot ft^2 \cdot {}^oF$	$W/m^2 \cdot K$	-	-
Houston, TX	2A	0.81	4.60	0.29	0.13
San Francisco, CA	3C	0.50	2.84	0.29	0.20
Baltimore, MD	4B	0.47	2.67	0.43	0.31
Chicago, IL	5A	0.47	2.67	0.43	0.31

4) Building HVAC

In the Baseline Models, the HVAC settings followed ASHRAE Standard 90.1-2010. Most elements of HVAC requirements were dependent on the fundamental choice of HVAC system types. The baseline models' HVAC used constant air volume (CAV) air distribution systems because the CBECS survey (Winiarski et al. 2007) noted that only 20% of the small office buildings had variable air volume (VAV) HVAC systems in the U.S. In our comparative simulation of the other models including Advanced Models, Ultra Models, and Kinetic Models, I kept the same type of HVAC system and the same characteristics of the other settings (e.g., efficiency, schedule, fans) so that the comparison could reveal the effects of building envelopes. The HVAC information is shown in the following Table 3.8.

Table 3.8. HVAC system settings of Baseline Models

System Type	
Heating type	Air-source heat pump with gas furnace as back up
Cooling type	Air-source heat pump
Distribution and terminal units	Single zone, constant air volume air distribution, one unit per occupied thermal zone
HVAC Sizing	
Air Conditioning	Auto sized to design day
Heating	Auto sized to design day
HVAC Efficiency	

Table 3.8. Continued

Air Conditioning	Various by climate location and design cooling capacity ASHRAE 90.1-2010 Requirements; Minimum equipment efficiency for Packaged Heat Pumps
Heating	Varies by climate location and design heating capacity ASHRAE 90.1-2010 Requirements Minimum equipment efficiency for Packaged Heat Pumps and Warm Air Furnaces
HVAC Control	
Thermostat Setpoint	75ºF Cooling/70ºF Heating
Thermostat Setback	85ºF Cooling/60ºF Heating
Supply air temperature	Maximum 104F, Minimum 55F
Chilled water supply temperatures	NA
Hot water supply temperatures	NA
Economizers	Various by climate location and cooling capacity Control type: differential dry bulb
Ventilation	ASHRAE Ventilation Standard 62.1
Demand Control Ventilation	ASHRAE 90.1 Requirements
Energy Recovery	ASHRAE 90.1 Requirements
Supply Fan	
Fan schedules	See under **Schedules**
Supply Fan Total Efficiency (%)	Depending on the fan motor size
Supply Fan Pressure Drop	Various depending on the fan supply air cfm
Pump	
Pump Type	NA

Table 3.8. Continued

Rated Pump Head	NA
Pump Power	Auto sized
Cooling Tower	
Cooling Tower Type	NA
Cooling Tower Efficiency	NA
Service Water Heating	
SWH type	Storage Tank
Fuel type	Natural Gas
Thermal efficiency (%)	ASHRAE 90.1 Requirements Water Heating Equipment, Gas storage water heaters, >75,000 Btu/h input
Tank Volume (gal)	40
Water temperature setpoint	120F

5) Lighting

The lighting sections had two parts including interior lighting and exterior lighting. With respect to interior lighting, the lights of Baseline Models were operated by the lighting schedule (e.g., 15% of lights energized during unoccupied in weekdays). The lighting power density (LPD) in Baseline Model was also applied 1.0 W/ft^2 (10.8 W/m^2) (ANSI/ASHRAE/IES, 2010). This value was used in all zones of the building models to control the lighting energy.

The models also had lighting control models to calculate the interior daylighting illuminance at specified reference points and then dim electric lighting to meet the illuminance target. Therefore, these automatic dimming controls took advantage of the daylight to reduce lighting energy and affected heating and cooling loads as well.

- The daylight zone extends 16.6 ft., which was the depth of the perimeter zones.
- In the daylight zones, lighting controls dimmed the lighting systems responding to the conditions of daylight. 85% of each perimeter zone was set up in *EnergyPlus* with the dimming controls. This value was assumed to account for internal obstructions and limited areas without daylight access (Thornton, Wang, Huang, Lane, & Liu, 2010).
- Two lighting sensors were used in four perimeter zones. Both sensors are located at 30 in. above the floor and 5.25 ft. inward from the exterior wall.
- The setpoint of illuminance was set to 300 lux in this simulation (DiLaura, Houser, Mistrick, & Steffy, 2011).
- The method of lighting controls was continuous/off mode.

In addition, the energy performance of Baseline Models was simulated with exterior lighting for parking lots, walkways, building façades, etc. These settings about the exterior lighting were kept for Advanced Models, Ultra Models, and Kinetic Models.

3.3.3 Advanced Models

The second reference model in this simulation was named Advanced Models, and these models were improved by changing building envelope systems related to enhanced insulation of the opaque assemblies and high performance windows. Except for these changes, the other settings of Advanced Models including HVAC systems, plug loads, and lighting systems were identical with the settings of Baseline Models. Therefore, the following descriptions focus on the modified sections relative to Baseline Models.

In Advanced Models, the building envelope properties were selected from AEDG for Small to Medium Office Buildings (ASHRAE, 2011). This latest version of the AEDG report was conducted to provide design recommendations for achieving a 50% energy savings compared to buildings that meet the minimum requirements of ANSI/ASHRAE/IESNA Standard 90.1-2004. As this report noted (ASHRAE, 2011), these values combined with the other improvements of HVAC systems achieved approximately 46% energy savings in relation to ASHRAE Standard 90.1-2007 and 31% savings in relation to ASHRAE Standard 90.1-2010.

1) Enhanced Insulation for Opaque Assemblies

The AEDG report of small to medium office buildings recommended thermal properties of walls and roofs for different zones. Tables 3.9 and 3.10 show the assembly U-factors and the equivalent insulation R-values for walls and roofs in Advanced Models.

Table 3.9. Thermal properties of walls in Advanced Models

Climate Zone		**Assembly U-factor**		**Equivalent R-value in ASHRAE AEDG**
-		Btu/h · ft² · °F	$W/m^2 \cdot K$	h · ft² · °F/Btu
Houston, TX	2A	0.074	0.420	R-13.0 + R-3.8 c.i.
San Francisco, CA	3C	0.074	0.420	R-13.0 + R-3.8 c.i.
Baltimore, MD	4B	0.066	0.374	R-13.0 + R-7.5 c.i.
Chicago, IL	5A	0.046	0.261	R-13.0 + R-10.0 c.i.

Table 3.10. Thermal properties of roofs in Advanced Models

Climate Zone		Assembly U-factor		Equivalent R-value in ASHRAE AEDG
-		Btu/h · ft² · °F	W/m² · K	h · ft² · °F/Btu
Houston, TX	2A	0.025	0.142	R-38
San Francisco, CA	3C	0.025	0.142	R-38
Baltimore, MD	4B	0.020	0.113	R-49
Chicago, IL	5A	0.020	0.113	R-49

2) Enhanced Performance for Fenestration

The windows in Advanced Models were improved by upgrading U-factors, SHGC, and VT but maintained the other settings including window area, locations, and all system settings as the input information of the Baseline Model. U-factors, SHGC, and VT values are shown in Table 3.11.

Table 3.11. Thermal properties of windows in Advanced Models

Climate Zone		Assembly U-factor		Assembly SHGC	VT
-		Btu/h · ft² · °F	W/m² · K	-	-
Houston, TX	2A	0.45	2.56	0.25	0.25
San Francisco, CA	3C	0.41	2.33	0.25	0.25
Baltimore, MD	4B	0.38	2.16	0.26	0.25
Chicago, IL	5A	0.35	1.99	0.26	0.25

3.3.4 Ultra Models

Ultra Models were the third reference case in this comparative study. Compared with Advanced Models, the thermal and optical properties of envelopes in Ultra Models were further improved. In these models, U-factors of the opaque assemblies and properties of fenestrations might be not available for several years, but they represent products that could realistically result from research in the next few decades. Furthermore, in order to analyze the potential advantages of kinetic building envelopes, it was necessary to compare the kinetic envelopes of Kinetic Models with the highly-insulated envelopes of Ultra Models.

In these models, therefore, only the properties of building envelopes were updated. The other settings of the Advanced Models were kept these Ultra Models.

1) Enhanced Insulation for Opaque Assemblies

To achieve the goal of net-zero buildings, many researchers have been exploring the highest possible thermal insulation resistance. The existing traditional insulation materials can theoretically meet the goals of net-zero, but the thickness of the insulation has to be greatly increased. Because this thickness applies to all the external walls on all floors, the useable floor areas are considerably reduced. Also, windows could be less effective in very thick walls in terms of light and window views. Jelle (2011) conducted a state-of-the-art review of building insulation materials and pointed out that the most promising insulation solutions are vacuum insulation panels (VIP) and aerogels. VIP can have around $0.004 W/m \cdot K$ ($0.028 Btu \cdot in/h \cdot ft^2 \cdot {}^{o}F$) in the pristine non-aged condition but will substantially increase to 0.02W/m · K (0.139 Btu · in/h · ft^2 · ° F) with time due to moisture and air penetration by diffusion. The typical low value for aerogel is 0.013W/m · K (0.09 Btu · in/h · ft^2 · ° F) and not considered to be dramatically increased with time. Therefore, 0.004W/m · K (0.028Btu · in/h · ft^2 · ° F) can be seen as the future thermal insulation target. This value was adopted in the Ultra Models. Based on these assumption values of the thermal conductivity, Tables 3.12 and 3.13 shows the assembly U-factors and equivalent insulation R-values for walls and roofs in Ultra Models.

Table 3.12. Thermal properties of walls in Ultra Models

Climate Zone		**Assembly U-factor**		**Equivalent R-value**
-		Btu/h · ft^2 · °F	W/m^2 · K	h · ft^2 · °F/Btu
Houston, TX	2A	0.016	0.091	R-75
San Francisco, CA	3C	0.016	0.091	R-75
Baltimore, MD	4B	0.013	0.074	R-90
Chicago, IL	5A	0.013	0.074	R-90

Table 3.13. Thermal properties of roofs in Ultra Models

Climate Zone		**Assembly U-factor**		**Equivalent R-value**	
-		Btu/h · ft² · °F	$W/m^2 \cdot K$	h · ft² · °F/Btu	$K \cdot m^2/W$
Houston, TX	2A	0.016	0.091	R-75	
San Francisco, CA	3C	0.016	0.091	R-75	
Baltimore, MD	4B	0.013	0.074	R-90	
Chicago, IL	5A	0.013	0.074	R-90	

2) Enhanced Performance for Fenestration

U-factors of windows were selected from studies on Highly Insulating Glazing Systems by LBNL's Windows and Daylighting Group. They reported a 0.57 W/m2-K (0.10 Btu/h-ft2-°F) window that had triple layer insulating glass units with two low-e coatings and an effective gas filled layer (Kohler, Arasteh, & Goudey, 2008). Thus, Ultra Models used these U-factors in windows for the energy simulation.

There were two levels of SHGC for different climates, but the values did not change for each climate: one was a relatively high SHGC of 0.35, while the other one had a low SHGC of 0.1. According to the simulation study of LBNL, we selected the high value (SHGC = 0.35) for the heating-dominated climate (Chicago, IL), the low value (SHGC = 0.10) for the cooling-dominated climate (Houston, TX), and the mixed-climate (San Francisco, CA). With respect to the value of SHGC for the models in Baltimore, MD, I conducted specific comparative studies on SHGC by energy simulation and found the value of 0.10 saved more energy than 0.35). In addition, the properties of VT of Advanced Models and Ultra Models were same.

Currently, the products with the aforementioned values are still not commercially available, but many studies are setting the values as the targets for future net-zero buildings. Table 3.14 shows the values used in this simulation.

Table 3.14. Thermal properties of windows in Ultra Models

Climate Zone		**Assembly U-factor**		**Assembly SHGC**	**VT**
-		Btu/h · ft² · °F	W/m^2 · K	-	-
Houston, TX	2A	0.10	0.57	0.10	0.25
San Francisco, CA	3C	0.10	0.57	0.10	0.25
Baltimore, MD	4B	0.10	0.57	0.10	0.25
Chicago, IL	5A	0.10	0.57	0.35	0.25

3.3.5 Energy Simulation Approach

The goal of this simulation study was not only to evaluate the whole energy uses, but also to analyze the effects for envelope assemblies, which included the relationships of walls vs. roofs vs. windows, and opaque vs. fenestration. Therefore, at least 60 *EnergyPlus* simulations required for these three reference models of the four climates, which was very time-consuming. The reference models developed by PNNL were used as the template IDF input, and then utilized *jEPlus* to run a batch of jobs.

As illustrated in Figure 3.8, a complete *jEPlus* simulation involved multiple steps. The first step was to select the IDF file and the climate data for that IDF file. The second step was to set up parameters related to values of walls' insulation, roofs' insulation, windows' U-factor, SHGC, and text strings for the input of weather files. The third step was to manage parameter trees and input their alternative values that could be inserted in to the IDF file. The last step was to identify the results information what was useful for the next analysis. Thus, by using *jEPlus*, we could compile a single output table containing the useful information from the batch. End-use (heating, cooling, fans, and interior lighting), peak cooling loads, and peak heating loads were selected for the further comparison with kinetic building envelopes.

3.4 Modeling and Simulation for Kinetic Models

3.4.1 Modeling and Simulation Approach

Kinetic building envelopes had different properties responding to the other stimuli, e.g., outside temperature, indoor temperature, air-conditioning status, etc. These variables were considered as independent variables. With regard to dependent variables, there were four variables in the Kinetic Models: U-factors of opaque components (walls and roofs), U-factors of windows, SHGC of windows, and external blinds.

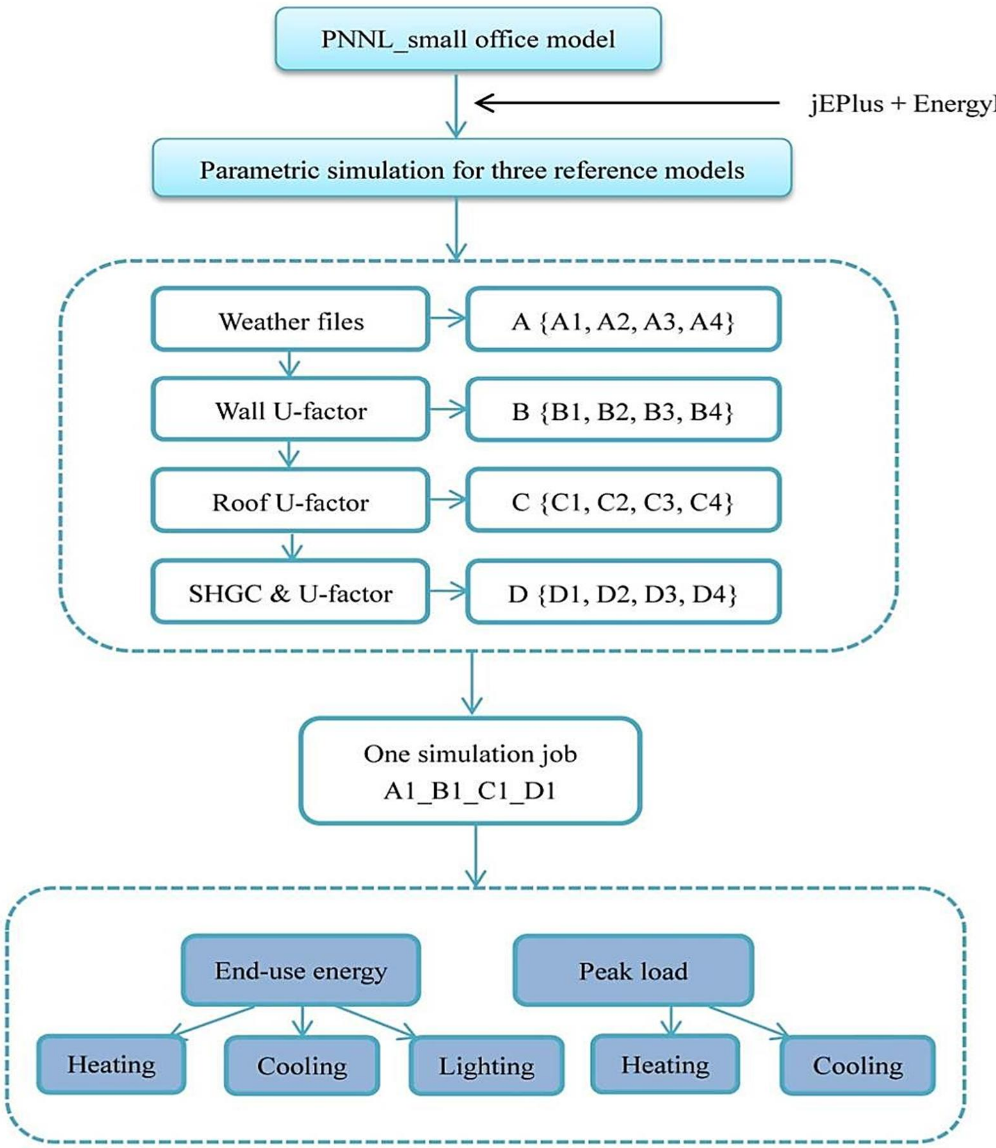


Figure 3.8. Parametric simulation of using *jEPlus* and *EnergyPlus* for reference models

The challenge was to conduct complex controls and modeling routines for how we want building envelopes to behave. On one hand, parametric design methods are widely used for exploring building morph and building components' behaviors. However, most existing programs deal with building geometry and basic information. On the other hand, *EnergyPlus* offers some options for users to conduct dynamic properties of building envelopes, such as phase change materials, variable thermal conductivity, thermochromic glazing, etc. However, the controls on these built-in functions in *EnergyPlus* are for specific materials, which may behave in response to only one or two types of parameters.

Therefore, the Energy Management System (EMS) features in *EnergyPlus* were explored and utilized in modeling and simulation. EMS is an advanced application for users who need to write *EnergyPlus* Runtime Language (Erl) for the high-level and supervisory control to override selected aspects of *EnergyPlus* modeling. The essential steps of using EMS are related to three issues: EMS sensors, EMS Actuators, and EMS calling points.

1) EMS Sensors

The input object “Energy Management System – Sensor” uses the normal *EnergyPlus* output variables, which can be obtained by looking at the RDD file generated by similar models with the same types of components and systems (DOE, 2013). In our simulation study, the input objects of the EMS sensors were "Site Outdoor Air Dry Bulb Temperature", "Surface Outside Face Incident Solar Radiation Rate Per Area", and "Zone/Sys Sensible Cooling Rate."

2) EMS Actuators

EMS actuators are defined to select features or components of *EnergyPlus* models and then override them by a series of new settings. *EnergyPlus* EMS developers have added some built-in actuators (e.g., HVAC systems, thermal envelopes, internal gains, air movement, etc.), which can be customized by users, but users are not able to create new actuators (DOE, 2013). In these simulations, I only manipulated the actuators of thermal envelopes, especially the “Construction State” of envelope components.

3) EMS Program Calling Manger

This input object requires users to confirm the timing for when and where Erl programs are initiated for custom controlling (DOE, 2013). This simulation analysis only used "Begin Time Step Before Predictor."

In addition, there are currently no optimization methods for dynamic properties of building envelopes. So, *jEPlus* was used in this research to assess the settings of kinetic envelope components for identifying the “optimal” properties.

3.4.2 Variable Insulation for Opaque Assemblies

1) Selection of Modeling Methods

Dynamic U-factors for the insulation of walls and roofs can be set up through several built-in methods in *EnergyPlus* including “Surface Control: Movable Insulation”, “Material Property: Phase Change”, and “Material Property: Variable Thermal Conductivity.” Moreover, beyond these built-in functions, a test by using EMS was conducted to model the behaviors of wall insulation.

Firstly, the actuators of thermal envelope in EMS (*EnergyPlus* 8.0 version) had only one option available to conduct dynamic wall insulation, which was the control type “Construction State.” This simulation used “CTF (Conduction Transfer Functions)” and “CondFD (Conduction Finite Difference)” to conduct assignments of different wall and roof constructions with the dynamic insulation properties. However, it was found that EMS did not simulate the models accordingly to our design due to “thermal history data” that evolved while using the previous configurations of wall and roof constructions. From the EMS Application Guide (DOE, 2013) “If this actuator is used inappropriately, for example to assign different constructions, to a single surface, that have radically different heat storage capacities, then the heat transfer modeling results may not be physically accurate.” In general, this EMS method was risky for any type of construction with thermal mass, whereas it worked well for windows because they do not have a thermal history.

Secondly, the method of using “Surface Control: Movable Insulation” is basically for using an extra amount of movable insulation on either the inside or outside surface of a wall, roof, etc. However, the proposed dynamic models in this study were theoretically working on one layer of building materials, so this method was also not appropriate. Thirdly, “Material Property: Phase Change” specifically describes the temperature dependent material properties and phase change materials (PCM) in *EnergyPlus*, so it was not effective to our models, either.

Lastly, the function of "Material Property: Variable Thermal Conductivity" was successfully used in our proposal, which was about temperature dependent insulation materials of walls and roofs. This method was only working with the regular "mass" materials rather than the no-mass insulation, thus it was required to clarify the thickness and thermal conductivity of the materials. Also, the dynamic process was described by a two column tabular temperature – conductivity function. This was a piece-wise linear relationship was between the outside temperature of the material surface and thermal conductivity of this insulation material. Up to ten pairs can be specified in *EnergyPlus,* and temperature values are required to be strictly increased according to the EMS Application Guide (DOE, 2013). The example is shown in Figure 3.9.

Field	Units	Obj1
Name		VariableInsulation
Temperature 1	C	15
Thermal Conductivity 1	W/m-K	.0091
Temperature 2	C	15.1
Thermal Conductivity 2	W/m-K	.051
Temperature 3	C	23
Thermal Conductivity 3	W/m-K	.051
Temperature 4	C	23.1
Thermal Conductivity 4	W/m-K	.0091
Temperature 5	C	
Thermal Conductivity 5	W/m-K	

Figure 3.9. Input example of variable thermal properties in *EnergyPlus*

The other two points were worth mentioning: 1) this function could only be used in the CondFD solution algorithm; 2) thermal conductivity value in regular material properties section in *EnergyPlus* was replaced by the values of "Material Property: Variable Thermal Conductivity" if this function was initiated.

2) Variable Thermal Conductivity

In order to compare with the other reference models, U-factor 0.013 Btu/h•ft^2•ºF (0.074 W/m^2•K) of Ultra Models was used as the low value setpoint, and U-factor 0.089

Btu/h•ft^2•°F (0.505 W/m^2•K) of Baseline Models was adopted as the high value setpoint. To achieve the aforementioned U-factor range, a new insulation material with mass was added in *EnergyPlus*, and its thermal conductivity and layer thickness were calculated. The thickness was input by 0.1m, and the values of thermal conductivity of "Material Property: Variable Thermal Conductivity" were ranging from 0.047 Btu · in/h · ft^2 · ° F (0.007 W/m • K) to 0.324 Btu · in/h · ft^2 · ° F (0.051 W/m • K).

The idea of the thermal insulation variation was that walls with higher R-values when the outside temperature was too high or too low but with lower R-values when outside temperature was within the comfort zone. Thus, walls and roofs ideally enabled indoor heat gains to be transferred to outside during the summer cooling period, and they maintained the indoor temperature during the winter heating period. One pseudo code example related to Houston is shown as follows:

```
IF outdoor temperature <= 63 F or >= 77 F
        Set Low U-value to the exterior walls
ELSE
        Set High U-value to the exterior walls
ENDIF
```

Furthermore, because U-factors were varied depending on temperature, I generated 10 pairs of temperature – conductivity settings for the four cities. The values of the temperature were set up as "search strings" in *jEPlus*, and energy simulation results of a batch of simulation jobs could be compared and in turn the "optimal" pairs for each climate were identified. Table 3.15 shows the final values of "Material Property: Variable Thermal Conductivity" in Kinetic Models for the four cities.

Table 3.15. Thermal properties of the opaque materials in Kinetic Models

Climate zone		**Condition 1**		**Condition 2**	
-		Temperature	U-factor	Temperature	U-factor
		F° (C°)	Btu/h · ft^2 · °F (W/m^2 · K)	F° (C°)	Btu/h · ft^2 · °F (W/m^2 · K)
Houston, TX	2A	<= 63 (17) or >= 77 (25)	0.016 (0.091)	> 63 (17) && < 77 (25)	0.089 (0.051)
San Francisco, CA	3C	<= 63 (17) or >= 79 (26)	0.016 (0.091)	> 63 (17) && < 79 (26)	0.089 (0.051)
Baltimore, MD	4B	<= 66 (19) or >= 79 (26)	0.016 (0.091)	> 66 (19) && < 79 (26)	0.089 (0.051)
Chicago, IL	5A	<= 66 (19) or >= 77 (25)	0.016 (0.091)	> 66(19) && < 77(25)	0.89 0.051)

3.4.3 Dynamic Windows

The EMS method of *EnergyPlus* was used in modeling and simulation of dynamic windows. In particular, the actuator called "Surface" with the control type of "Construction State" was used for the dynamic U-factors and SHGC. Here, I used the site air temperature and the zone sensible cooling or heating load rate as the stimuli.

At first, the four pairs of U-factor and SHGC were established for suiting different climatic conditions, as shown in Table 3.16. The high U-factors were from the Baseline Models and the low values were from Ultra Models. Thus, the range of U-factors was 0.1Btu/h•ft^2•°F (0.57W/m^2•K) ~ 0.81Btu/h•ft^2•°F (4.6W/m^2•K), and the range of SHGC was 0.10~0.35, which was according to the input of Ultra Models in different cities.

Table 3.16. Thermal properties of windows in Kinetic Models

Window01	**Window02**	**Window03**	**Window04**
Low_U_High_SHGC Btu/h · ft^2 · °F	Low_U_Low_SHGC Btu/h · ft^2 · °F	High_U_Low_SHGC Btu/h · ft^2 · °F	High_U_High_SHGC Btu/h · ft^2 · °F
U = 0.10	U = 0.10	U = 0.81	U = 0.81
SHGC = 0.35	SHGC = 0.10	SHGC = 0.10	SHGC = 0.35

The control scheme related to four types of windows:

- Switch to Window01, whenever outside temperature was lower than the comfort zone and there was heating loads. It was assumed that the building model could get the benefits of the external solar radiation but prevent the heat transfer between indoor environment and outdoor environment.
- Switch to Window02, whenever outside temperature was higher than the comfort zone and there was cooling loads. Similarly, this behavior contributed to reduce heat gains from outside because indoor HVAC system was producing cooling loads.
- Switch to Window03, whenever outside temperature was appropriate but there was cooling loads. Because the transmitted solar heat was a problem when there was a cooling load but the outside temperature was good to the indoor environment, the high U-factor and low SHGC window of the models was selected.
- Switch to Window04, whenever outside temperature was appropriate but there was heating loads. Once the EMS sensor noticed heating loads in zones, solar heat gains and heat exchange with outside appropriate temperature were advantages to energy savings. Thus, high U-factor and high SHGC was utilized in these scenarios.

According to this scheme, by using the Erl programming language, IFELSEIF-ELSE-ENDIF blocks could be set up for all windows of the building models. One pseudo code example related to the dynamic windows in Houston is shown in

Figure 3.10.

```
IF there are indoor heating loads &&  outdoor temperature < 59 F
     Set Low U-value and High SHGC windows
ELSEIF there are indoor cooling loads && outdoor temperature is > 72 F
     Set Low U-value and Low SHGC windows
ELSEIF there are indoor cooling loads && outdoor temperature is >= 59 F && <= 72 F
     Set High U-value and Low SHGC windows
ELSEIF there are indoor heating loads && outdoor temperature is >= 59 F && <= 72 F
     Set High U-value and High SHGC windows
ELSE
     Set Low U-value and Low SHGC windows

ENDIF
```

Figure 3.10. Pseudo code example of dynamic windows in Houston

The EMS actuator could override the “Fenestration Detailed” input object and achieved dynamic window systems. However, each climatic condition might have different temperature boundaries for achieving the minimum energy results. Thus, I conducted a series of simulations by using *jEPlus* and identified the “best” boundaries of temperature for each climate. The values of the temperature boundaries were set up as “search strings” in *jEPlus*, and a few options of the temperature variables were inserted into the simulation process. After a batch of simulation jobs, all energy simulation results could be compared and the “best” solution was selected. Table 3.17 shows the settings for each climate.

3.5 Energy Savings Analysis and Results

This section contains a summary of the four comparative small office models, and the energy savings results that are achieved by kinetic building envelopes. The annual energy consumption in this study was related to the sum of heating, cooling, and interior lighting, which did not include end use energy from inside equipment and exterior lighting. Also, energy savings of each envelope assembly in the four models were analyzed.

3.5.1 Summary of Key Parameters in the Four Models

Aside from movable blinds, the differences of the four models were linked to two parts of envelopes: opaque assemblies and fenestrations. It included three variables: U-factors of walls and roofs, U-factors of windows, and SHGC of windows. In Table 3.18, the principal simulation parameters of Baseline Models, Advanced Models, and Ultra Models are offered along with the dynamic envelope characteristics of Kinetic Models to facilitate comparison.

Table 3.17. Window options for different situations for each climate in Kinetic Models

Climate zone		Condition 1 Heating Loads	Condition 2 Cooling Loads	Condition 3 Cooling Loads	Condition 4 Heating Loads
Houston, TX	2A	Outside temperature < 59 (15)	Outside temperature > 72(22)	Outside temperature 59 (15) ~72(22)	Outside temperature 59 (15) ~72(22)
		Window01 Low_U_High_SHGC	Window02 Low_U_Low_SHGC	Window03 High_U_Low_SHGC	Window04 High_U_High_SHGC
San Francisco, CA	3C	Outside temperature < 59 (15)	Outside temperature > 77(25)	Outside temperature 59 (15) ~77(25)	Outside temperature 59 (15) ~77(25)
		Window01 Low_U_High_SHGC	Window02 Low_U_Low_SHGC	Window03 High_U_Low_SHGC	Window04 High_U_High_SHGC
Baltimore, MD	4B	Outside temperature < 59 (15)	Outside temperature > 77(25)	Outside temperature 59 (15) ~77(25)	Outside temperature 59 (15) ~77(25)
		Window01 Low_U_High_SHGC	Window02 Low_U_Low_SHGC	Window03 High_U_Low_SHGC	Window04 High_U_High_SHGC
Chicago, IL	5A	Outside temperature < 59 (15)	Outside temperature >68 (20)	Outside temperature 59 (15) ~ 68 (20)	Outside temperature 59 (15) ~ 68 (20)
		Window01 Low_U_High_SHGC	Window02 Low_U_Low_SHGC	Window03 High_U_Low_SHGC	Window04 High_U_High_SHGC

Table 3.18. Summary information for all models

Climate Zone		Wall			Roof			Fenestration			
		Assembly U-factor		Equivalent R-value	Assembly U-factor		Equivalent R-value	Assembly U-factor		Assembly SHGC	VT
——		Btu/h · ft² · °F	$W/m^2 \cdot K$	h · ft² · °F/Btu	Btu/h · ft² · °F	$W/m^2 \cdot K$	h · ft² · °F/Btu	Btu/h · ft² · °F	$W/m^2 \cdot K$	——	——
Baseline Models											
Houston, TX	2A	0.09	0.51	R-13	0.03	0.16	R-38	0.81	4.60	0.29	0.13
San Francisco, CA	3C	0.09	0.51	R-13	0.03	0.16	R-38	0.50	2.85	0.29	0.20
Baltimore, MD	4B	0.09	0.51	R-13	0.03	0.16	R-38	0.47	2.65	0.43	0.31
Chicago, IL	5A	0.06	0.36	R-13 + R-3.8 c.i.	0.03	0.16	R-38	0.47	2.65	0.43	0.31
Advanced Models											
Houston, TX	2A	0.07	0.42	R-13.0 + R-3.8 c.i.	0.03	0.14	R-38	0.45	2.56	0.25	0.25
San Francisco, CA	3C	0.07	0.42	R-13.0 + R-3.8 c.i.	0.03	0.14	R-38	0.41	2.33	0.25	0.25
Baltimore, MD	4B	0.07	0.37	R-13.0 + R-7.5 c.i.	0.02	0.11	R-49	0.38	2.16	0.26	0.25
Chicago, IL	5A	0.05	0.26	R-13.0 + R-10.0 c.i.	0.02	0.11	R-49	0.35	1.99	0.26	0.25
Ultra Models											
Houston, TX	2A	0.02	0.09	R-75	0.02	0.09	R-75	0.10	0.57	0.10	0.25
San Francisco, CA	3C	0.02	0.09	R-75	0.02	0.09	R-75	0.10	0.57	0.10	0.25
Baltimore, MD	4B	0.01	0.07	R-90	0.01	0.07	R-90	0.10	0.57	0.10	0.25
Chicago, IL	5A	0.01	0.07	R-90	0.01	0.07	R-90	0.10	0.57	0.35	0.25
Kinetic Models											
Houston, TX	2A	0.01~0.09	0.07~0.5	R-13~R-90	0.01~0.09	0.07~0.5	R-13~R-90	0.10~0.81	0.57~4.60	0.10~0.35	0.25
San Francisco, CA	3C	0.01~0.09	0.07~0.5	R-13~R-90	0.01~0.09	0.07~0.5	R-13~R-90	0.10~0.81	0.57~4.60	0.10~0.35	0.25
Baltimore, MD	4B	0.01~0.09	0.07~0.5	R-13~R-90	0.01~0.09	0.07~0.5	R-13~R-90	0.10~0.81	0.57~4.60	0.10~0.35	0.25
Chicago, IL	5A	0.01~0.09	0.07~0.5	R-13~R-90	0.01~0.09	0.07~0.5	R-13~R-90	0.10~0.81	0.57~4.60	0.10~0.35	0.25

3.5.2 Annual Heating and Cooling Loads

Table 3.19 presents the annual heating and cooling loads of four models in four locations, which also include energy consumption of fans. Thus, these energy analyses are HVAC related. Compared to Baseline Models, Figure 3.11 presents the savings percentages of heating loads in all models. It shows the energy savings percentages of Advanced Models were 32.5%, 26.6%, 30.0%, and 23.0% for the four cities, which is approximately consistent with results (28%) of the AEDG study by ASHRAE (ASHRAE, 2011) comparing recommended energy efficient strategies to ASHRAE Standard 90.1-2010. Regarding Kinetic Models, Figure 3.11 shows high energy savings for the four cities compared to Baseline Models, which were 47.2% for Houston, 47.9% for San Francisco, 47.7% for Baltimore, and 42.6% for Chicago in relation to the baseline energy usages.

Table 3.19. Summary of annual heating and cooling loads for the four climates

	Houston		**San Francisco**		**Baltimore**		**Chicago**	
	MMBtu	GJ	MMBtu	GJ	MMBtu	GJ	MMBtu	GJ
Baseline Model								
Heating	6.32	6.67	7.51	7.92	22.20	23.41	33.09	34.90
Cooling	28.31	29.86	7.52	7.93	14.74	15.55	12.28	12.95
Fans	21.28	22.44	16.15	17.03	19.25	20.30	19.17	20.22
Advanced Model								
Heating	5.64	5.95	7.27	7.67	20.47	21.59	30.05	31.69
Cooling	26.09	27.51	7.53	7.94	13.74	14.49	11.24	11.85

Table 3.19. Continued

	Houston		San Francisco		Baltimore		Chicago	
Fans	18.44	19.45	15.63	16.48	17.08	18.01	16.34	17.23
Ultra Model								
Heating	4.88	5.15	6.61	6.97	16.73	17.64	21.44	22.61
Cooling	20.99	22.14	5.84	6.16	11.25	11.86	12.61	13.30
Fans	11.87	12.52	10.44	11.01	11.37	11.99	15.65	16.50
Kinetic Model								
Heating	4.86	5.13	6.75	7.12	11.98	12.63	18.81	19.84
Cooling	14.09	14.86	3.54	3.73	10.02	10.57	11.36	11.98
Fans	10.55	11.13	6.18	6.52	7.42	7.82	6.88	7.26

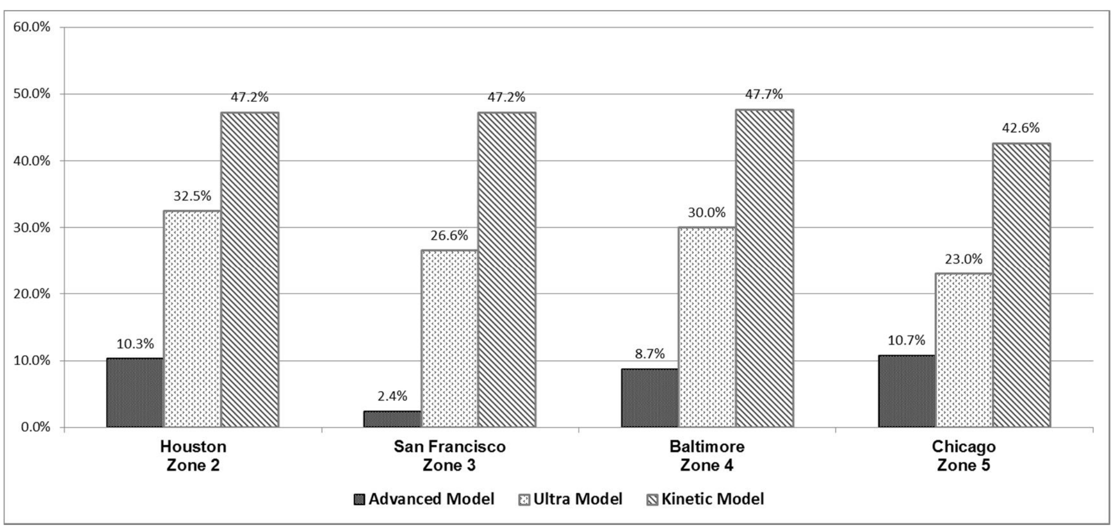
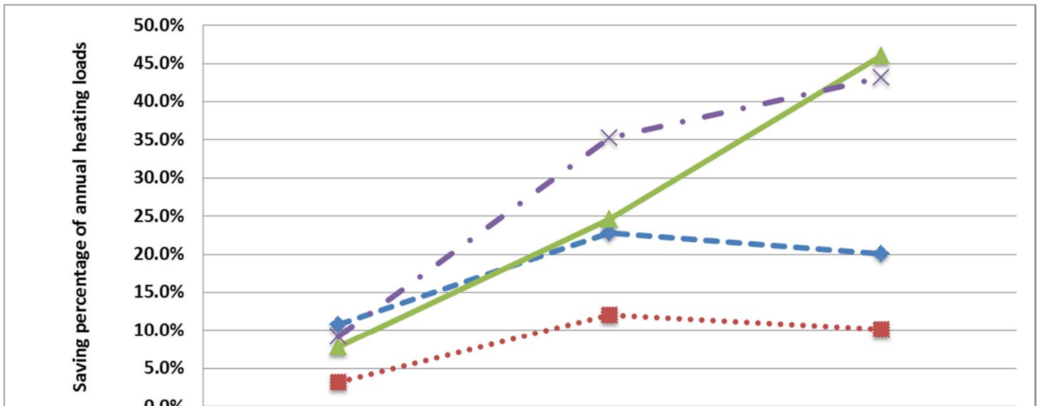


Figure 3.11. Savings percentages of the annual heating and cooling loads on a basis of Baseline Models

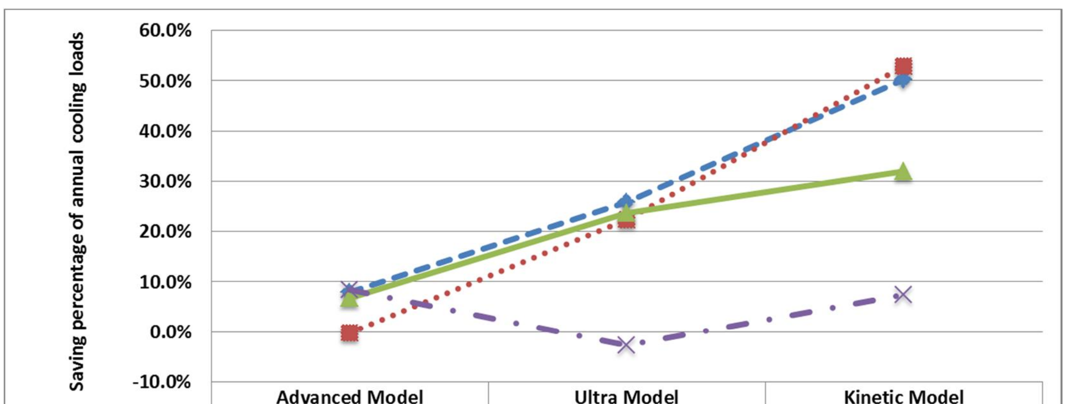


	Advanced Model	Ultra Model	Kinetic Model
Houston Zone 2	10.8%	22.8%	20.1%
San Francisco Zone 3	3.2%	12.0%	10.1%
Baltimore Zone 4	7.8%	24.6%	46.0%
Chicago Zone 5	9.2%	35.2%	43.2%

Figure 3.12. Savings percentages of heating loads on a basis of Baseline Models

In the perspective of annual heating loads, in relation to Baseline Models, Figure 3.12 shows that Kinetic Models of Baltimore and Chicago achieved similar energy savings percentages (46.0% for Baltimore and 43.2% for Chicago). This is because the heating loads of these two cities occupied more percentages of total energy consumption. As above figure shows, in the cooling-dominated climate of Houston and the mixed-climate of San Francisco, the highly-insulated building envelopes (in Ultra Models) performed slightly better than dynamic envelopes (in Kinetic Models). This corresponded to the settings of dynamic properties of envelopes, particularly with the variable thermal insulation of the opaque materials. This situation was explained in Section 5.4 – envelope assemblies.

At the level of annual cooling loads (Figure 3.13), savings in the cooling-dominated climate of Houston and San Francisco were about 50.2% and 53.0% respectively compared to their Baseline Models. Kinetic Models of Baltimore also achieved 32.0% energy savings. Although the overall heating and cooling loads were reduced for Chicago's Ultra Model compared to its Baseline Model, the annual cooling loads of Chicago's Ultra Model increased relative to Baseline Models. After analysis of detailed zone cooling loads, it was found the highly-insulated envelopes (glazing U-value 0.1 Btu/h•ft²•°F and the opaque U-value 0.016 Btu/h•ft²•°F) made the building so tight that indoor heat gains from equipment and people could not be transferred to outside when there were proper external temperature conditions.



	Advanced Model	Ultra Model	Kinetic Model
Houston Zone 2	7.9%	25.9%	50.2%
San Francisco Zone 3	-0.1%	22.3%	53.0%
Baltimore Zone 4	6.8%	23.7%	32.0%
Chicago Zone 5	8.5%	-2.7%	7.5%

Figure 3.13. Savings percentages of cooling loads on a basis of Baseline Models

The comparison of annual heating and cooling loads reveals great HVAC load savings from kinetic building envelopes that for each climate zone ranged from 42.6% to 47.7%. With respect to separate heating and cooling loads, Ultra Models with highly insulated envelopes produced a small degree of savings (around 2%) compared to Kinetic Models with dynamic properties, but, at the level of total HVAC loads, Kinetic Models obviously reduced the loads (18.5% for Houston, 19.3% for San Francisco, 18.1% for Baltimore, and 20.9% for Chicago) in relation to Ultra Models.

3.5.3 Peak Demands Comparisons

Obtaining the information of peak heating and cooling loads is the necessary step to determine the adequate size of HVAC equipment. An undersized HVAC system cannot provide desired indoor temperatures, while inefficiency and possible uncomfortable conditions (particularly humidity control during summer months) can result from oversized HVAC equipment. This section presents peak demands of heating and cooling for four models in each climatic zone. The simulation results were only related to the changes of envelope properties in each model. Table 3.20 shows the summary of peak demands for the four climates.

Table 3.20. Summary of peak heating and cooling loads for the four climates

	Houston		**San Francisco**		**Baltimore**		**Chicago**	
	Btu/hr	W	Btu/hr	W	Btu/hr	W	Btu/hr	W
Baseline Model								
Heating	20.5	6.0	14.4	4.2	21.2	6.2	19.3	5.6

Table 3.20. Continued

	Houston		San Francisco		Baltimore		Chicago	
Cooling	25.2	7.4	15.8	4.6	23.2	6.8	21.3	6.2
Advanced Model								
Heating	21.3	6.2	12.8	3.8	18.5	5.4	16.8	4.9
Cooling	23.1	6.8	15.3	4.5	21.4	6.3	19.4	5.7
Ultra Model								
Heating	20.2	5.9	3.5	1.0	11.5	3.4	9.2	2.7
Cooling	16.9	5.0	11.1	3.3	16.1	4.7	18.8	5.5
Kinetic Model								
Heating	17.4	5.1	6.3	1.8	3.4	1.0	5.4	1.6
Cooling	12.5	3.7	3.2	0.9	10.7	3.1	9.8	2.9

On one hand, Figures 3.14 presents peak heating loads of these four models in each climate and savings percentages in relation to Baseline Models. Basically, except for Houston, the other climates provided obvious savings percentages by Ultra Models and Kinetic Models. The greatest savings percentage, 83.9%, occurred in Baltimore. 56.4% and 71.9% savings were related to San Francisco and Chicago respectively. As discussed previously in the annual heating loads comparisons, Ultra Models with the highly-insulated envelopes in San Francisco performed better than Kinetic Models. Similarly, the saving percentage (76.0%) of the peak heating demand from Ultra Models in San Francisco was still greater than the savings (56.4%) in Kinetic Models. This is the only exception of the comparison of peak heating demands between Kinetic Models and Ultra Models. This trend was linked to the inputs of variable insulation for walls and roofs in *EnergyPlus*, which is explained below in Section 3.5.4.

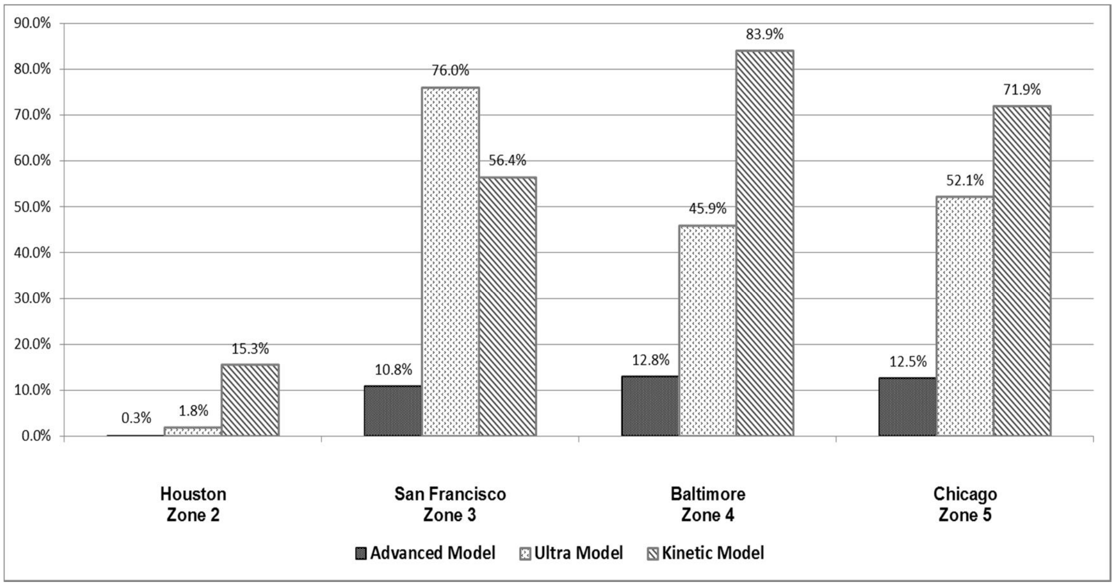


Figure 3.14. Savings percentages of peak heating loads on a basis of Baseline Models

On the other hand, as seen from Figures 3.15, Kinetic Models and Ultra Models in the four climates offered high impacts on reducing the peak cooling demands. The highest 79.7% saving percentage was from Kinetic Models in San Francisco, and the other three climates showed similar saving percentages at over 50% in Kinetic Models. Also, Ultra Models of the four climates achieved 11.5~32.8% savings of peak heating demands in relation to Baseline Models.

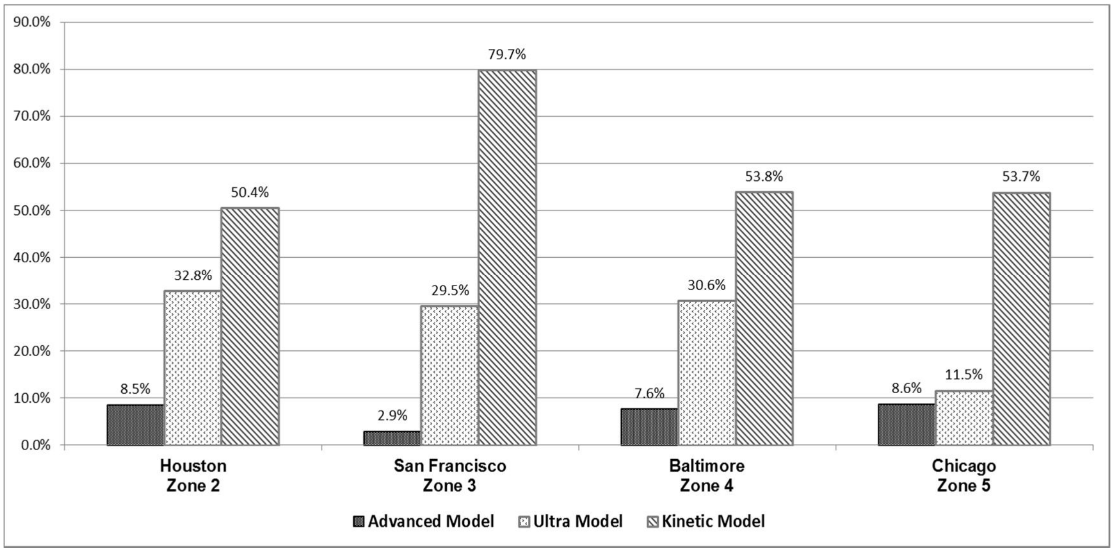


Figure 3.15. Savings percentages of peak cooling loads on a basis of Baseline Models

3.5.4 Effects of Kinetic Envelope Assemblies

In order to know the detailed reasons why Kinetic Models offered great impacts on energy performance, I explored the performance of each assembly of building envelopes of Kinetic Models and the other three models as well in the four cities. Besides, it is important to recognize the contributions to energy savings from single envelope component with kinetic properties, and in turn it can be known which parts of building envelopes are worthy being dynamic in selected climates. By using *EnergyPlus* and *jEPlus* as discussed previously, the simulation results for separated components including Roofs Only, Walls Only, Roofs and Walls, and Windows Only could be obtained.

1) Roofs Only

Thermal properties of roofs considerably impact heating and cooling loads, particularly for one-floor buildings. Figure 3.16 shows the comparison of HVAC loads related to heating, cooling and fans of four *EnergyPlus* models with different thermal properties of roofs in four different climates. Firstly, compared to Baseline Models, Advanced Models with enhanced roof insulation only achieved a very light level of saving percentages. Secondly, Ultra Models with super insulated roofs offered more savings (2.9~5.0%) of heating and cooling loads than the loads in Baseline Models. Thirdly, Kinetic Models with dynamic properties of roofs as shown from Table 3.21 greatly reduced heating and cooling loads, which was 8.9% for Houston, 10.2% for San Francisco, 8.5% for Baltimore, and 8.1% for Chicago compared to Baseline Models.

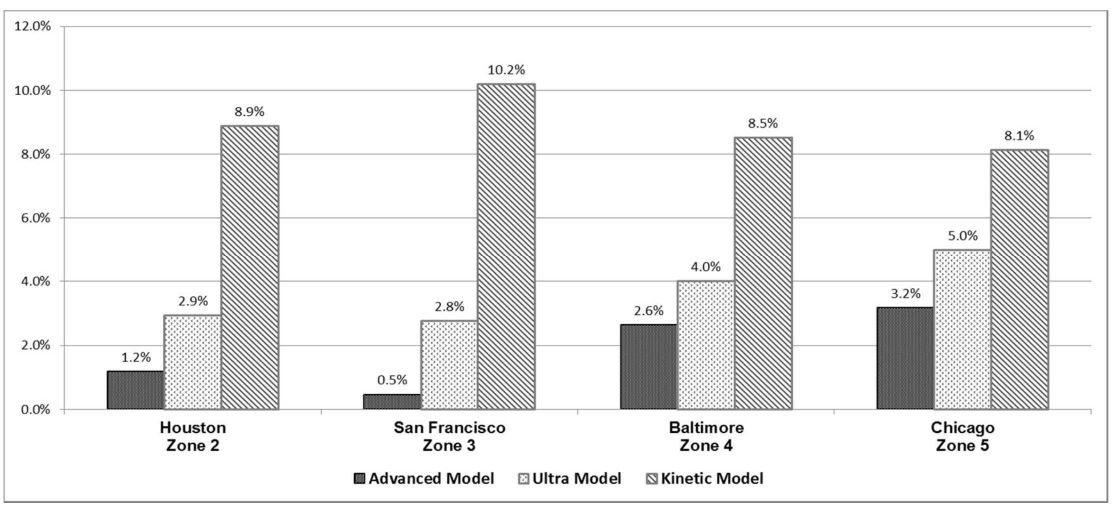


Figure 3.16. Savings percentages of the annual heating and cooling loads by roofs on a basis of Baseline Models

Table 3.21. Summary of the annual heating and cooling loads by roofs for the four climates

	Houston		San Francisco		Baltimore		Chicago	
	MMBtu	GJ	MMBtu	GJ	MMBtu	GJ	MMBtu	GJ
Baseline Model								
Heating	6.3	6.7	7.5	7.9	22.2	23.4	33.1	34.9
Cooling	28.3	29.9	7.5	7.9	14.7	15.6	12.3	13.0
Advanced Model								
Heating	6.3	6.6	7.5	7.9	21.5	22.7	31.6	33.4
Cooling	28.2	29.8	7.5	7.9	14.5	15.3	12.2	12.9
Ultra Model								
Heating	6.1	6.5	7.3	7.8	21.1	22.3	31.1	32.8
Cooling	27.7	29.3	7.4	7.8	14.4	15.2	12.1	12.7
Kinetic Model								
Heating	6.2	6.5	7.4	7.8	21.5	22.7	31.5	33.2
Cooling	25.5	27.0	6.0	6.4	12.9	13.6	10.9	11.5

Figure 3.17 separates heating loads and cooling loads for each model in the four cities. It was cooling loads generated by dynamic roof's insulation that played the significant role in saving whole HVAC loads, as discussed above. In relation to Baseline Models, the savings percentages of the cooling loads in Kinetic Models with the dynamic insulation ranged from 9.7~19.8% for each climate. Ultra Models performed

almost as well as Advanced Models on annual cooling loads. However, with respect to the annual heating loads, Ultra Models showed better performance than Kinetic Models in all climatic zones. This is because of the input settings of Variable Thermal Insulation in Kinetic Models in *EnergyPlus*, which was described in Table 3.15. U-factors of insulation of roofs were replaced according to external surface temperature of roofs. Based on *jEPlus*, I compared and identified the best pairs of temperature and U-factors for total energy usages, so the setpoints of temperature may not be optimal to save heating loads but rather to the sum of heating and cooling loads. Consider, for instance, the optimal input settings of Houston in which the high U-factor 0.089 Btu/h•ft^2•°F (0.507 W/m^2•K) of roofs was set when the outside temperature was within the range of 63 F° (17 C°) and 77 F° (25 C°). However, the temperature situation with 63 F° (17 C°) may cause heating loads and enhance peak heating demands. This resulted in the heating loads of kinetic envelopes were higher than the highly-insulated envelopes.

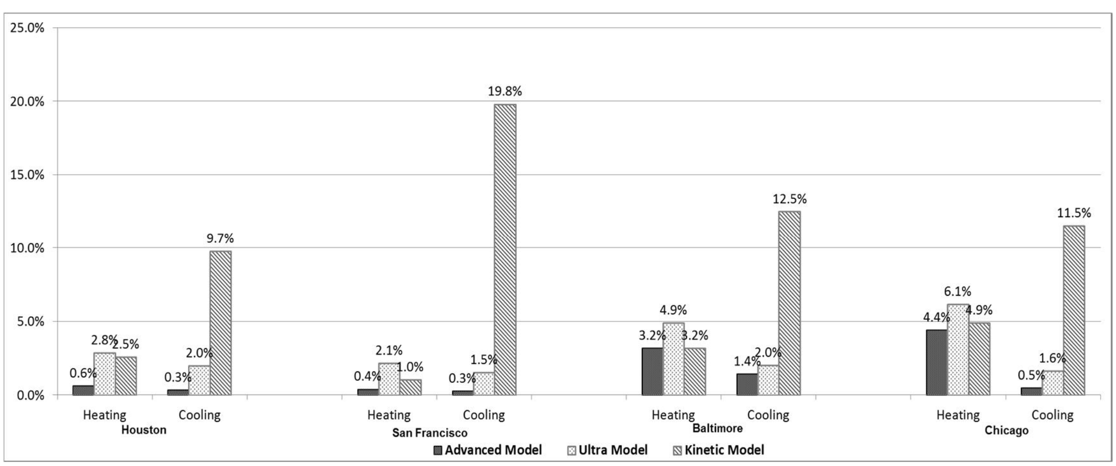


Figure 3.17. Separated savings percentages of heating / cooling loads by roofs on a basis of Baseline Models

Regarding the peak demands of the four models, Figure 3.18 shows the peak heating loads for each climate, and Figure 3.19 presents the peak cooling loads. On one hand, the reductions of the peak cooling loads from Kinetic Models for all cities were from 7.4% to 11.8% compared to Baseline Models. This trend of Roof Only was consistent with the peak cooling demands in the previous discussion related to the entire kinetic building envelopes. But, on the other hand, the peak heating demands of each climate showed different trend. Ultra Models achieved more reductions on the peak heating loads among the four simulation models. The reductions percentages of Advanced Models were also greater (except for Baltimore) than the results of Kinetic Models. The reason of this result was also the modeling methods of variable insulation of roofs in *EnergyPlus*. Nevertheless, if compared the peak heating loads and the peak cooling loads for the four cities, it was find that the peak cooling loads were always greater than the peak heating loads in all models, even the models in the heating-dominated climate. So, the amount (around 1.9MMBtu or 2.0GJ for the four cities) of cooling loads savings was apparently larger than the amount (less than 0.9MMBtu or 1GJ for the four cities) of heating loads savings. This might explain why these input settings were selected by comparing the results from *jEPlus* batch simulation.

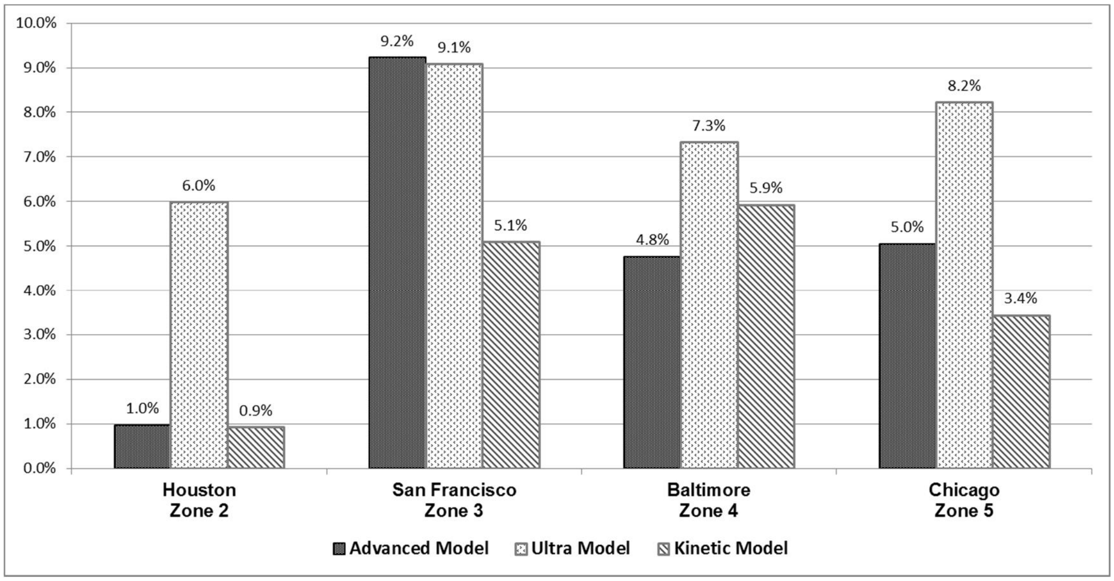


Figure 3.18. Savings percentages of peak heating loads by roofs on a basis of Baseline Models

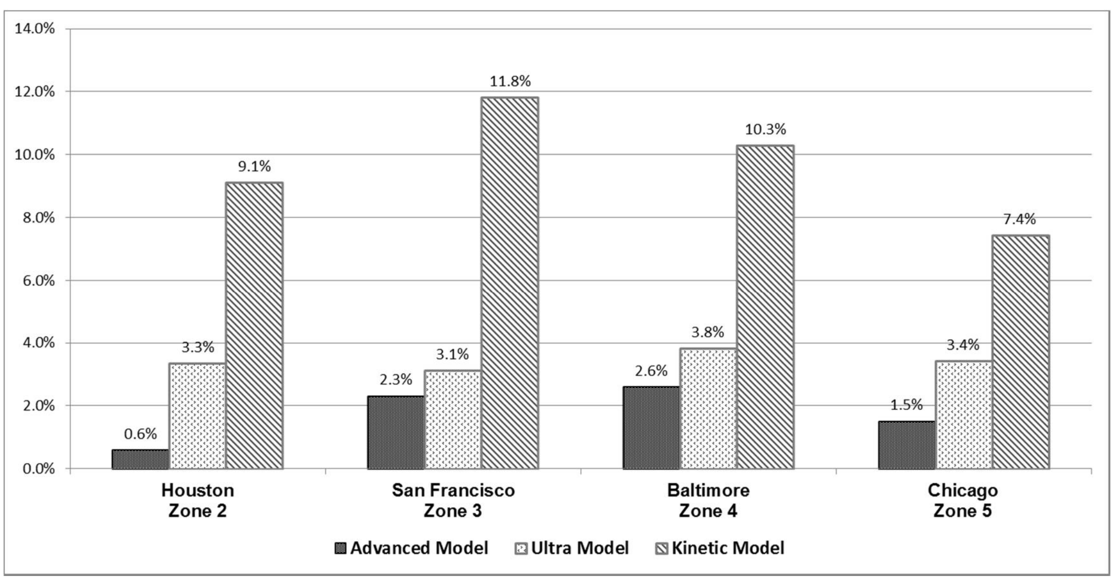


Figure 3.19. Savings percentages of peak cooling loads by roofs on a basis of Baseline Models

2) Walls Only

This section illustrates the contributions from walls in each model because only thermal properties of walls were changed according to different models and climates, which were same input settings with previous comparative models (Baseline Models, Advanced Models, Ultra Models, and Kinetic Models).

The results from the comparisons of HVAC loads related to walls in the four models in the four cities were similar to the features of the comparisons of roofs. As seen from Figure 3.20, compared to Baseline Models, the dynamic insulation settings of walls in Kinetic Models achieved more savings of heating and cooling loads in the four climates, which were 8.1% for Houston, 7.4% for San Francisco, 11.3% for Baltimore, and 9.6% for Chicago. The highly-insulated walls of Ultra Models also saved 4.2~9.3% heating and cooling loads on the basis of Baseline Models. In addition, Table 3.22 displays the detailed values of heating and cooling resulted from only changing walls in the different models for each climate.

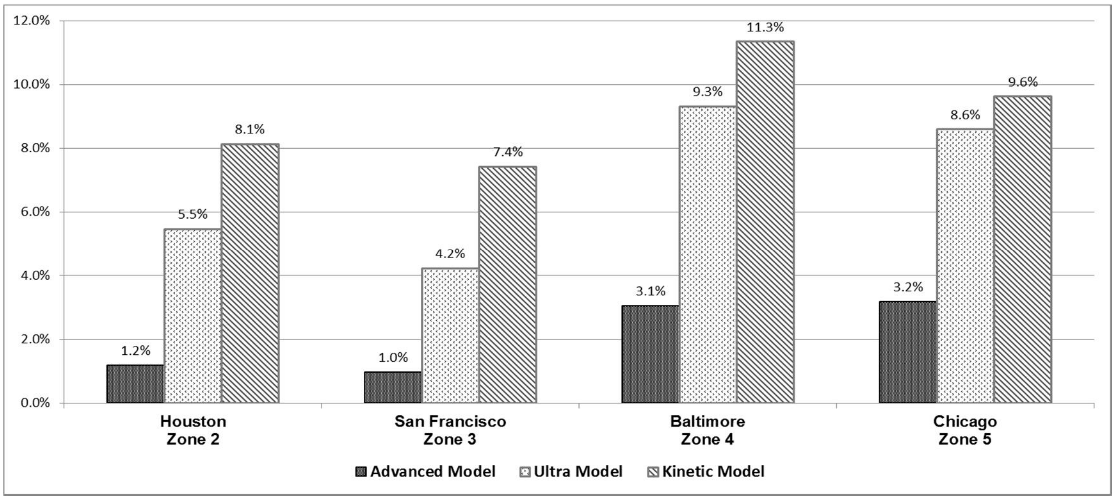


Figure 3.20. Savings percentages of the annual heating and cooling loads by walls on a basis of Baseline Models

Table 3.22. Summary of the annual heating and cooling loads by walls

	Houston		San Francisco		Baltimore		Chicago	
	MMBtu	GJ	MMBtu	GJ	MMBtu	GJ	MMBtu	GJ
Baseline Model								
Heating	6.3	6.7	7.5	7.9	22.2	23.4	33.1	34.9
Cooling	28.3	29.9	7.5	7.9	14.7	15.6	12.3	13.0
Advanced Model								
Heating	6.2	6.5	7.4	7.8	21.2	22.4	31.6	33.4
Cooling	28.1	29.7	7.5	8.0	14.6	15.4	12.2	12.9
Ultra Model								
Heating	5.8	6.1	7.0	7.4	19.1	20.2	29.2	30.8
Cooling	27.4	28.9	7.7	8.1	14.4	15.2	12.1	12.8
Kinetic Model								
Heating	5.9	6.2	7.1	7.5	19.5	20.5	29.5	31.1
Cooling	26.2	27.7	7.0	7.4	13.5	14.3	11.5	12.2

When it comes to the separate heating and cooling loads (Figure 3.21), the savings percentages related to walls showed almost same trends with roofs; that is, Ultra Models with super insulation performed with more savings percentages of heating loads in the four climates than the dynamic insulation of walls in Kinetic Models. The highest value 13.8% of heating loads savings from occurred in Ultra Models of Baltimore, but the total number (33.5MMBtu or 35.4GJ) of heating and cooling loads of Ultra Models was still higher than the loads (33.0MMBtu or 34.8GJ) of Kinetic Models.

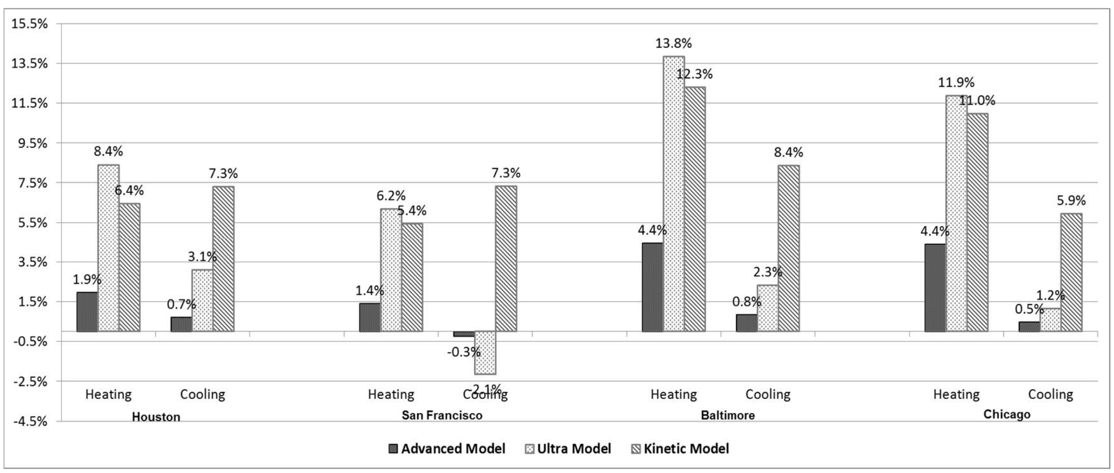


Figure 3.21. Separated savings percentages of heating / cooling loads by walls on a basis of Baseline Models

Regarding the peak demands related to walls' properties of four models, Figure 3.22 shows the peak heating loads for each climate, and Figure 3.23 presents the peak cooling loads. Compared to Baseline Models, Ultra Models with super insulated walls achieved more percentages on reduction of peak heating demands. However, dynamic insulated walls in Kinetic Models reduced more peak cooling demands.

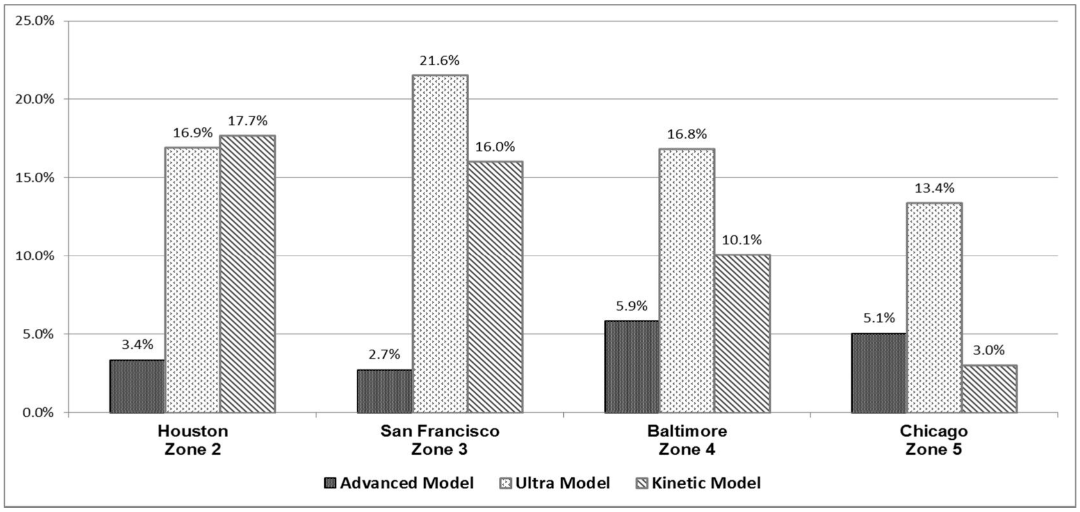


Figure 3.22. Savings percentages of peak heating loads by walls on a basis of Baseline Models

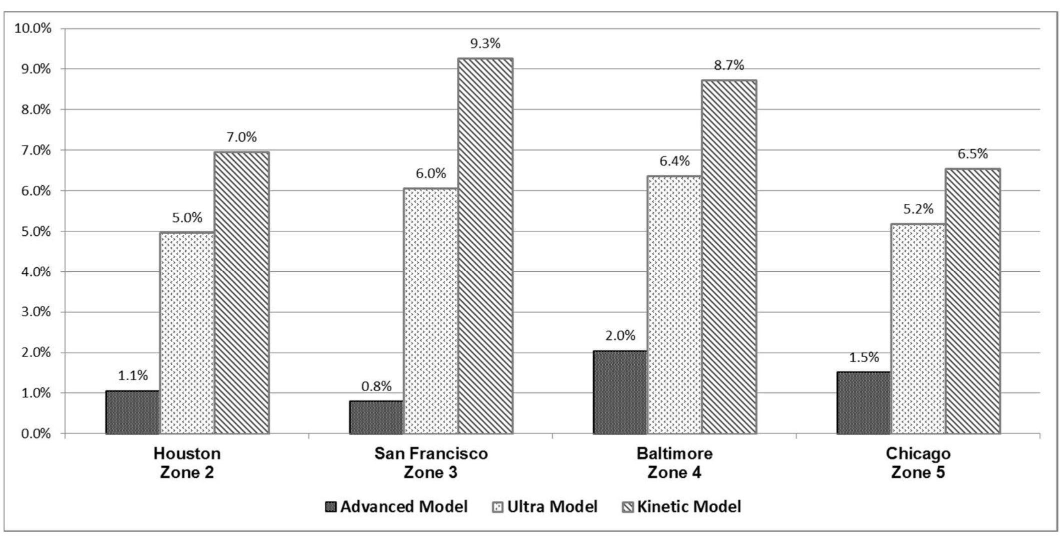


Figure 3.23. Savings percentages of peak cooling loads by walls on a basis of Baseline Models

3) Roofs and Walls

Basically, Figure 3.24, Figure 3.25 and Table 3.23 of simulation results from different thermal properties of walls and roofs combined the aforementioned trends of Walls Only and Roofs Only. The dynamic properties of walls and roofs were identical and described in Table 3.15. The dynamic insulation of the opaque assemblies of building envelopes presented more savings and higher percentages on heating and cooling loads in relation to the other three levels' models. As Figure 3.25 shows, the savings of cooling loads were the most significant parts to explain why Kinetic Models with dynamic insulated walls and roofs had the biggest savings among four models in each climate. However, Figure 3.25 also describes that the highest percentages of heating loads savings were from Ultra Models rather than Kinetic Models. This corresponded to the similar trends from the simulation results of Walls Only and Roofs Only.

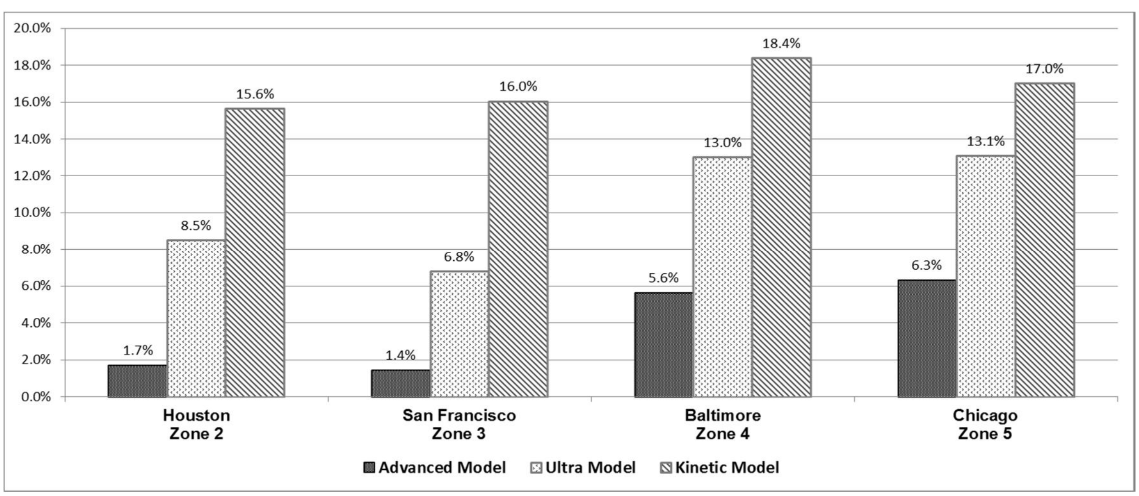


Figure 3.24. Savings percentages of the annual heating and cooling loads by roofs and walls on a basis of Baseline Models

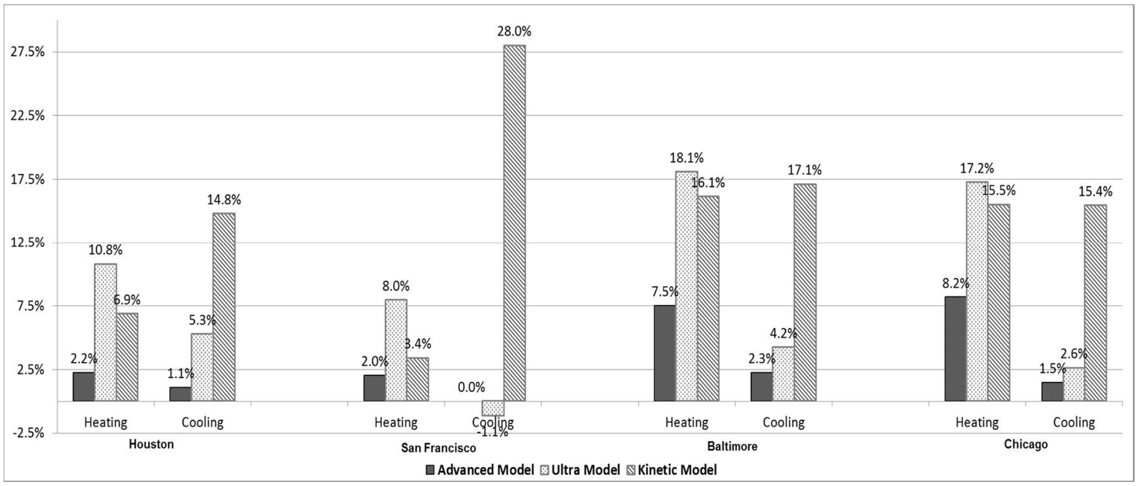


Figure 3.25. Separated savings percentages of heating / cooling loads by roofs and walls on a basis of Baseline Models

Table 3.23. Summary of the annual heating and cooling loads by walls and roofs for the four climates

	Houston		**San Francisco**		**Baltimore**		**Chicago**	
	MMBtu	GJ	MMBtu	GJ	MMBtu	GJ	MMBtu	GJ
Baseline Model								
Heating	6.3	6.7	7.5	7.9	22.2	23.4	33.1	34.9
Cooling	28.3	29.9	7.5	7.9	14.7	15.6	12.3	13.0
Advanced Model								
Heating	6.2	6.5	7.4	7.8	20.5	21.7	30.4	32.0
Cooling	28.0	29.5	7.5	7.9	14.4	15.2	12.1	12.8
Ultra Model								
Heating	5.6	6.0	6.9	7.3	18.2	19.2	27.4	28.9
Cooling	26.8	28.3	7.6	8.0	14.1	14.9	12.0	12.6
Kinetic Model								
Heating	5.9	6.2	7.3	7.7	18.6	19.6	28.0	29.5
Cooling	24.1	25.4	5.4	5.7	12.2	12.9	10.4	11.0

Regarding the peak heating / cooling demands related to the opaque' properties of four models, Figure 3.26 shows the peak heating loads for each climate, and Figure 3.27 presents the peak cooling loads. The combination of walls and roofs revealed the similar trends of the results from the simulation of Walls Only and Roofs Only but it had more apparent differences. The greatest value of reduction percentages of peak heating loads was 33.0% in Ultra Models of San Francisco, and the other cities' Ultra Models also had over 22.0% reduction percentages on peak heating demands. With respect to peak cooling loads, dynamic insulated walls and roofs showed the highest reduction percentages compared to the other models on the basis of Baseline Models.

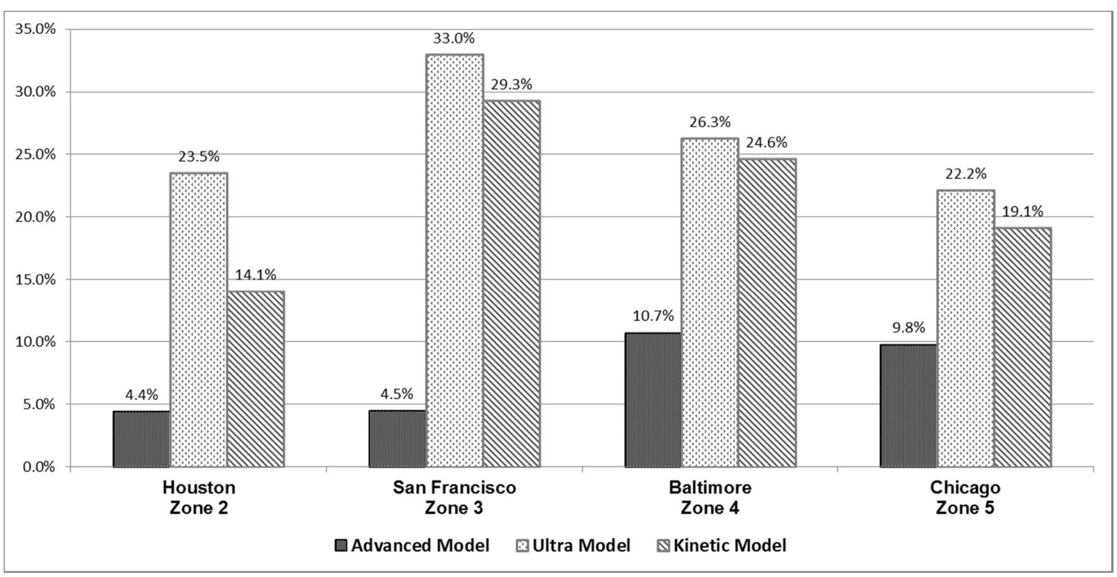


Figure 3.26. Savings percentages of peak heating loads by walls and roofs on a basis of Baseline Models

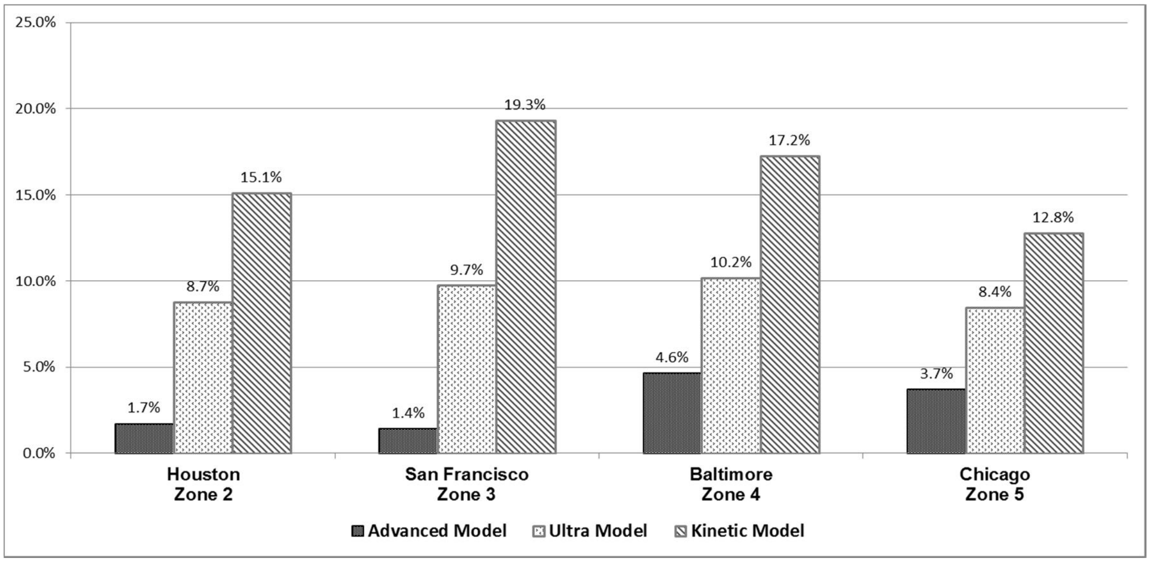


Figure 3.27. Savings percentages of peak cooling loads by walls and roofs on a basis of Baseline Models

4) Windows Only

The dynamic features of windows in these simulations were similar to the previous windows input of Kinetic Models and described in Table 3.16 and Table 3.17. Super insulated windows of Ultra Models were explained in Table 3.14. Except for the windows' settings, the other settings were identical in all four models for each climate. As shown in Figure 3.28 (see below), dynamic U-factors and SHGC of windows in Kinetic Models achieved more savings of heating and cooling loads than the other models. The savings percentages based on the basis of Baseline Models were 49.9% for Houston, 30.2% for San Francisco, 38.5% for Baltimore, and 40.6% for Chicago. In addition, Table 3.24 displays the detailed values of heating and cooling resulted from only changing thermal properties of windows in the different models for each climate.

Also, in these climates (with two exceptions of Houston's cooling loads and Baltimore's heating loads), Figure 3.29 presents dynamic properties of windows in Kinetic Models offered higher saving percentages in relation to the other types of models on the basis of Baseline Models. One exception was the heating loads of Houston; that is, the heating loads of Ultra Models were slightly higher (0.1 MMBtu) than the ones of Kinetic Models. Another exception was related to the cooling loads of Baltimore. The highly-insulated windows with the static SHGC value (0.10) performed almost as well as the dynamic insulation windows with kinetic SHGC (0.10 to 0.35) on an annual cooling load basis. Figure 3.29 presents an interesting issue about the annual cooling loads in Chicago. Ultra Model's windows with 0.10 Btu/h•ft^2•°F (0.57 W/m2•K) U-factor and 0.35 SHGC did not save the cooling load but rather increased around 4.2% loads compared to Baseline Models that had 0.47 Btu/h•ft^2•°F (2.65 W/m2•K) U-factor and 0.43 SHGC. Since the extreme lower U-factor of windows may prevent the heat exchange from indoor spaces to outdoor environment, the heat gains from interior equipment and people were hard to be moved to outside during some summer cooling periods with appropriate outside temperature. After reviewing the weather data of Chicago and the simulation results, it was found that this climate during the summer season has comfortable outdoor temperatures. Nevertheless, dynamic windows with changeable U-factors and SHGC can identify exterior and interior conditions and then provide optimal thermal performance.

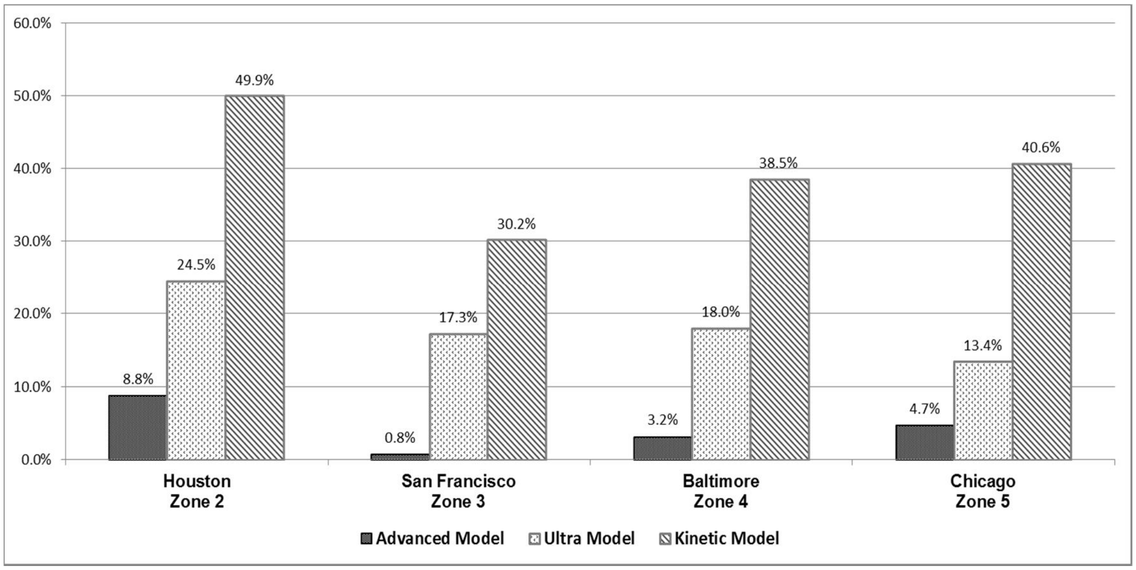


Figure 3.28. Savings percentages of the annual heating and cooling loads by windows on a basis of Baseline Models

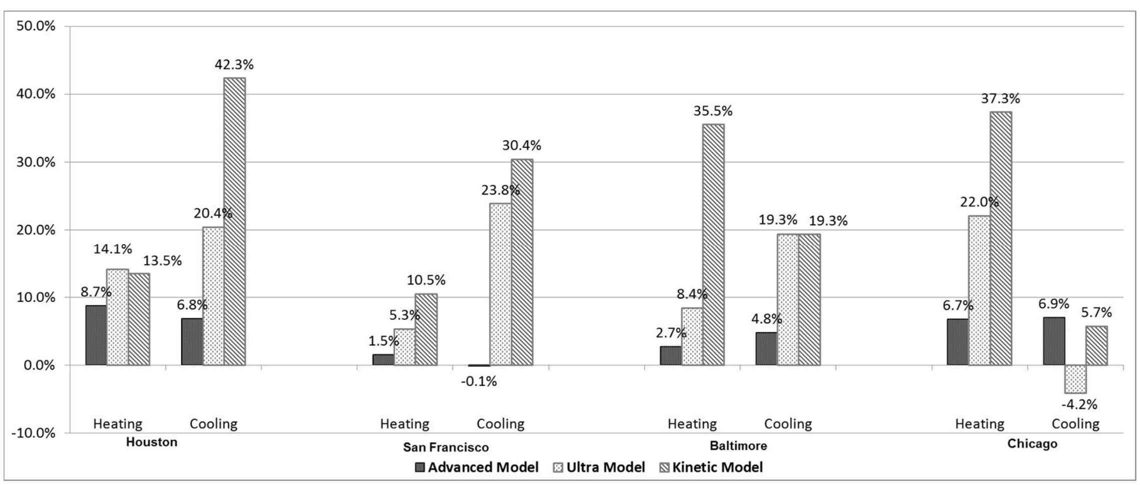


Figure 3.29. Separated savings percentages of heating / cooling loads by windows on a basis of Baseline Models

Table 3.24. Summary of the annual heating and cooling loads by windows on a basis of Baseline Models

	Houston		San Francisco		Baltimore		Chicago	
	MMBtu	GJ	MMBtu	GJ	MMBtu	GJ	MMBtu	GJ
Baseline Model								
Heating	6.3	6.7	7.5	7.9	22.2	23.4	33.1	34.9
Cooling	28.3	29.9	7.5	7.9	14.7	15.6	12.3	13.0
Advanced Model								
Heating	5.8	6.1	7.4	7.8	21.6	22.77	30.9	32.55
Cooling	26.4	27.8	7.5	7.9	14.0	14.81	11.4	12.05
Heating-savings	0.5	0.6	0.1	0.1	0.6	0.63	2.2	2.4
Cooling-savings	1.9	2.1	0	0	0.7	0.79	0.9	0.9
Ultra Model								
Heating	5.4	5.7	7.1	7.5	20.3	21.4	25.8	27.2
Cooling	22.5	23.8	5.7	6.0	11.9	12.6	12.8	13.5
Heating-savings	0.9	1	0.4	0.4	1.9	2	7.3	7.7
Cooling-savings	5.8	6.1	1.8	1.9	2.8	3	-0.5	-0.5
Kinetic Model								
Heating	5.5	5.8	6.7	7.1	14.3	15.1	20.7	21.9
Cooling	16.3	17.2	5.2	5.5	11.9	12.6	11.6	12.2
Heating-savings	0.8	0.9	0.8	0.8	7.9	8.3	12.4	13
Cooling-savings	12	12.7	2.3	2.4	2.8	3	0.7	0.8

Figures 3.30 and 3.31 show peak heating demands and peak cooling demands respectively. Compared to the previous discussed contents of the opaque assemblies, the trend of windows in the peak heating loads is different. Dynamic windows, in the four

climates, significantly reduced the peak heating demands in relation to the other types of windows. Except for Houston, the savings percentages in the other three climates were around 70% on the basis of Baseline Models. Regarding the peak cooling loads, kinetic windows of Kinetic Models also performed better than Ultra Models and Advanced Models for all cities, especially in Chicago (54%).

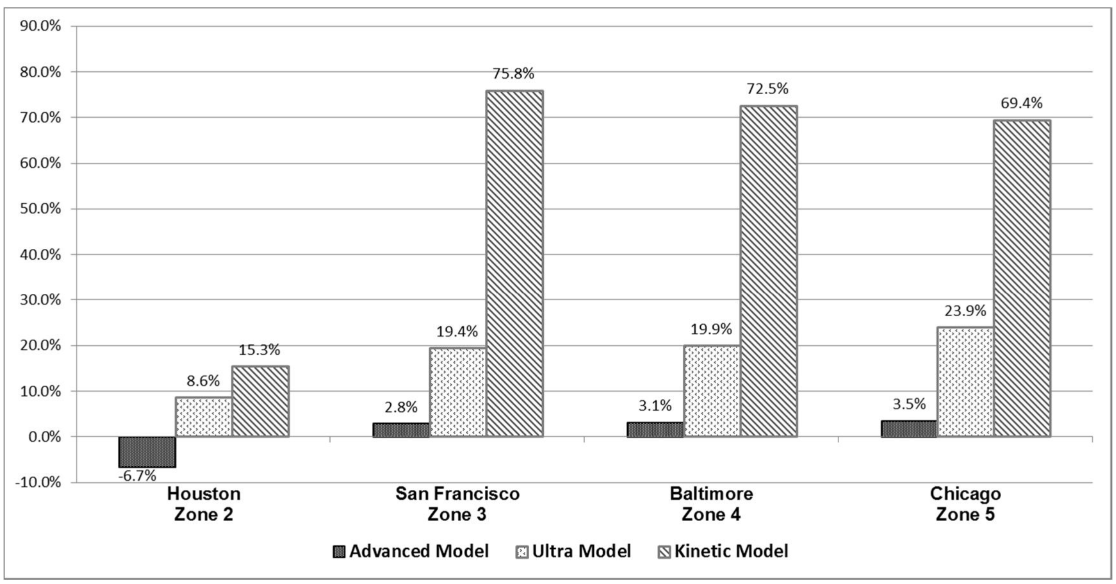


Figure 3.30. Savings percentages of peak heating loads by windows on a basis of Baseline Models

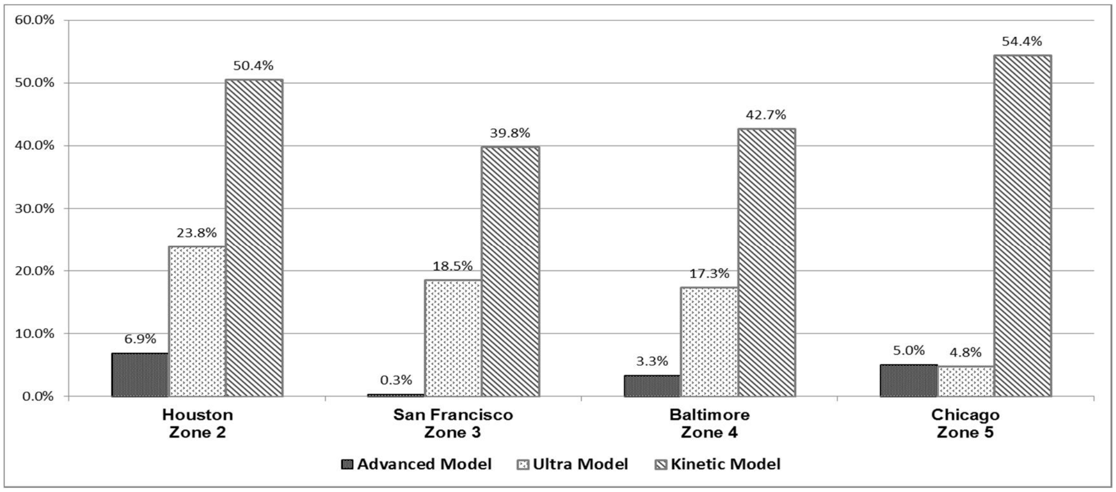


Figure 3.31. Savings percentages of peak cooling loads by windows on a basis of Baseline Models

5) Comparison on Envelope Assemblies

Because the savings of the four models with each envelope assembly were based on the same baseline for each climate, we can compare the contributions of each assembly to the savings of the heating and cooling loads. In general, Figure 3.32 illustrates that kinetic envelope assemblies achieved more savings percentages for the four climates on the basis of Baseline Models.

- Windows played more significant roles of saving energy than the other envelope components, and the highest value from windows was 49.9% from Kinetic Models of Houston. The lowest value, 30.2%, occurred in Kinetic Models of the mixed-climate of San Francisco. When it comes to the amount of loads savings, dynamic windows saved loads 56.01GJ for Houston, 21.56GJ for San Francisco, 44.1GJ for Baltimore, and 52.65GJ for Chicago.

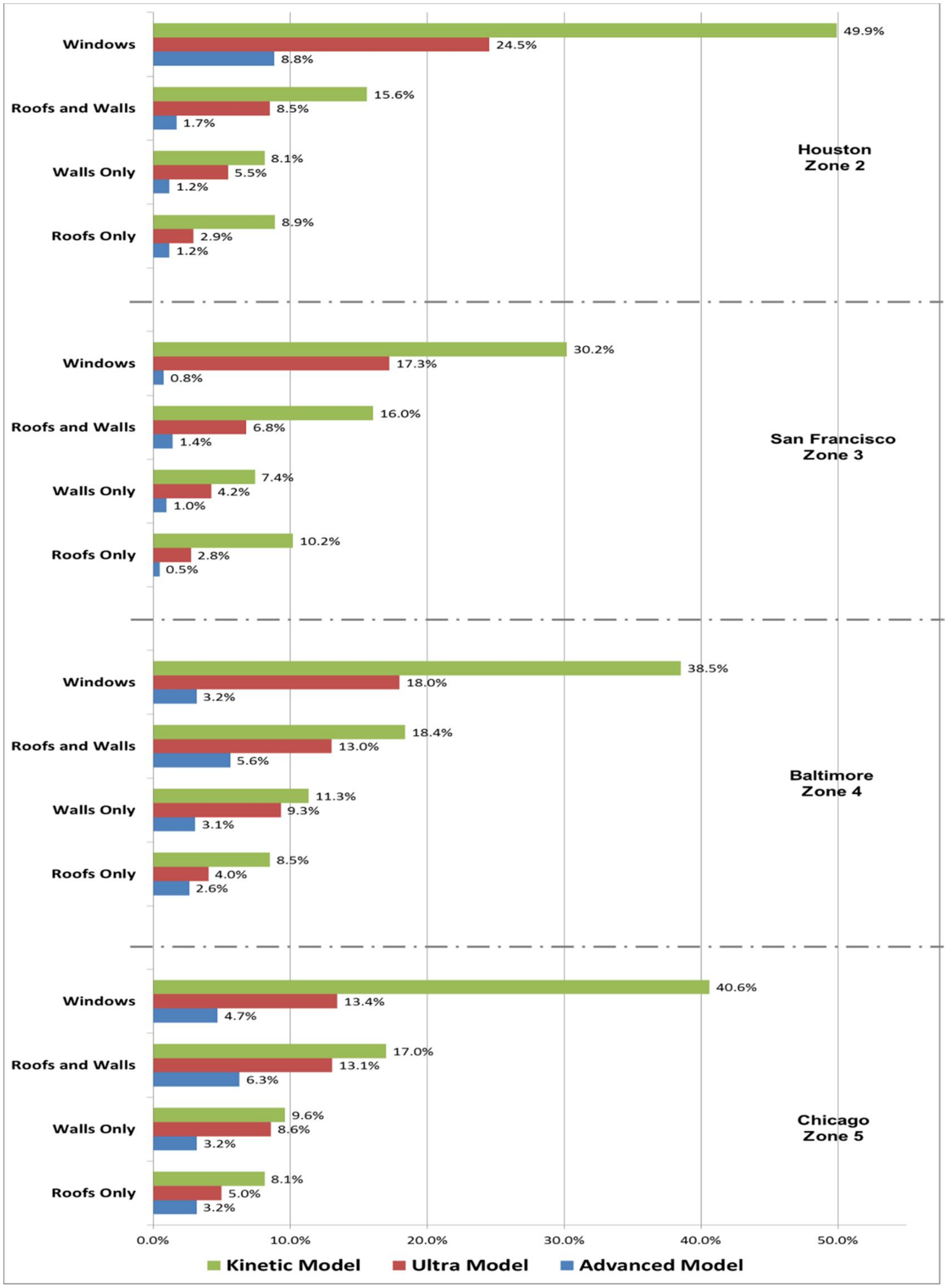


Figure 3.32. Summary of savings percentages of heating and cooling loads by each envelope assembly on a basis of Baseline Models

- In Ultra Models of the four climates, windows also contributed more savings than the other opaque assemblies. However, in the Advanced Models, the opaque parts of envelopes achieved more savings than the windows in these climates except for Houston.
- The opaque parts (combination of walls and roofs) of Kinetic Models produced the second highest percentages in heating and cooling loads for each climate, which ranged from 15.6% to 18.4%.
- The values related to Walls Only and Roofs Only from Kinetic Models displayed a clear trend. In Houston and San Francisco, dynamic insulated roofs offered more savings of heating and cooling loads than walls. However, walls in the climates of Baltimore and Chicago achieved more savings than the roofs. Thus, in the heating-dominated climate, dynamic properties of walls performed better than the same settings of roofs. In the cooling-dominated climate, the trend was reversed.
- In Ultra Models and Advanced Models, walls with enhanced U-factors consistently offered more savings percentages than the percentages by roofs with same enhanced U-factors for each climate.

Figures 3.33 and 3.34 depict the savings of the annual heating loads and the savings of the annual cooling loads respectively.

- As previously discussed, the savings of the annual heating loads from dynamic windows in the heating-dominated climate (8.1GJ for Baltimore and 13.3GJ for Chicago) were over twice as large as the savings of the opaque assemblies, and the savings of the annual cooling loads in the cooling-dominated climate (12.64GJ for Houston) were nearly three times as large as the savings of the opaque assemblies. For the mixed-climate in San Francisco, the dynamic insulated opaque parts performed nearly as well as dynamic windows.

- In Ultra Models, windows with super insulation and static SHGC did not perform better than opaque parts in saving heating loads and saving cooling loads in the four climates. In Advanced Models, windows with enhanced thermal properties offered fewer savings in cooling loads than the savings of the opaque parts in most climates. However, opaque parts performed with smaller reductions for cooling loads than windows in the four climates.
- With respect to heating loads, the dynamic insulation of walls produced more savings than dynamic characteristics of roofs in the four climates. On the contrary, in the annual cooling loads, the savings from kinetic roofs were larger than the savings from kinetic walls in the four climates. These detailed comparisons can describe the aforementioned trends of savings percentages of walls and roofs. However, these trends in Ultra Models and Advanced Models were different; that is, walls with enhanced thermal properties consistently saved more heating and cooling loads than roofs with same enhanced thermal properties.

The possible reasons for these trends are related to the input settings of Baseline Models. Table 3.5 and Table 3.6 shows that roofs in Baseline Models in accordance with

ASHRAE Standard 2010 have higher insulation materials than walls. Therefore, the improvements of R-values of roofs in Ultra Models and Advanced Models were lower than the enhancements of walls, which may result in more energy savings occurred in changing walls rather than changing roofs in Ultra Models and Advanced Models.

Regarding Kinetic Models, it was demonstrated that the highly-insulated walls and roofs performed better than the dynamic insulation of walls and roofs in terms of the annual heating loads. Since the insulation's U-factors were changed to the high values when the outside temperature was within certain appropriate ranges, the dynamic insulation of the opaque assemblies was more to do with heat exchanges between indoor and outdoor. Especially, these high values of U-factors facilitate moving heat gains out which are from equipment and people during summer cooling periods. Therefore, compared to the highly-insulated opaque assemblies, variable thermal properties were more suitable to the cooling-dominated climate because the highly-insulated opaque assemblies performed better in saving heating loads, which were illustrated by the previous detailed comparisons (e.g., Figure 3.17, 3.21, and 3.25). Moreover, there are two reasons to explain why roofs contributed more cooling savings than walls. On one hand, the input of R-value of roofs in Baseline Models was already higher than the values of walls. The same range of variation of U-factors provided more influences on roofs than walls. On the other hand, these simulation results were based on one-floor prototypical small office. The area of roofs (5,500 sq. ft.) was larger than the area of perimeter walls (3,026 sq. ft.). This may have created more potential heat transfer through the roofs during summer cooling periods under appropriate external temperature conditions. So, the dynamic insulation of roofs played a more significant role in the reductions of the annual cooling loads and the entire energy consumption than the variable insulation of walls.

Figure 3.35 shows that dynamic windows reduced the largest number of the peak demands for the four climates compared to the other envelope assemblies. In particular, in the Kinetic Model of Chicago and Houston, the reduction of peak demands was nearly four times larger than the opaque parts. Between walls and roofs, the dynamic insulation of roofs obtained more reductions of peak demands than walls. This corresponded to the similar reasons that were discussed above. In Ultra Models of these climates, with the exception of Chicago, the peak demand savings for the highly-insulated windows were also higher than the other assemblies.

The previous analysis on peak heating and cooling loads demonstrated that peak demands were related to cooling loads for almost all models for each climate. Thus, I only compared the peak cooling demands for the four cities in this section.

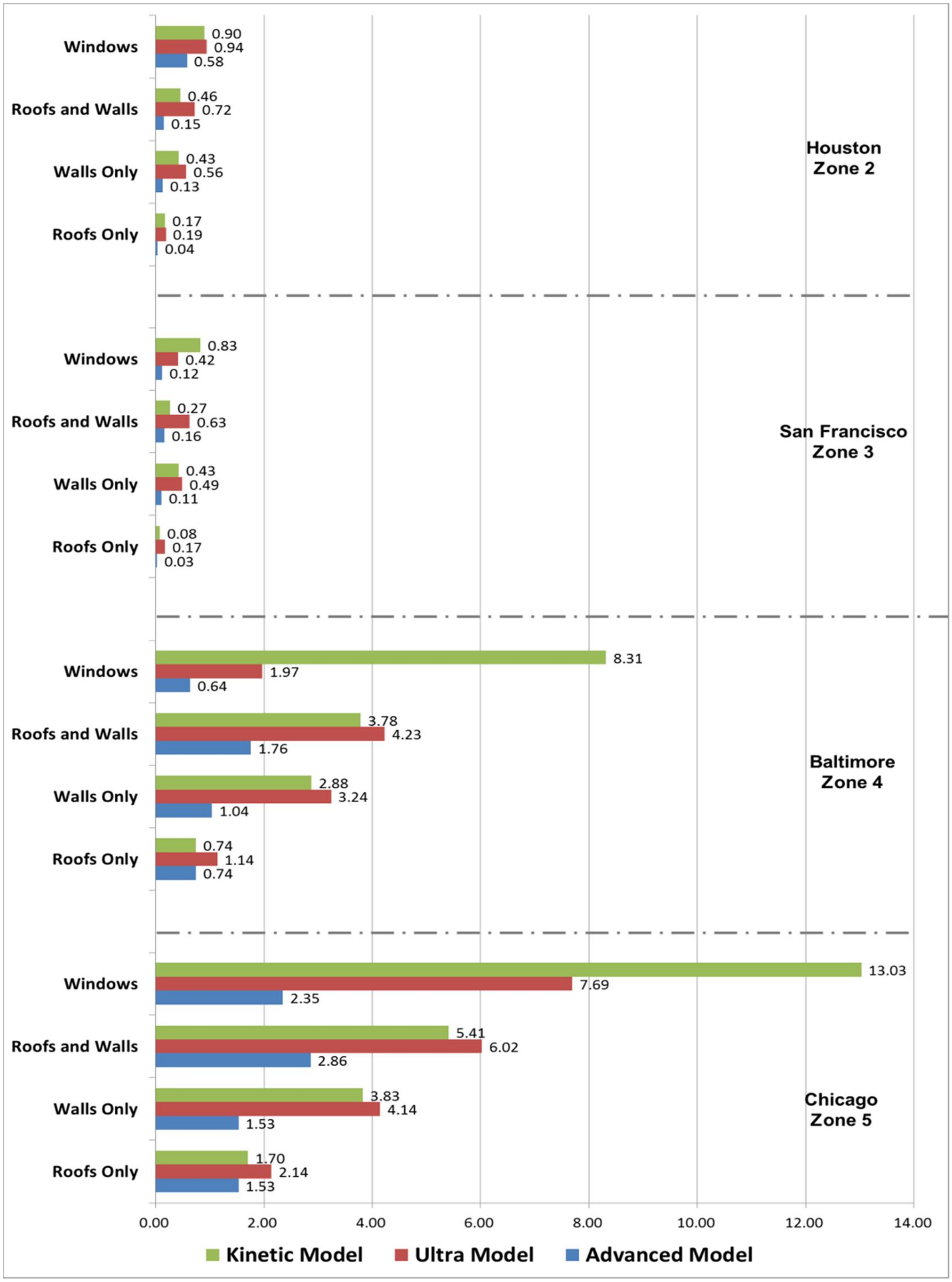


Figure 3.33. Summary of savings percentages of heating loads by each envelope assembly on a basis of Baseline Models

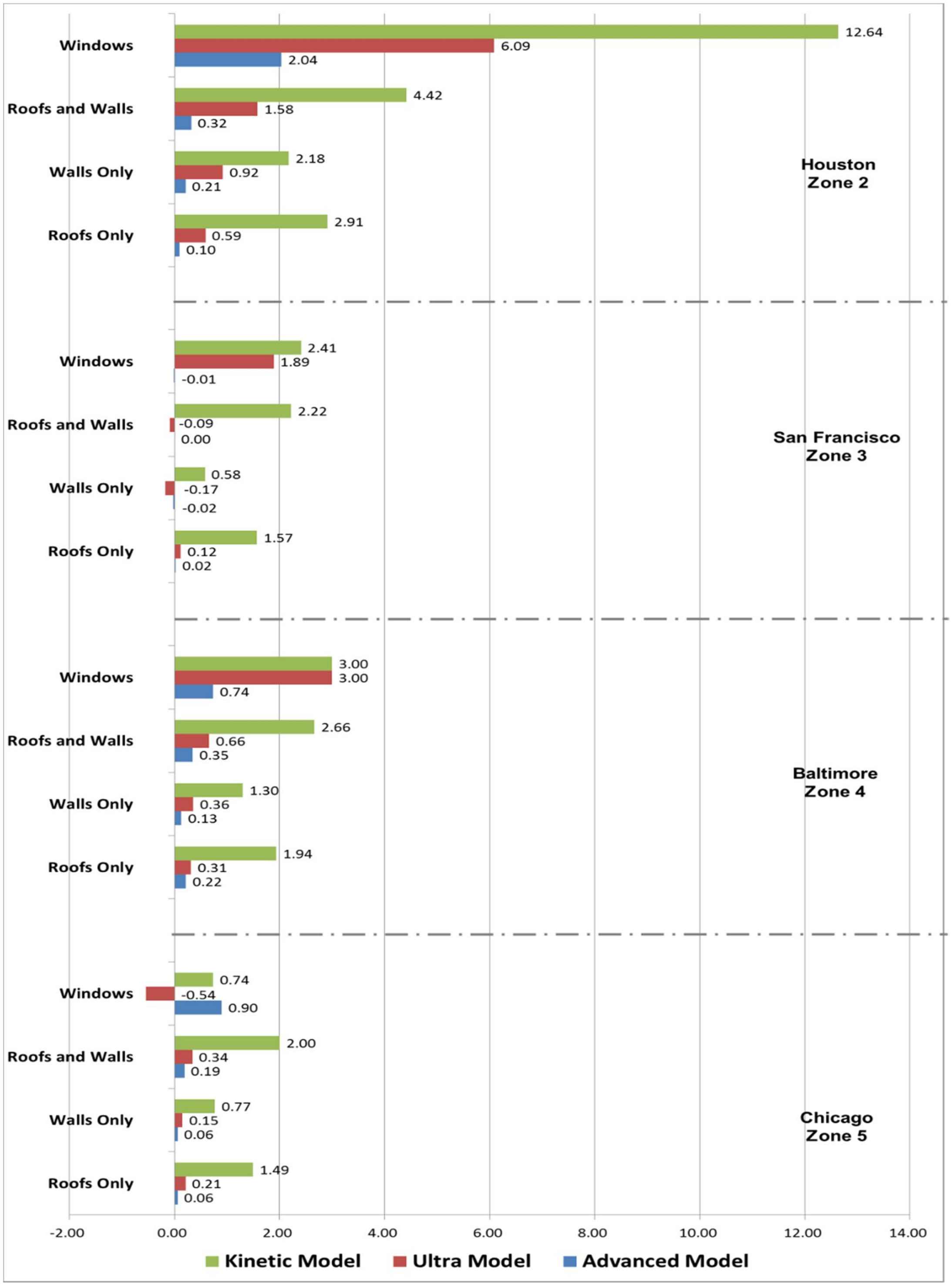


Figure 3.34. Summary of savings percentages of cooling loads by each envelope assembly on a basis of Baseline Models

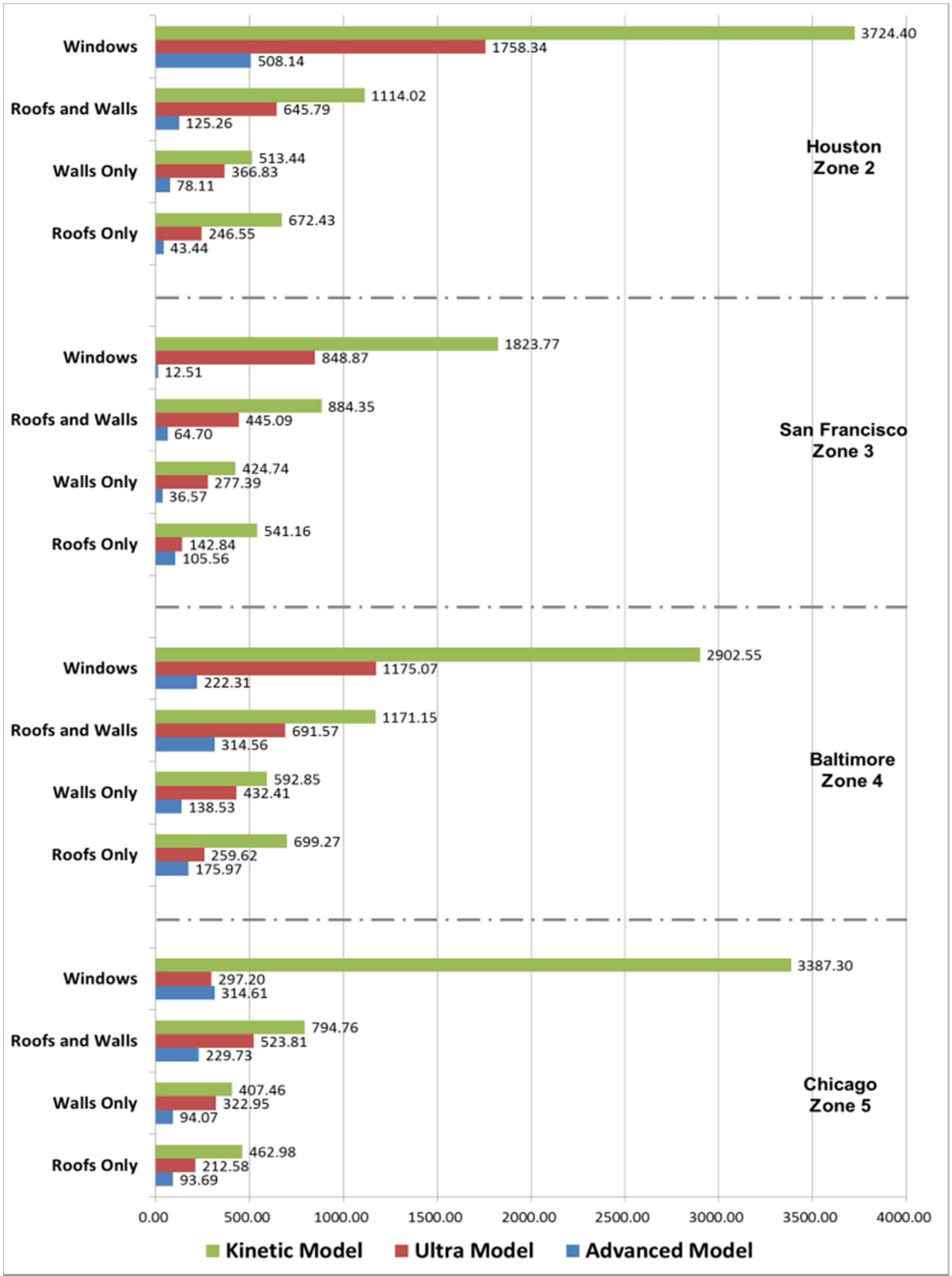


Figure 3.35. Summary of reductions of peak demands by each envelope assembly on a basis of Baseline Models

3.5.5 Effects of External Movable Blinds

The original prototypical models from PNNL had no exterior shadings. The mockup test of this research employed external movable blinds, so I conducted some *EnergyPlus* simulations with specific shading strategies (external Venetian blinds) for south, east, and west façade windows for the four climates. In order to meet the basic requirement of glare comfort, I used discomfort glare index (DGI) in *EnergyPlus* simulation.

The simulation calculated the DGI at the zone's first daylighting reference point from all of the exterior windows and compared the numbers with the maximum glare index. In *EnergyPlus*, the maximum allowable DGI was set at 22. In the *EnergyPlus* models, the reference points were set to the locations with 5.25 ft. to the side windows.

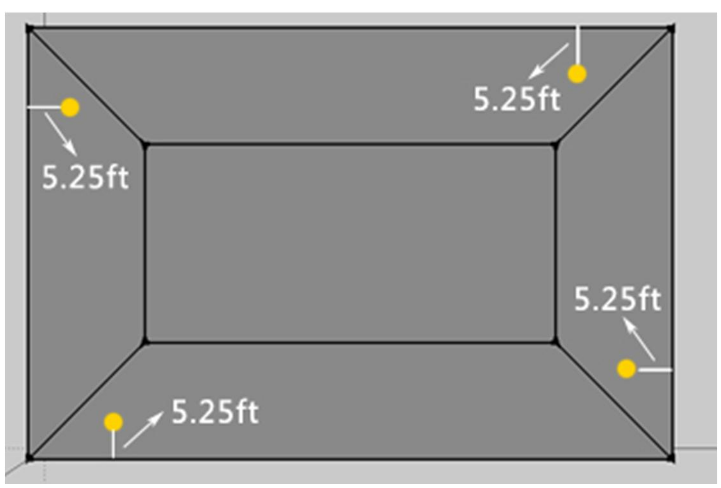


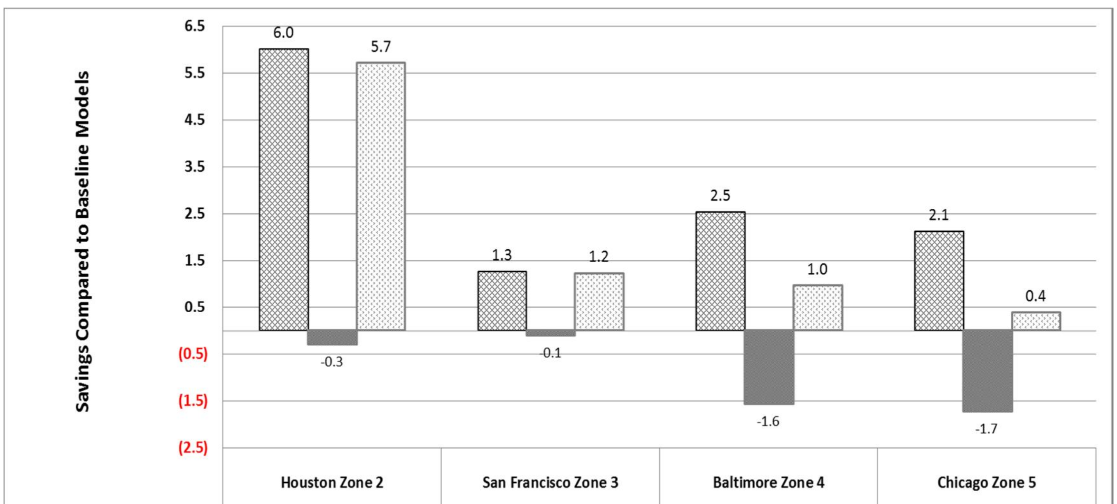
Figure 3.36. Reference points in perimeter zones

In addition, external blinds can also be used for blocking solar radiation during the summer cooling period. Therefore, I chose “On If High Zone Cooling” and “On If High Glare” input objects in *EnergyPlus* for the blinds, thus the blinds were activated in terms of two conditions: 1) The DGI at the zone’s reference point was higher than the maximum allowable of 22 (DOE, 2013). The slat angles were changeable according to thedirect solar beams. The “block beam solar” option enabled the blinds to block direct sunlight. 2) If there was no solar beam on the window, the blind’s movement was still activated by the cooling loads. When the blinds were deactivated, the slat angles remained horizontal. The following Figure 3.37 describes the settings in *EnergyPlus*.

Field	Units	Obj1
Name		Blinds
Slat Orientation		Horizontal
Slat Width	m	0.085
Slat Separation	m	0.07
Slat Thickness	m	.00025
Slat Angle	deg	0
Slat Conductivity	W/m-K	100
Slat Beam Solar Transmittance		
Front Side Slat Beam Solar Reflectance		0.7
Back Side Slat Beam Solar Reflectance		0.7
Slat Diffuse Solar Transmittance		
Front Side Slat Diffuse Solar Reflectance		0.7
Back Side Slat Diffuse Solar Reflectance		0.7
Slat Beam Visible Transmittance		0.1
Front Side Slat Beam Visible Reflectance		0.9
Back Side Slat Beam Visible Reflectance		0.9
Slat Diffuse Visible Transmittance		0.1
Front Side Slat Diffuse Visible Reflectance		0.9
Back Side Slat Diffuse Visible Reflectance		0.9
Slat Infrared Hemispherical Transmittance		
Front Side Slat Infrared Hemispherical Emissivity		.9
Back Side Slat Infrared Hemispherical Emissivity		.9
Blind to Glass Distance	m	.05
Blind Top Opening Multiplier		.5
Blind Bottom Opening Multiplier		
Blind Left Side Opening Multiplier		.5
Blind Right Side Opening Multiplier		.5
Minimum Slat Angle	deg	0
Maximum Slat Angle	deg	80

Figure 3.37. Input information of external movable blinds in *EnergyPlus*

Figure 3.38 shows the savings and the percentages of external movable blinds for each climate. Cooling energy savings were largely the result of the incorporation of the blinds, and the highest value occurred in the cooling-dominated climate of Houston. However, integrating blinds into models increased winter heating loads particularly in the heating-dominated climate. The HVAC loads savings of Chicago demonstrated that cooling savings by blinds were generally offset by heating energy increases. Thus, the annual HVAC loads of Baseline Models in Chicago and Baltimore were only slightly greater (0.6% to 1.6%) than that of the Models with external blinds.



	Houston Zone 2	San Francisco Zone 3	Baltimore Zone 4	Chicago Zone 5
Cooling Loads Savings (GJ)	6.0 (11.5%)	1.3 (5.1%)	2.5 (11.3%)	2.1 (6.4%)
Heating Loads Savings (GJ)	-0.3 (-4.5%)	-0.1 (-0.5%)	-1.6 (-6.7%)	-1.7 (-5.0%)
HVAC Savings (GJ)	5.7 (9.7%)	1.2 (3.7%)	1.0 (1.6%)	0.4 (0.6%)

Figure 3.38. Savings and percentages of heating and cooling loads by movable blinds

Furthermore, movements of blinds in these models increased indoor lighting energy for the four climates. So, considering the increases of lighting loads, the effects on total energy of blinds is shown in Figure 3.39. The lighting loads for each climate were increased from 2.3GJ to 3.2GJ. These increased lighting loads offset of the HVAC loads savings by blinds so that the final loads with interior lighting energy were higher than the values in Baseline Models. The only exception is Houston in which the energy still had 2.9% savings since the cooling loads were significantly reduced by blinds.

External movable blinds can reduce cooling loads, but they increase the heating and the interior lighting loads. Therefore, only the installations of the moveable blinds in cooling-dominated climates can obtain the energy savings. In the mixed-climate and heating-dominated climate, the movable blinds did not save energy because of the resulting increased winter energy and the lighting energy outweighed the summer cooling energy savings. However, movable blinds were proposed for glare protection, so the indoor visual comfort should be enhanced (This was demonstrated by the surveys at the mockup workspaces in Chapter IV).

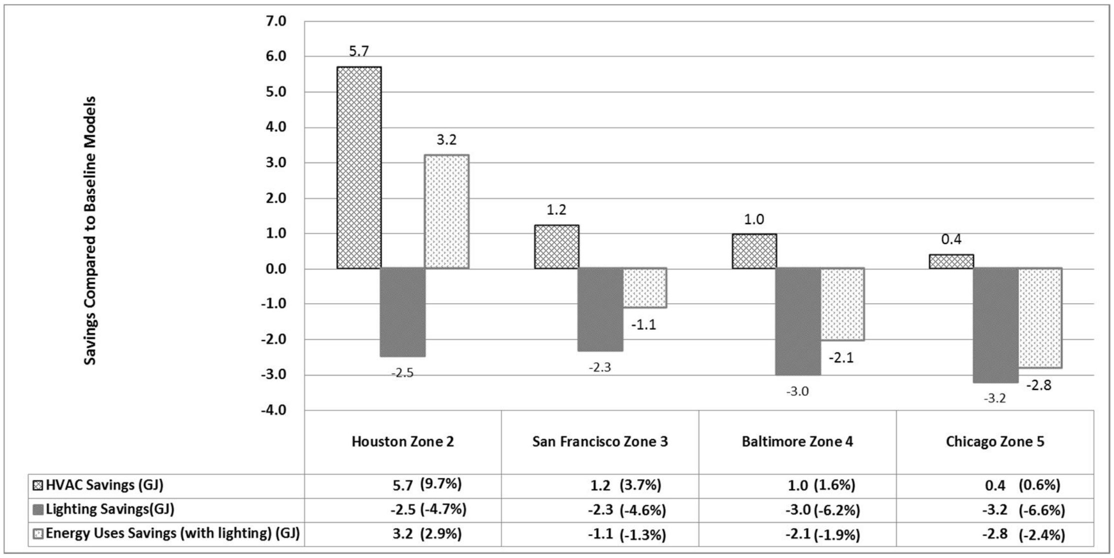


Figure 3.39. Savings and percentages of energy uses with lighting loads by movable blinds

3.5.6 Building Site Energy Usage

In this section, the building site energy generated by *EnergyPlus* of Advanced Models, Ultra Models, and Kinetic Models in four climatic zones was compared to Baseline Models. The site energy referred to utility, electricity, and natural gas delivered and used at the building site, thus it included plug and process loads. This work aimed to investigate the potential energy savings of the entire building with kinetic envelopes. Since the plug and process loads occupied a large percentage of the total site energy uses, I compiled some recommended energy saving strategies for indoor and outdoor lights, water systems, interior equipment, HVAC systems, etc. from multiple sources including *Technical Support Document: 50% Energy Savings for Small Office Buildings* (Thornton, Wang, Huang, Lane, & Liu, 2010), and *AEDG for Small to Medium Office Buildings*

(ASHRAE, 2011). Table 3.25 presents the input information related to these parameters of the simulation models for four climatic zones. The other input information of simulation models was the same with above Kinetic Models, e.g., dynamic insulation of opaque materials, variable U-factors, and SHGC of windows, etc.

Table 3.25. Summary of input parameters related to HVAC, lighting, and envelopes

		Houston, TX	San Francisco, CA	Baltimore, MD	Chicago, IL
Envelopes	Floors	R-4.2	R-10.4	R-12.5	R-14.6
	Doors	U-0.70	U-0.70	U-0.50	U-0.50
	Shading	External movable blinds (except for north façade)			
Lighting / daylighting	Setpoint	Illuminance setpoint of 300 lux			
	Glare protection	DGI < 22			
	Interior lighting	LPD= 0.68 W/ft^2			
	Interior finishes	Ceilings = 80%; wall surfaces = 70%			
	Lighting controls	This continuous dimming control can dim down to 10% of maximum light output with a corresponding 10% of maximum power input.			
	Lighting control areas	Dim all fixtures in daylight zones			
	Exterior lighting	750 watts			

Table 3.25. Continued

Plug	Equipment options	0.45 W/ft2 (4.8 W/m^2)
HVAC	System type	Ground source heat pump with a DOAS for ventilation
	GSHP cooling efficiency	GSHP cooling efficiency 15 SEER
	GSHP heating efficiency	3.55 COP
	Boiler efficiency	90% Ec
	Maximum fan power	0.4 W/cfm
Fan	System type	Fan-coil system with DOAS
	Boiler efficiency	90% Ec
	Maximum fan power	0.4 W/cfm
SWH	Thermal efficiency	90%

Figure 3.40 shows the percentage savings of kinetic-integrated models (kinetic envelopes and above recommendations in Table 3.25) and 90.1-2010 base cases. The savings ranged from 38.8% to 42.0% for each climate.

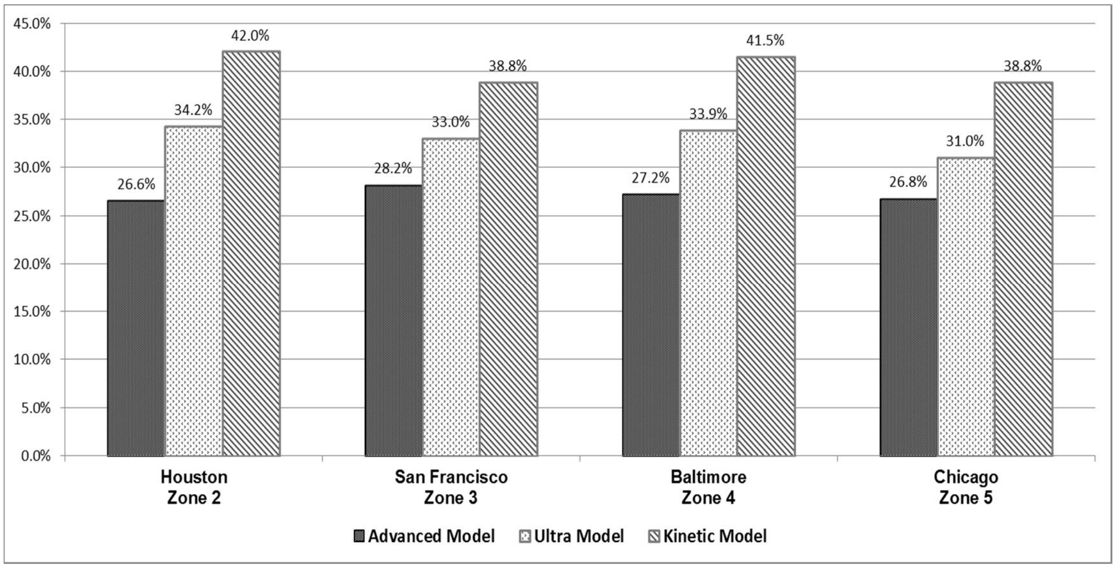


Figure 3.40. Savings percentages of energy uses by kinetic envelopes on a basis of Baseline Models

Also, Table 3.26 presents the final energy loads for these kinetic-integrated models. The values of site energy use intensity (EUI) were 18.9 KBtu/ft^2·yr (214.5MJ/m^2·yr) for Houston, 17.2 KBtu/ft^2·yr (195.6 MJ/m^2·yr) for San Francisco, 19.1 KBtu/ft^2·yr (216.8 MJ/m^2·yr) for Baltimore, and 20.8 KBtu/ft^2·yr (236.1 MJ/m^2·yr) for Chicago. To achieve zero-energy building (ZEB), National Renewable Energy Laboratory (NREL) (NREL, 2007) assessed the energy performance for a large set of commercial buildings based on technologies that are projected to be available in 20 years. They noted the average EUI value could be as little as 40.3 kBtu/ft^2·yr (458 MJ/m^2·yr). One characteristic example is the new Research Support Facility at DOE's NREL in Golden, Colorado, which was considered as one of the world's most energy-efficient office buildings. Also, rooftop PV systems led the building energy to the net-zero level during certain days (NREL, 2011). The real EUI value was 35.4 kBtu/ft^2 ·yr (402.3 MJ/m^2·yr). Therefore, compared with these EUI remarks, the kinetic-integrated models with proposed dynamic features performed much better.

Table 3.26. Summary of building site energy

Category	Heating	Cooling	Interior Lighting	Exterior Lighting	Interior Equipment	Fans	Water Systems
Houston, TX, Zone 2							
KBtu/ft^2	1.4	1.5	5.5	1.1	6.7	1.2	1.5
MJ/m^2	15.7	17.2	62.0	12.3	76.1	13.8	17.4
San Francisco, CA, Zone 3							
KBtu/ft^2	1.2	0.6	5.4	1.1	6.7	0.7	1.5
MJ/m^2	14.0	7.3	61.1	12.3	76.1	7.4	17.4
Baltimore, MD, Zone 4							
KBtu/ft^2	2.5	1.4	5.1	1.1	6.7	0.8	1.5
MJ/m^2	28.0	16.2	57.7	12.3	76.1	9.0	17.4
Chicago, IL, Zone 5							
KBtu/ft^2	3.4	2.1	5.1	1.1	6.7	0.9	1.5
MJ/m^2	38.8	23.4	57.7	12.6	76.1	10.0	17.4

In addition, Figure 3.41~3.44 show the proportions of each part of energy end uses in these future kinetic models with the recommended energy efficient strategies on the other parts including HVAC, water system, plug and process. Over 35% of the energy usage was interior equipment loads, which was mainly because of office requirements, and the remaining proportion around 30% was from interior lighting. As discussed in the NREL's study (Long, Torcellini, Judkoff, Crawley, & Ryan, 2007), office buildings have a below-average chance to achieve zero energy due to plug and process loads. HVAC (heating, cooling, and fans) occupies approximately 20% for Houston, San Francisco, and Chicago. Baltimore's HVAC shared 32.4% of energy uses. The HVAC load savings were largely the result of the kinetic envelope properties. Therefore, if these kinetic envelopes will be available in future, a further step to save overall building energy is related to the plug loads and the interior lighting loads, which occupied around 60~70% of energy consumption for the four cities.

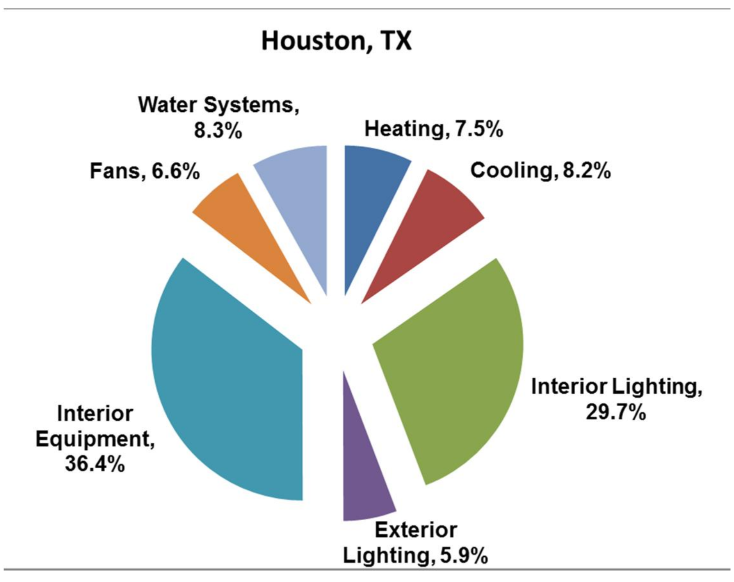


Figure 3.41. Proportions of each category of energy uses for Houston

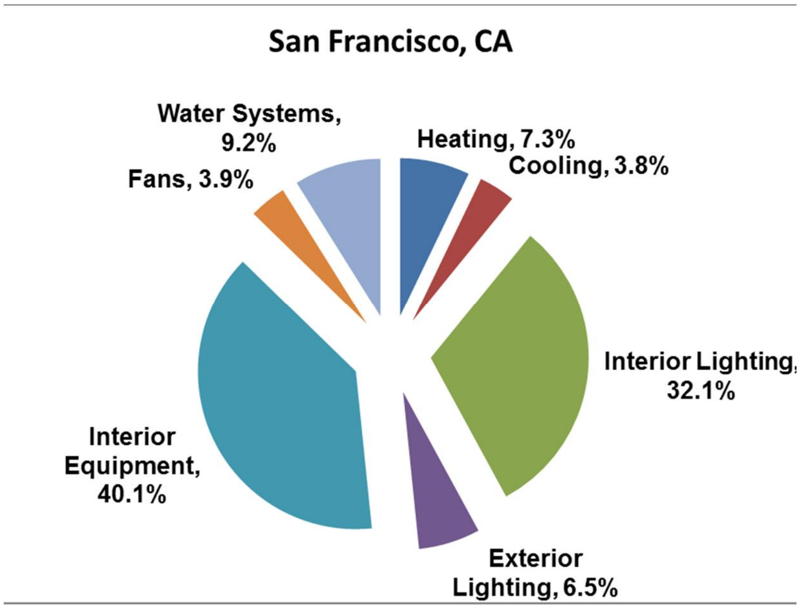


Figure 3.42. Proportions of each category of energy uses for San Francisco

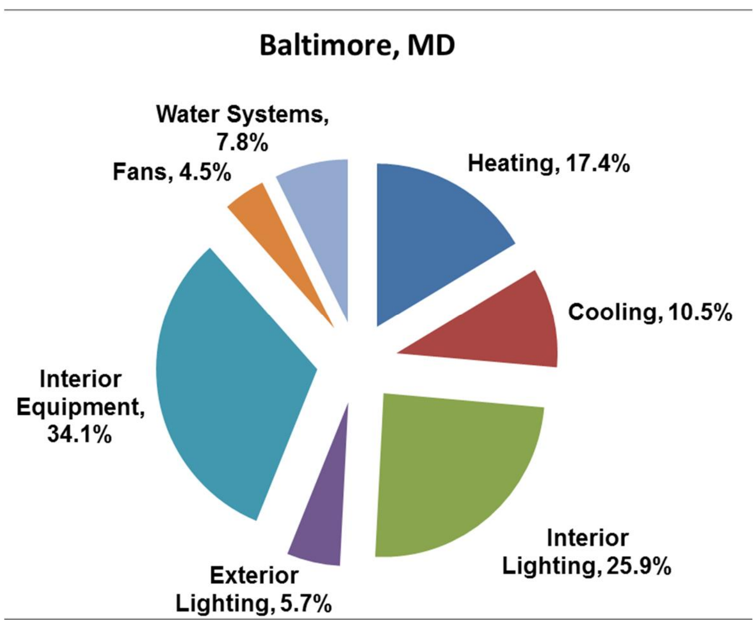


Figure 3.43. Proportions of each category of energy uses for Baltimore

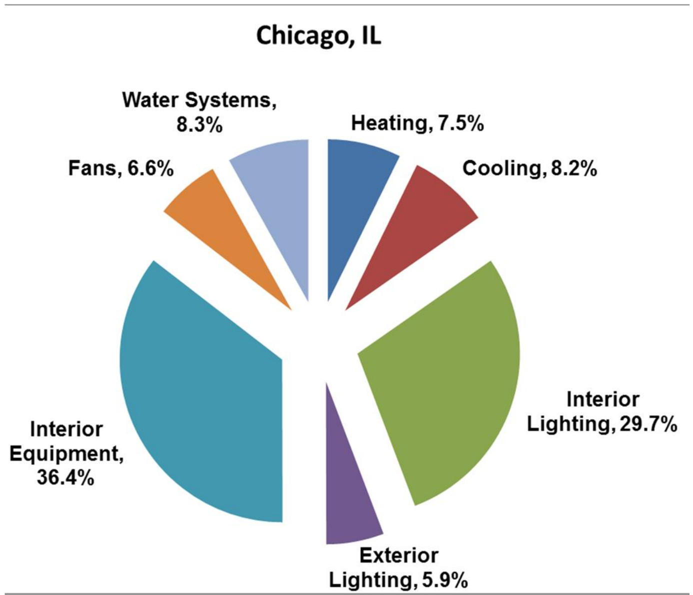


Figure 3.44. Proportions of each category of energy uses for Chicago

3.6 Chapter Summary

This chapter shows the energy simulation techniques for kinetic building envelopes. Based on *EnergyPlus*, some specific built-in features related to "Variable Thermal Properties", the Energy Management Simulation (EMS), and *jEPlus* were utilized for this study. Especially, EMS of *EnergyPlus* offered an effective approach to model and simulated kinetic envelopes with variable properties. Table 3.27 presents the detailed approaches for kinetic modeling and this whole simulation study.

Table 3.27 Programs for this simulation study

Models	Components	Programs
Reference Models	Building envelopes	*jEPlus* and *EnergyPlus*
Kinetic Models	Walls and roofs	Variable Thermal Conductivity of *EnergyPlus* and *jEPlus*
	Fenestration	EMS of *EnergyPlus*
	Movable blinds	Built-in features of blinds

Afterwards, a series of energy simulation were carried out to evaluate the effects of the kinetic envelope assemblies including variable insulation of opaque parts, dynamic windows and glazing, and movable blinds. The baseline model was set up in compliance with ASHRAE 90.1-2010 Energy Standard's requirements. Also, the other two advanced models with the enhanced envelope properties were compared to kinetic envelope models.

Finally, it described the simulation results in four different climates and compared Kinetic Models with other three referenced models: Baseline Models, Advanced Models, and Ultra Models. Kinetic Models in this study were considered with variable insulation of opaque parts, dynamic windows and glazing, and movable blinds:

- Variable insulation of opaque assemblies – The high U-factor 0.089 Btu/h•ft^2•°F (0.507 W/m^2•K) was used in walls and roofs when the outside temperature was within the comfort zone, and the low U-factor 0.016

Btu/h•ft²•°F (0.091 W/m^2•K) was used when the outside temperature was too high or too low. The high value and the low value of changeable U-factors were from the Baseline Models and Ultra Models respectively.Dynamic windows and glazing – The windows had two seasonally-changeable parameters: U-factors and SHGC. The U-factors were changed from 0.1Btu/h•ft²•°F (0.57W/m^2•K) to 0.81Btu/h•ft²•°F (4.6W/m^2•K), and the values of SHGC ranged from 0.10 to 0.35. These values were grouped into the four window types (window01 referring to Low_U_High_SHGC, window02 referring to Low_U_Low_SHGC, window03 referring to High_U_Low_SHGC, and window04 referring to High_U_High_SHGC). These windows were switched according to the outside temperature, the indoor heating rates, and the indoor cooling rates. Basically, during the winter heating period, these windows had the low U-factor and the high SHGC, which was window01 to maximize solar heat gains and minimize heat loss. During the summer cooling period, these windows had the low U-factor and the low SHGC, which was window02. Window03 and window04 had higher U-factors but different SHGC values that responded to the indoor heating and cooling rates.

- Movable blinds – These blinds were activated in terms of two conditions: 1) the daylight glare index at the zone's reference point was higher than maximum allowable DGI 22. The slat angles were changeable according to direct solar beams. The "block beam solar" option enabled blinds to block direct sunlight. 2) If there was no solar beam on windows, the blinds' movement was still activated by the indoor cooling rates. When the blinds were deactivated, the slat angles stayed at the horizontal level.

These dynamic characteristics of building envelopes may not be available currently or recently in the real world. Also, this process did not explicitly consider the factors including costs, durability, installation, and maintenance in this study. However, the comparisons based strictly on energy performance of these hypothetic circumstances can offer the potentials of energy benefits generated by kinetic building envelopes. The central conclusion from the simulation results is that kinetic envelope properties can significantly reduce heating and cooling loads and peak demands of buildings under certain climatic conditions. Specific conclusions are presented below according to the categories discussed in this chapter:

1) Annual Heating and Cooling Loads

- Kinetic envelope properties offered significant savings on the annual heating and cooling loads in the four climates, which were 47.2% for the cooling-dominated climate in Houston, 47.9% for mixed-climate in San Francisco, 47.7% and 42.6% for the heating-dominated climate in Baltimore and Chicago respectively in relation to the baseline energy usages. Even compared to the highly-insulated envelopes, the dynamic features produced relatively large savings.
- In respect of the annual cooling loads, the kinetic properties performed obviously better than the future high-insulated envelopes (in Ultra Models),

and the reduction percentages of the loads ranged from 32.0% to 53.0% (7.5% for Chicago) in relation to the baseline energy uses. Regarding the heating loads, the kinetic envelopes achieved significant savings percentages in the heating-dominated climate (46.0% for Baltimore and 43.2% for Chicago compared to the baselines) and even saved more energy than the future highly-insulated envelopes (in Ultra Models). However, in the cooling-dominated climate of Houston and the mixed-climate of San Francisco, the highly-insulated envelopes (in Ultra Models) performed slightly better than the dynamic envelopes (in Kinetic Models).

2) Peak Demands

- The kinetic envelopes dramatically reduced the peak heating loads and the peak cooling loads in the four climates. Compared to the other models, the kinetic envelopes in Kinetic Models reduced the peak cooling loads around 50.4% (Houston) ~79.7% (San Francisco) relative to Baseline Models. The savings percentages of the peak heating loads relative to Baseline Models ranged from 15.3% (Houston) to 83.9% (Baltimore).

3) Effects of Kinetic Envelope Assemblies

- In the four climates, the kinetic windows played more significant roles of saving energy than the other kinetic elements, and the savings were around two to three times as large as the savings produced by the opaque assemblies. Also, relative to the future highly-insulated glazing (in Ultra Models), the energy savings of the kinetic windows were around two times greater.

- The opaque parts (walls and roofs) of Kinetic Models produced the second higher percentages in the heating and cooling loads for each climate, which ranged from 15.6% to 18.4% relative to the baselines. However, compared to the future highly-insulated opaque assemblies (in Ultra Models), the variable thermal properties were more suitable to the cooling-dominated climate because the highly-insulated opaque assemblies performed better in saving the heating loads.
- The energy savings generated by kinetic properties were obviously were larger than the effects by highly-insulated opaque parts. Between walls and roofs, in the heating-dominated climate, the dynamic characteristics of the walls performed better than the same settings of the roofs. In the cooling-dominated climate, the trend was reversed.

4) Effects of External Movable Blinds

- The external movable blinds in this study as one of shading strategies saved the cooling energy but increased the heating energy and the interior lighting loads. Thus, only the cooling-dominated climate installations could obtain the energy savings by setting up the movable blinds. In the mixed-climate and the heating-dominated climate, incorporation of blinds failed to save energy because the resulting increased the winter energy, and the lighting energy outweighed the summer cooling energy savings. However, the external movable blinds were proposed for glare protection, so the indoor visual comfort could be guaranteed.

5) Site Energy Use

- Besides the application of the kinetic envelopes, some recommended energy saving strategies for indoor and outdoor lights, water systems, interior equipment, and HVAC systems were compiled. The savings percentages related to the baselines of ASHRAE 90.1-2010 Energy Standard ranged from 38.8% to 42.0% for each climate.
- The values of site energy use intensity (EUI) of kinetic-integrated models for the four cities ranged from 17.2 $KBtu/ft^2 \cdot yr$ to 20.8 $KBtu/ft^2 \cdot yr$. Compared with the NREL's projection (40.3 $kBtu/ft^2 \cdot yr$) of ZEB and some typical ZEB examples (e.g., 35.4 $kBtu/ft^2 \cdot yr$ for Research Support Facility in Golden, Colorado), the kinetic-integrated models with proposed dynamic features performed much better.
- Regarding the proportions of each part of energy end uses, the HVAC load savings are largely the result of the kinetic characteristics. However, there was still around 60~70% of the energy usage related to the interior equipment loads and the interior lighting. Therefore, if these kinetic envelopes in this study will be available in future, a further step to save overall building energy is related to plug loads and interior lighting loads, which occupied around 60~70% of the energy consumption for the selected four cities.

CHAPTER IV

MOCKUP TESTS AND SURVEYS

4.1 Mock-up Structure

For this research, we adapted the Daylight Laboratory that was built for the EPA P3 solar light pipe project at the Riverside Campus of Texas A&M University (TAMU) in Bryan, TX (30°39′56″N 96°22′0″W). Figures 4.1 and 4.2 show the exterior and interior views of this mockup test structure.

Figure 4.1. Exterior view of the mockup test structure

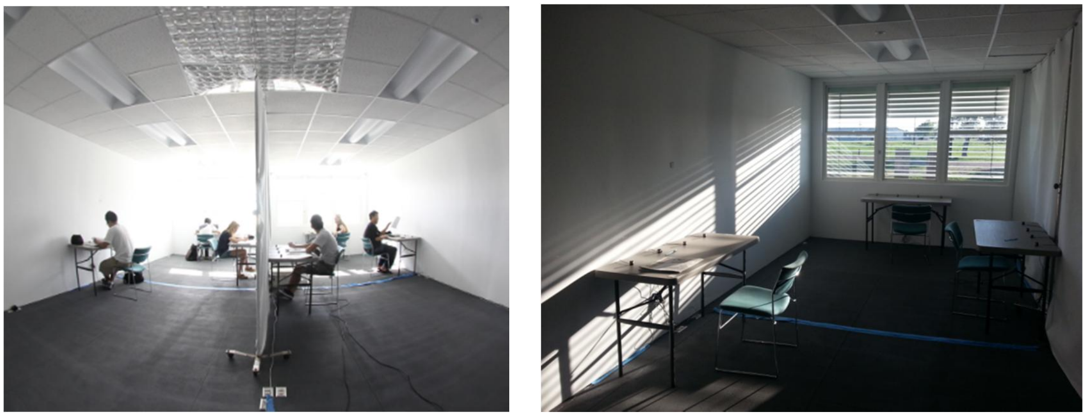


Figure 4.2. Interior views of the two workspaces

The mock upstructure was divided into two identical rooms (10 ft. × 16 ft.) representing two small open plan workspaces (see Figures 4.3 and 4.4 for the layout and section). Three grey desks with 24 in. width, 48 in. length, and 29 in. height were placed in each room. One desk faced the windows, and other two desks faced the walls. Also, two identical window exterior blinds were installed in the two rooms. The window blinds had upper and lower sections with different angles of rotation. The slat width was 0.033in. (0.085cm), and the spacing was 0.028in. (0.07cm).

Furthermore, the entire mock-up structure could be rotated to satisfy the requirements of different orientations for measurements and surveys. By rotating the mockup structure, we could simulate more possibilities with different solar positions and conditions.

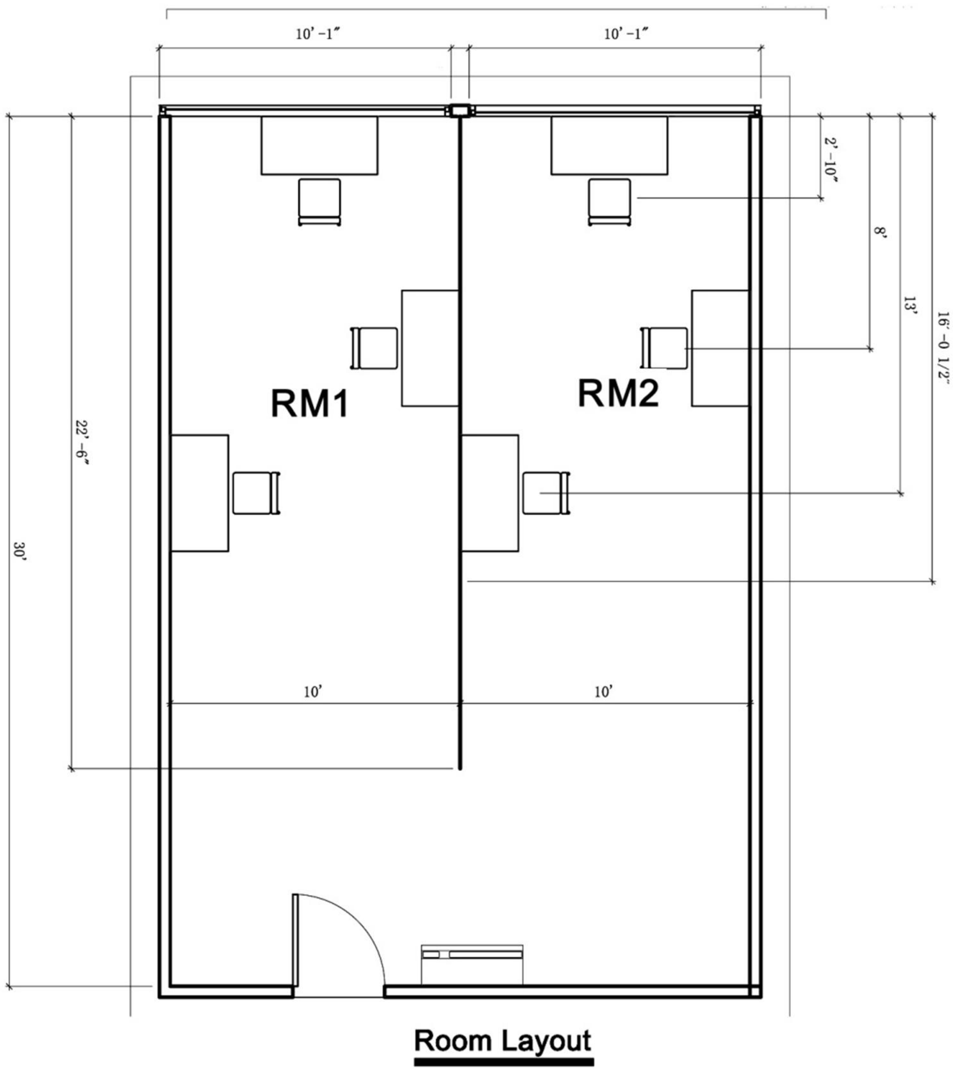


Figure 4.3. Layout of the mockup rooms

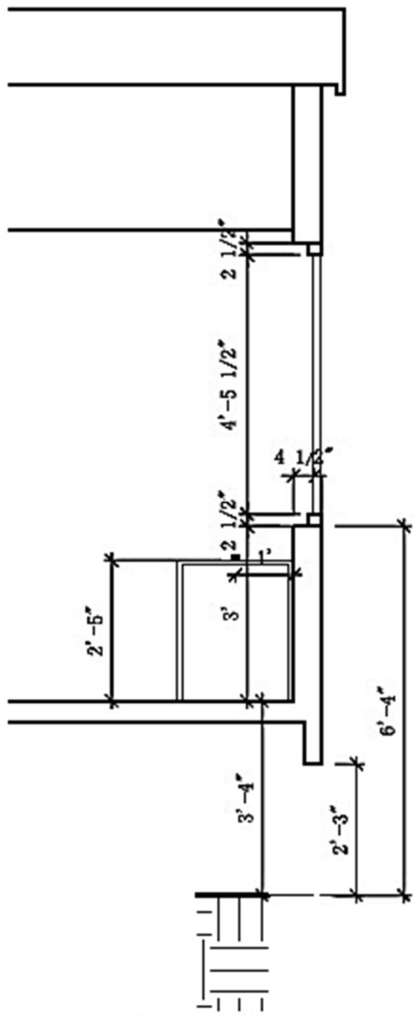


Figure 4.4. Section of the mockup rooms

4.2 Set-up of Measurement Tools

We set up four lighting sensors with 1 ft. interval distance for each desk, as shown in Figure 4.5. These sensors can record lighting levels and reflect the contrast ratio of horizontal illuminance on the desks. A total of 24 sensors were connected to the

CR1000 Campbell Scientific datalogger, which was placed in the center of the two workspaces. Figure 4.6 shows the datalogger and the wiring connections of the photometric sensors.

While conducting the surveys, a photographic camera and a vertical photometric sensor (at 48 in.) were used to document the lighting conditions at each desk. Two external photometric sensors were placed on the roof to record the external global horizontal and vertical illuminances.

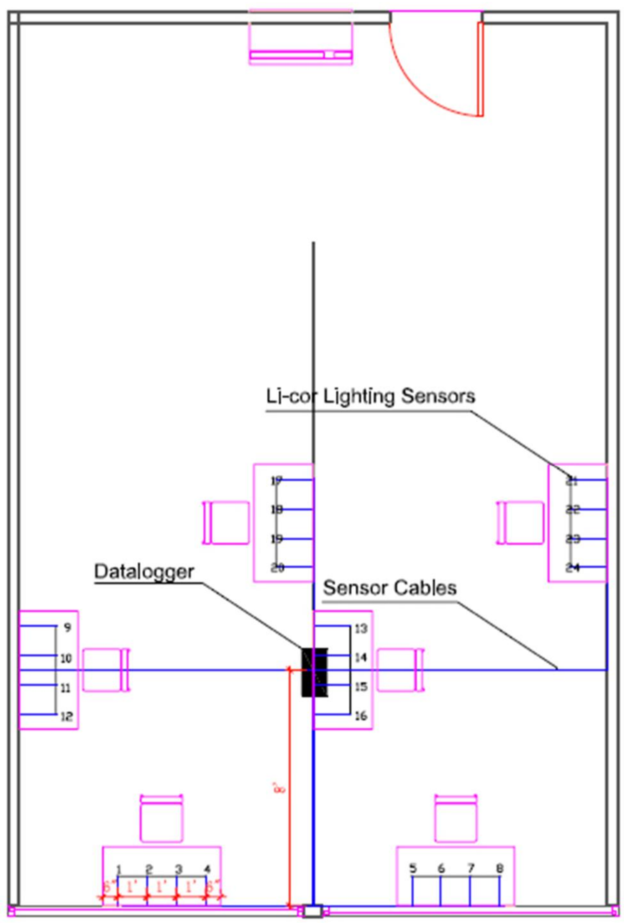


Figure 4.5. Sensor layout in mockup rooms

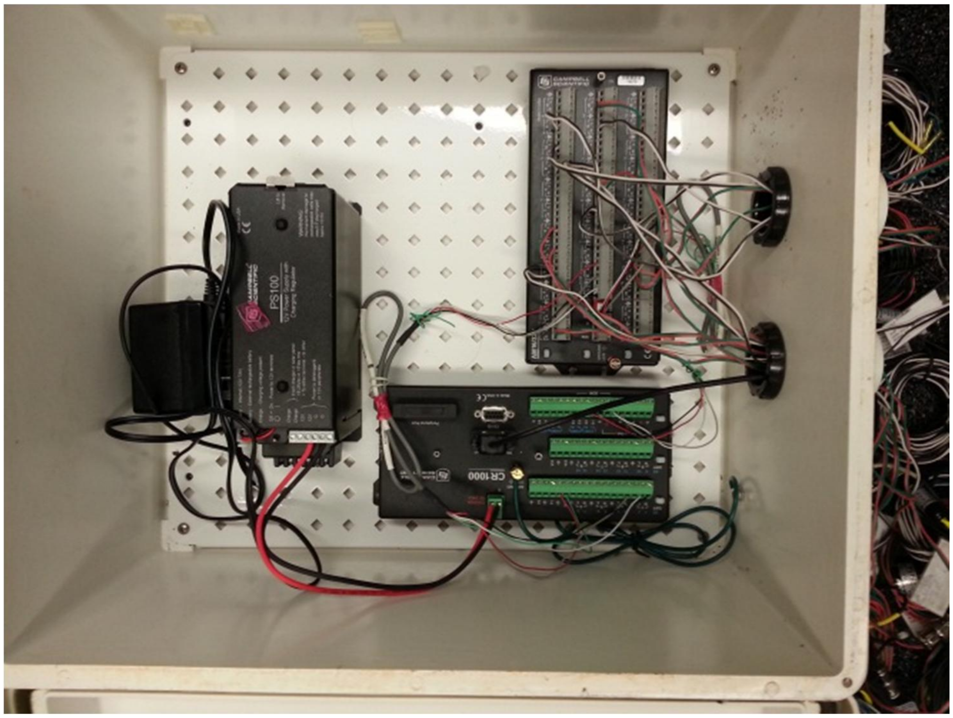


Figure 4.6. The CR1000 datalogger and wirings of lighting sensors

4.3 Scenarios for Different Window Configurations

One room was considered the reference model (RM1) with CEE solutions referring to external static Venetian blinds for the surveys. Comparatively, the other room was equipped with motorized movable blind systems (RM2). Both blinds in each room were identical, but the one in RM1 was left with fixed slat angles (36.5 º view angle for the lower section and 0 º view angle for the upper section), while the other one in RM2 was simulating an automated blind. The automated blinds were manufactured by the German company WAREMA, and the blinds were controlled by a system prepared by the Austrian company Loytec.

In order to identify the optimal slat angles for the RM1, a parametric simulation study through *jEPlus* and *EnergyPlus* was conducted. Because the surveys were designed to simulate the visual environment under low solar positions in winter, the simulation only analyzed the impacts on building energy use with slat angles for winter (December, January, and February). All geometric information and system settings were identical to the prototypical small office building model in Chapter III, including the blinds' geometry. The reflections of the slats were set at 90%; other information can be found in Figure 3.37.

The simulation runs were conducted with the weather file of College Station by varying the slat angle in 5° intervals to investigate variations in building energy uses. The range of the slat angles was from 0° to 50°, so there were totally 11 runs of simulation in this comparison. As shown in Table 4.1, the final results are as follows: the optimal slat angle to minimize the total loads including heating, cooling, and lighting were around 5° (slat towards the ground) during the winter season (December, January, and February).

Table 4.1. Energy use variations by different blind angles

	MMBtu	MMBtu	MMBtu	MMBtu	MMBtu	MMBtu	MMBtu	MMBtu	MMBtu	MMBtu	MMBtu
Angles	0°	5°	10°	15°	20°	25°	30°	35°	40°	45°	50°
Cooling	1.61	1.51	1.46	1.31	1.23	1.11	1.02	0.94	0.88	0.85	0.82
Heating	4.49	4.52	4.55	4.67	4.76	4.85	5.05	5.12	5.35	5.41	5.44
Lighting	6.92	6.93	7.56	7.89	8.32	8.85	9.11	9.51	9.72	9.87	9.92
Total	13.02	12.96	13.57	13.87	14.31	14.81	15.18	15.57	15.95	16.13	16.18

The operation for RM2 was a semi-automatic mode that enabled the blinds to move automatically according to an embedded computation. This operation could adjust the angles of the blinds to provide glare protection. Because our mockup structure can rotate at any angle, we set up an interface for inputting different orientations, which we named "scenes." Six scenes according to six window orientations represented a range of solar positions in winter time in College Station and some other months in different locations. Section 4.3.3 contains the reasons that this survey study selected six orientations. In each scene, two types of variables were used: solar positions and window orientations.

- Solar positions —— The solar positions include solar azimuth and solar altitude which could be entered by a series of equations about the sun paths for the selected locations. The solar elevation azimuth could be derived by using surface elevation azimuth (orientations).
- Window orientations —— The window orientations in this research had six options: 90º, 115º, and 145º (0 = NORTH, 90 = EAST, 180 = SOUTH, 270 = WEST) for morning and 225º, 240º , and 255º for afternoon.

Figure 4.7 shows the framework of blind operation modes for the six scenes used in this survey.

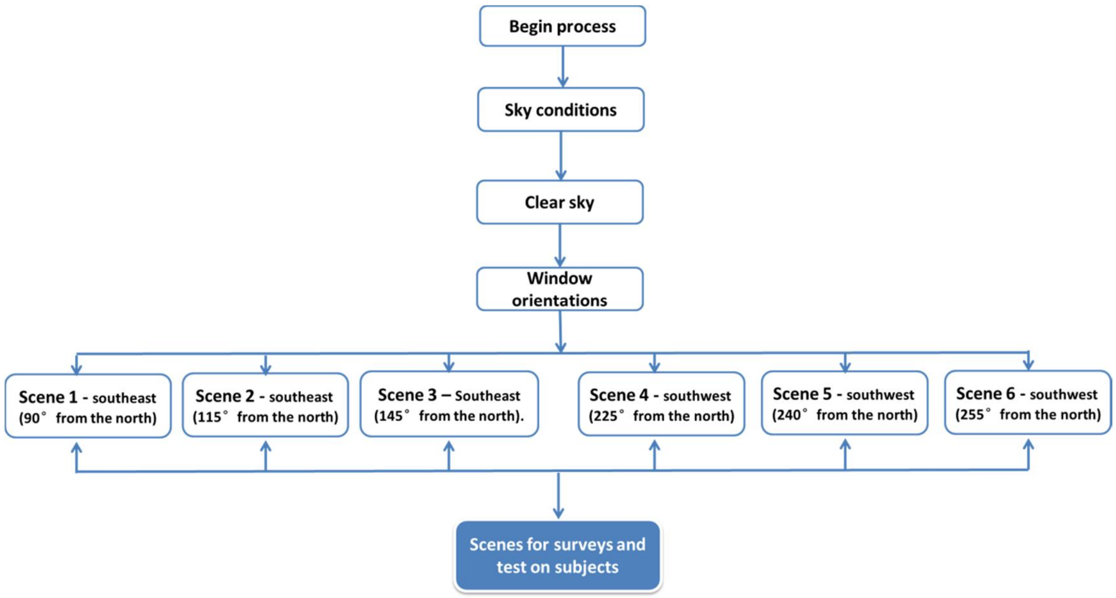


Figure 4.7. Framework of blind operation modes

4.3.1 Solar Positions

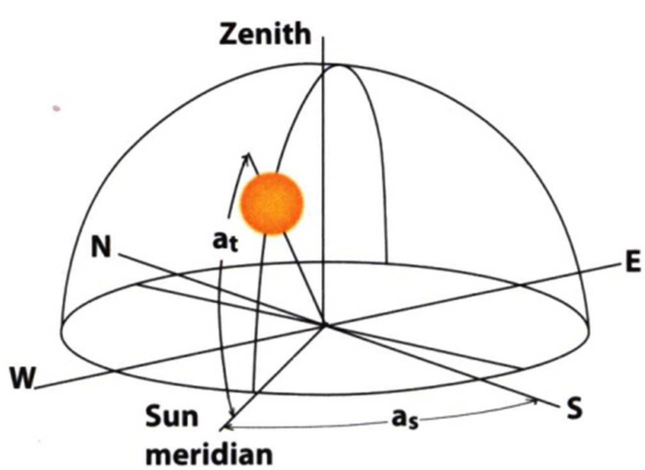


Figure 4.8. Basic geometric variables related to solar positions (DiLaura, Houser, Mistrick, & Steffy, 2011)

The solar azimuth, α_s, and altitude, α_t, define the solar position, as shown in Figure 4.8. In the selected location, the solar azimuth, α_s, and altitude, α_t, can be obtained through a series of equations (IESNA, 2011).

$$\alpha_t = \arcsin(\sin \ell \sin \delta - \cos \ell \cos \delta \cos \frac{\pi t}{12}) \quad (1)$$

$$\delta = 0.4093 \sin(\frac{2\pi(J-81)}{368}) \quad (2)$$

$$\alpha_s = \arctan \frac{\cos \delta_s \sin(\pi t / 12h)}{\cos l \sin \delta_s + \sin l \cos \delta_s \cos(\pi t / 12h)}. \quad (3)$$

Where:

α_t = solar altitude in radians

α_s = solar azimuth in radians

ℓ = site latitude in radians

δ = solar declination in radians

t = solar time in decimal hours

J = Julian date

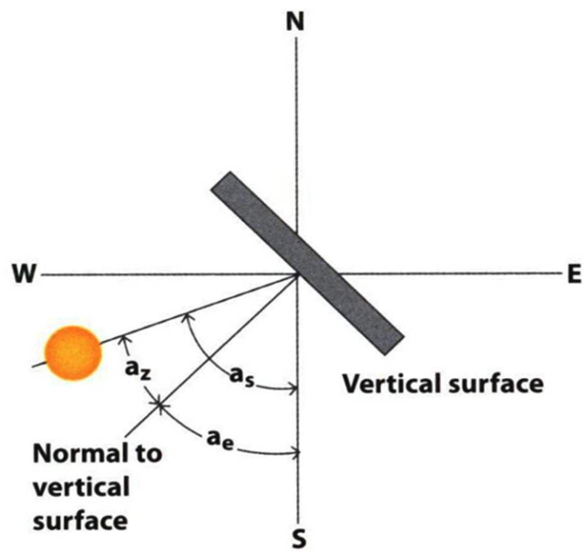


Figure 4.9. Basic geometric variables related to solar azimuth (DiLaura, Houser, Mistrick, & Steffy, 2011)

In analyzing the blind systems and utilizing vertical and horizontal illuminance for sky conditions, it is necessary to determine the incident angle, α_i, the solar elevation azimuth, α_z, which is the sun's azimuth relative to the façade. Figure 4.9 describes these three variables.

$\alpha_i = \cos^{-1}(\cos\alpha_t \cos\alpha_z)$ [1] (4)

$\alpha_z = \alpha_s - \alpha_e$ [1] (5)

Where:

α_s = solar azimuth in radians

α_t = solar altitude in radians

α_i = incident angle in radians

α_z = solar elevation azimuth in radians (the sun's azimuth relative to the façade)

α_e = window orientations in radians

Note: Positive angles are measured in a clockwise direction referenced from north.

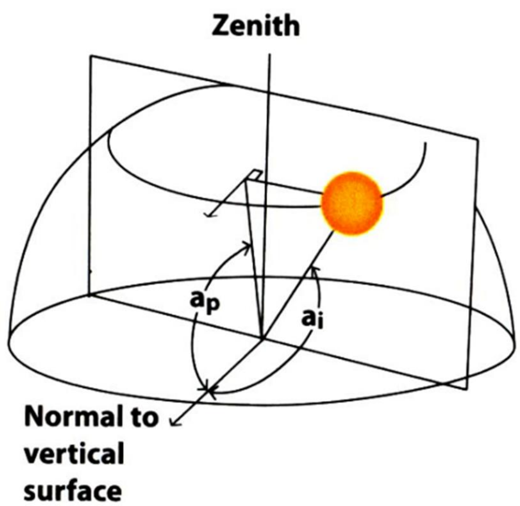


Figure 4.10. Geometric relations related to building surface and solar positions (DiLaura, Houser, Mistrick, & Steffy, 2011)

Furthermore, for determining the blind angle, α_b, the solar profile angle, α_p, should be used to evaluate the relations between sunlight penetration and blind angles. Figure 4.10 explains the geometric relations of α_p and α_i (DiLaura, Houser, Mistrick, & Steffy, 2011).

$$\alpha_p = \tan^{-1}\left(\frac{\sin\alpha_t}{\cos\alpha_i}\right) = \tan^{-1}\left(\frac{\tan\alpha_t}{\cos\alpha_z}\right) \quad (6)$$

Where:

α_p = solar profile angle in radians

α_t = solar altitude in radians

α_i = incident angle in radians

α_z = solar elevation azimuth in radians

The overlap for the blinds in this research is on the order of around 17.6%. The following diagram (Figure 4.11) shows that the geometric relations between blind angles and solar profile angles that can be blocked.

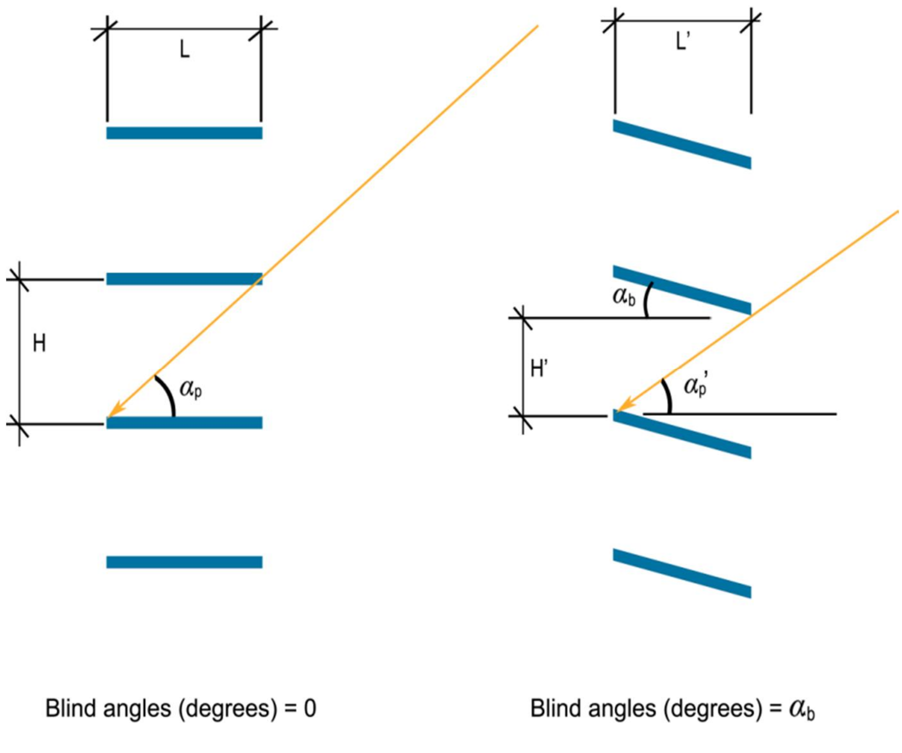


Figure 4.11. Blind angles and solar profile angles

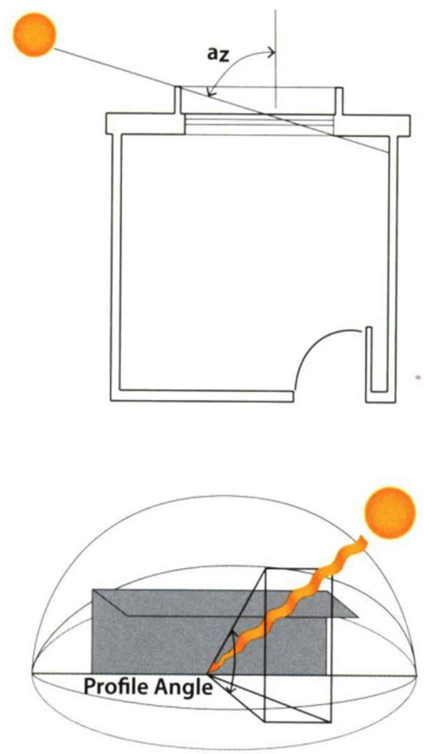


Figure 4.12. Profile angles of solar (DiLaura, Houser, Mistrick, & Steffy, 2011)

As shown from Figure 4.12, we can find:

$$\tan \alpha_p = \frac{(H+L\ \sin \alpha_b)}{L\ \cos \alpha_b} = \frac{(0.82+\sin \alpha_b)}{\cos \alpha_b} \qquad (7)$$

Where:

H = 0.82L

α_p = solar profile angle in radians

α_b = blind angle in radians (positive refers to the angle above the horizontal position)

Therefore, the blind's blocking angles can be then expressed by as a function of the solar profile angles, $\alpha_b = \alpha_p - \sin^{-1}(0.82 \cos \alpha_p)$ (8)

Where:

α_p = solar profile angle in radians

α_b = blind angle in radians (positive refers to the angle above the horizontal position)

According to this equation, we generated the following Table 4.2 about the relationship between blind angles and solar profile angles. Therefore, the RM1's optimal angle (-5º) of the blinds could block the direct sunlight with 36.5º solar profile angles.

Table 4.2. Relation between blind angles and solar profile angles

Blind Angles (Degrees)	**Solar Profile Angles Blocked (Degrees)**
0	39.4
-10	33.3
-20	27.0
-30	20.3
-40	13.0
-50	4.8

4.3.2 Window Orientations

The LBNL subjective surveys (that we discussed in the literature review) were issued during the worst-case solar condition with low solar altitude (35±9º), and subjects were exposed to both clear sky and cloudy conditions (Lee et al., 2006). In order to present the abilities of the movable blinds for indoor visual comfort, low solar altitudes and sunny or partially sunny conditions were selected. The following steps present how and why this mockup survey study selected six particular orientations.

- First, the sunlight penetration in this mockup was evaluated as shown in the Figure 4.13 so that we could identify the ranges of the solar azimuth angles and the solar altitude angles.

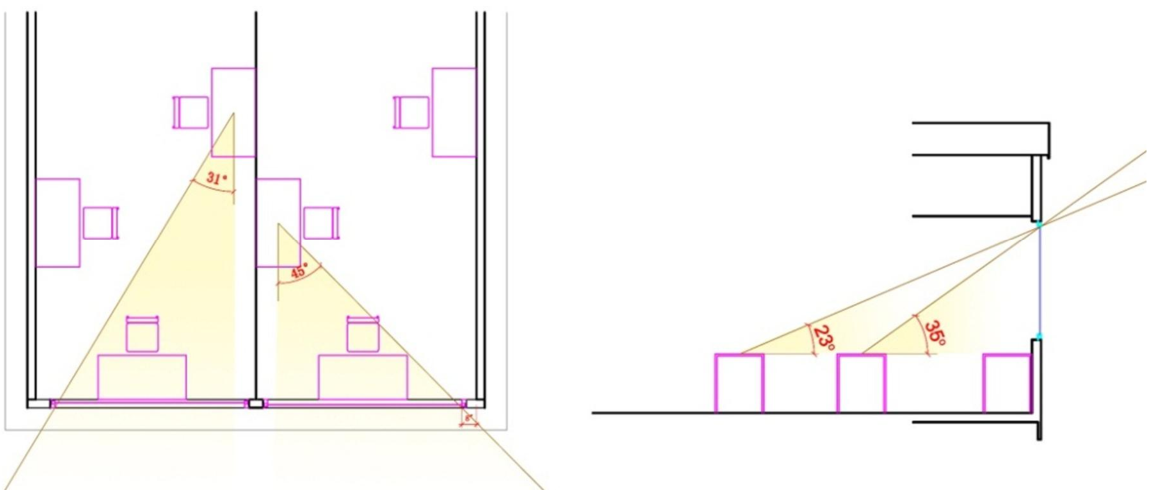


Figure 4.13. Evaluations of sun penetration

- Second, in order to meet our requirements of low solar altitude degrees, a web-based solar position calculator (http://aa.usno.navy.mil/data/docs

/AltAz.php) was used to identify the appropriate periods. Table 4.3 shows the time slots selected for conducting surveys and changing windows orientations. It presents the solar altitude and azimuth data for the dates from September 23rd to October 4th obtained by using the web-based solar position calculator. Thus, the range of the solar altitude angles was 31.1º - 40.3º. According to this range of solar altitudes, the surveys would be conducted between 9:50 - 10:20 or 16:00 ~ 16:30 from September 23rd to September 28th. Since different dates had small changes in solar positions, the time periods of 10:00 - 10:30 and 15:50 - 16:20 were chosen for the days from September 29th to October 4th.

- Third, according to the survey times selected, the solar azimuth moved within 112 º - 124º (0 = NORTH, 90 = EAST, 180 = SOUTH, 270 = WEST) in the morning and 238 º - 245 º in the afternoon for these days. In order to simulate the worst solar conditions during the year (winter time in College Station or early morning or late afternoon in some months in College Station), three windows orientations for morning and three orientations for afternoon were selected on these specific days. In addition, the window views of these six orientations were studied. It was important to keep the view the same as much as possible, as research shows that views impact spatial experience (Ulrich, 1984). Therefore, the following tables were generated for the scenes related to the six orientation options (see Tables 4.4, 4.5, 4.6, and 4.7).

Table 4.3. Solar positions of College Station on the dates for surveys

09/24/2013 Tue			**09/25/2013 Wed**		
Local time	Altitude	Azimuth (E of N)	Local time	Altitude	Azimuth (E of N)
Afternoon			**Morning**		
16:00	40.2	238.6	09:50	31.6	112.9
16:10	38.3	240.8	10:00	33.6	114.7
16:20	36.4	242.8	10:10	35.5	116.7
16:30	34.5	244.8	10:20	37.4	118.7
09/25/2013 Wed			**09/26/2013 Thu**		
Local time	Altitude	Azimuth (E of N)	Local time	Altitude	Azimuth (E of N)
Afternoon			**Morning**		
16:00	39.9	238.3	09:50	31.4	113.3
16:10	38.0	240.5	10:00	33.4	115.2
16:20	36.1	242.5	10:10	35.3	117.1
16:30	34.2	244.5	10:20	37.2	119.1
09/26/2013 Thu			**09/30/2013 Mon**		
Local time	Altitude	Azimuth (E of N)	Local time	Altitude	Azimuth (E of N)
Afternoon			**Morning**		
16:00	39.5	238.0	10:00	32.7	116.9
16:10	37.7	240.2	10:10	34.6	118.8
16:20	35.8	242.2	10:20	36.4	120.8
16:30	33.9	244.2	10:30	38.2	123.0
09/30/2013 Mon			**10/01/2013 Tue**		
Local time	Altitude	Azimuth (E of N)	Local time	Altitude	Azimuth (E of N)
Afternoon			**Morning**		
15:50	40.0	234.6	10:00	32.5	117.3
16:00	38.2	236.9	10:10	34.4	119.2
16:10	36.4	239.0	10:20	36.2	121.3
16:20	34.5	241.1	10:30	38.0	123.4
10/02/2013 Wed			**10/04/2013 Fri**		
Local time	Altitude	Azimuth (E of N)	Local time	Altitude	Azimuth (E of N)
Afternoon			**Morning**		
15:50	39.4	234.1	10:00	31.9	118.5
16:00	37.6	236.3	10:10	33.8	120.4
16:10	35.8	238.4	10:20	35.6	122.5
16:20	33.9	240.5	10:30	37.4	124.7
16:20	35.8	242.2	16:20	35.5	241.9
16:30	33.9	244.2	16:30	33.6	243.9

Table 4.4. Orientation selections part I

	Scene 1	**Scene 2**	**Scene 3**
Date	Sep.23 ~ Sep. 28		
Time	9:50~10:00	10:00~10:10	10:10~10:20
Solar altitude a_t	31.1º~33.9º	33.0º~35.9º	34.9º~37.8º
Solar azimuth a_s	112.1 º ~116.0 º	113.9 º~117.9 º	115.8 º~120.0 º
Selected orientation a_e	90º	115º	135º
Solar elevation azimuth a_z	22.1 º ~26.0º	-1.1 º~2.9 º	-20.0º~-24.2 º

Table 4.5. Orientation selections part II

	Scene 1	**Scene 2**	**Scene 3**
Date	Sep.29 ~ Oct. 04		
Time	10:00~10:10	10:10~10:20	10:20~10:30
Solar altitude a_t	31.9º~34.7º	33.8º~36.6º	35.6º~38.5º
Solar azimuth a_s	116.4 º ~120.4 º	118.4 º~122.5 º	120.4 º~124.7 º
Selected orientation a_e	90º	115º	135º
Solar elevation azimuth a_z	26.4 º ~30.4º	3.4 º~7.5 º	-20.3º ~ -24.6º

Table 4.6. Orientation selections part III

	Scene 4	Scene 5	Scene6
Date	Sep.23 ~ Sep. 28		
Time	16:00~16:10	16:10~16:20	16:20~16:30
Solar altitude a_t	37.1º~40.5º	35.2º~38.7º	33.3º~36.8º
Solar azimuth a_s	237.5º ~241.1º	239.6º~243.1º	241.6º~245.1º
Selected orientation a_e	225º	240º	255º
Solar elevation azimuth a_z	12.5º ~16.1º	-0.4º~2.9º	-9.9º~-13.4º

Table 4.7. Orientation selections part IV

	Scene 4	Scene 5	Scene 6
Date	Sep.29 ~ Oct. 04		
Time	15:50~16:00	16:00~16:10	16:10~16:20
Solar altitude a_t	36.9º~40.3º	35.1º~38.6º	33.3º~36.7º
Solar azimuth a_s	233.5º ~237.2º	235.8º~239.3º	237.9º~241.3º
Selected orientation a_e	225º	240º	255º
Solar elevation azimuth a_z	8.5º ~12.2º	0.7 º ~4.2º	-14.3º ~-17.1º

α_z = solar elevation azimuth (which is related to the window orientations);
a_s = solar azimuth in radians
a_e = window orientations in radians;
Note: Positive angles of a_z are measured in a clockwise direction referenced from the window orientations, with a_s and a_e referenced from north.

Based on the above solar positions and equations (6) and (8), the blinds' slat angles were calculated for blocking direct sunlight. The final results are shown in Table 4.8.

Table 4.8. Solar positions and corresponding blinds angles

Sep.23th ~ Sep. 28th	***Scene 1***	***Scene 2***	***Scene 3***	***Scene 4***	***Scene 5***	***Scene 6***
Time	9:50~10:00	10:00~10:10	10:10~10:20	16:00~16:10	16:10~16:20	16:20~16:30
Selected orientation	90º	115º	145º	225º	240º	255º
Solar altitude a_t	31.1º~33.9º	33.0º~35.9º	34.9º~37.8º	37.1º~40.5º	35.2º~38.7º	33.3º~36.8º
Solar elevation azimuth a_z	22.1 º ~26.0º	-1.1 º~2.9 º	-20.0º~-24.2 º	12.5º ~16.1º	-0.4º~2.9º	-9.9º~-13.4º
Solar profile angles a_p	32.8º~33.8º	33.0º~35.9º	37.4º~39.5º	37.8º~41.2º	35.2º~38.7º	33.7º~37.2º
Slats angles a_b	-11º~-10º	-11º~-6º	-4º~-1º	-3º~0	-7º~-2º	-10º~-4º
Sep.29th ~ Oct. 04th	***Scene 1***	***Scene 2***	***Scene 3***	***Scene 4***	***Scene 5***	***Scene 6***
Time	10:00~10:10	10:10~10:20	10:20~10:30	15:50~16:00	16:00~16:10	16:10~16:20
Selected orientation	90º	115º	145º	225º	240º	255º
Solar altitude a_t	31.9º~34.7º	33.8º~36.6º	35.6º~38.5º	36.9º~40.3º	35.1º~38.6º	33.3º~36.7º
Solar elevation azimuth a_z	26.4 º ~30.4º	3.4 º~7.5 º	-20.3º ~ -24.6º	8.5º ~12.2º	0.7 º ~4.2º	-14.3º ~-17.1º
Solar profile angles a_p	34.8º~38.4º	33.8º~36.7º	37.4º~40.3º	37.2º~40.9º	35.1º~38.6º	33.7º~37.2º
Slats angles a_b	-8º~-2º	-10º~-5º	-4º~0º	-3º~0	-7º~-2º	-10º~-4º

4.4 Surveys on Occupant Comfort, Satisfaction and Acceptance

4.4.1 Study Design

A survey was carried out to assess and compare the visual environments created by two different window blinds. The two-group posttest-only randomized experiment was adopted as the research type. In the beginning, two groups were randomly assigned. After randomized assignments, one group was in a room with the automated blinds, and the comparison group was in a room with typical external static Venetian blinds. Random assignments were used so we can assume that the two groups were probabilistically equivalent, thereby eliminating the need for a pretest. In this mockup experiment, we were most interested in determining whether the two groups differed in response to the automation blinds. The data were related to multiple measures (overall satisfaction, glare sensation, blind controls, and light controls) and compared by using a *t-test*.

This study was carried out between the end of September and the beginning of October in 2013 with an experimental design. Sixty subjects were selected for this mockup study (30 in the experimental group, 30 in the control group). Subjects were asked to fill out questionnaires after having spent about 30 minutes exposed to one of the workspaces.

4.4.2 Setting and Subjects

Based on the LBNL's research on the visual comfort of daylighting environments of Electrochomic windows, a power analysis was used to decide the number of subjects for sampling. In the case of 30 participants in each group, to achieve a medium effect size with 95% confidence interval and .05 margin of error, it was calculated the investigation would be at least .80 for a one tail two samples *t-test*. Figure 4.14 shows the information of calculating sample size in this study by using the web-based calculator: http://www.stat.ubc.ca/~rollin/stats/ssize/n2.html.

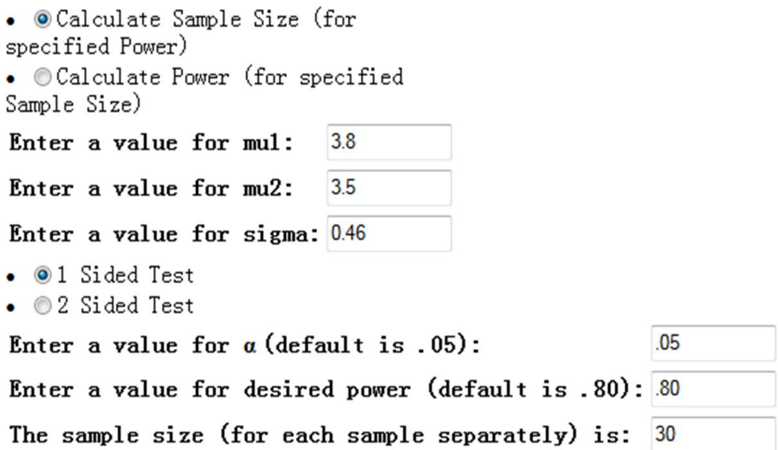


Figure 4.14. Power analysis of the survey study

Subjects were 60 students from Texas A&M University 18 years or over. I visited four undergraduate classes in the College of Architecture to introduce the research and invite students to participate. I also sent an email to graduate students in Architecture. I explained that this study was voluntary. During the recruitment, no personal identification information was gathered. Furthermore, no subjects were directly associated with the research team. By using MS Excel random number generator function, the 60 subjects were randomly assigned to either the experimental group or the control group.

In addition, an initial pilot test was run with six subjects, but the results of the pilot were not included in the final analysis.

4.4.3 Intervention

Subjects in the experimental group's room (RM2) were offered motorized external blinds according to the lighting sensors and the embedded computational control. Except for the operation mode (automation) of the blinds, all settings related to windows, glazing, blind geometry, furniture, room color, and others were identical to the control group's room (RM1). Subjects in the experimental group used a web interface to control the blinds. People assigned to the control group had external static venetian blinds with optimal slat angles; they could not control the blinds. No other aspects of the procedure for either group were controlled by the study protocol. Subjects were not told about the blind type difference in the two workspaces.

4.4.4 Data Collection Tools

A questionnaire was developed by the LBNL for measuring visual comfort and window technology acceptance and used multiple-choice questions (for subject background information). Based on this instrument, our instrument retained around 40 of the questions (for each group); some were modified to fit into the two window systems focus of this study. Regarding the rating scale, 7-point rating scales have been widely used in numerous indoor environmental comfort studies on subjective responses (e.g., the ASHRAE 7-point scale for indoor comfort levels [ASHRAE, 2004]), lighting color impacts visual comfort (Shamsul, Sia, Ng, & Karmegan, 2013), discomfort glare from non-uniform luminance (Eble-Hankin, 2008), overhead glare on visual comfort (Ngai & Boyce, 2000), on the basis that a 7-point scale offers a distinguishable number of judgments between levels of sensation without confusion (Miller, 1956). Therefore, 7-point scales have been widely used to measure subjective responses of occupants in comfort studies. The two groups were administered identical questionnaires that were divided into three parts: I, II, and III.

Part I and Part II were conducted based on the study results related to what kinds of attributes of human factors might affect the subjective responses to visual environment (Lee et al., 2006). In Part I, Background Information, subjects self-reported information on their age, gender, eyesight (whether or not they wore glasses), and other characteristics. Part II was an Attitudinal Survey on subject attitudes toward the importance of certain items in making a comfortable visual office environment. The items included good lighting, window views, attractive environment, no noise, privacy, and others. The rating scale ranged from 1 (unimportant) to 7 (very important). In addition to rating the importance of items for making a comfortable visual space, subjects also rated their own sensitivity to a number of environmental factors. The factors included sunlight, glare, noise, visual distraction, and gloominess. Ratings ranged from 1 (least sensitive), through 4 (moderately sensitive), to 7 (very sensitive). The main purposes for collecting information on the attributes and attitudes of the study population were to characterize the population and to test for possible correlations to the appraisals of the different test modes.

Based on LBNL visual comfort questionnaire, Part III focused on human responses to the visual environment and window blinds. It contained multiple choice questions on subject view directions, work tasks, etc. It also used a 7-point rating scale on questions about window views, glare control, visual distraction, overall satisfaction, etc. In Part III, two questions related to light control and blind control were created. For the control group, the questions concerned their intent to control the electrical lights and blinds during a 30 minutes study period in the room. For the experimental group, the questions were related to their actual control behaviors regarding the blinds during a 30 minute studying period in the room. At the end of Part III, subjects could offer additional comments (e.g., window operation, lighting, visibility, comfort, etc.).

Besides the questionnaires, when the subjects adjusted the blinds, the researchers observed their behaviors, recorded the time, frequency, and visual conditions with a camera with a fisheye lens and photometric sensors (LI-COR), as well. Data regarding reasons to control the blinds was used to analyze particular stimuli and the potential benefits of blind movements. Also, the frequency of control behaviors in each room was recorded in order to study the correlations among blind control behaviors, overall environmental comfort levels, lighting distribution comfort level, and occupants' acceptance of blind types.

4.4.5 Data Collection

- Depending on the sky conditions, the dates and the specific time for conducting surveys were selected according to the solar positions (see Section 4.3.3).
- From the random assignment list, six subjects were selected each time: three

for the control group and three for the experimental group. Before starting the survey, the procedures and surroundings were introduced to each group individually. Especially, the subjects in the experimental group were taught how to use the web interface to adjust the window blinds.

- At the beginning of the survey, the windows faced 90 ° in the morning or 225 ° in the afternoon by rotating the mockup room. The six subjects were allowed to bring their own work including basic study or office work tasks (e.g., reading, writing), or basic computer work, to the mock-up rooms. The control group's room window blinds were set at an angle of -5 ° (minus means the angle is below the horizontal level). The experimental group's room window blinds were set to "Scene 1" or "Scene 4." The six subjects in the experimental group were allowed to adjust the blind angles. The time was recorded as well.
- After 10 minutes, the windows were rotated to face 115 ° in the morning or 240 ° in the afternoon. The control group's room window blinds were still at -5 ° . The experimental group's room window blinds were set to "Scene 2" or "Scene 5." The six subjects in the experimental group were allowed to adjust the blind angles. This session also lasted 10 minutes.
- At the beginning of the last 10 minutes, the orientation was changed to 145 ° in the morning or 255 ° in the afternoon. The control group's room window blinds were still the same as with previous conditions. The experimental

group's room window blinds were set to "Scene 3" or "Scene 6." The six subjects in the experimental group were allowed to adjust the blind angles. The time was recorded as well. This session also lasted 10 minutes.

- The subjects filled out the questionnaire after spending 30 minutes in the space.

4.4.6 Data Analysis

Part I's background information about the subjects and details of the procedure were compared across the two study groups using means and proportions. The data from other parts of questionnaire were conducted using SAS JMP 10.0 statistical analyses. An independent paired sample *t-test* and Chi-square test were used to compare the measures of the control and experimental groups. The confidence interval was 95%. A $p < .05$ was considered statistically significant.

4.4.7 Ethical Considerations

The protocol was approved by the Institutional Review Board (IRB) of TAMU. Informed consent was obtained from each participant in written format. The subjects were also informed of the purpose of the research prior to the beginning of the study and were assured of their right to refuse to participate or to withdraw from the study at any stage.

4.5 Results

4.5.1 External Conditions During the Surveys

This mockup study had ten tests, and each test was around 30 minutes for three subjects in the experimental group and three subjects in the control group. Thus, the external conditions of each test for the two groups were identical. During these time periods, the external lighting conditions, including horizontal illuminance and vertical illuminance, were recorded. Figures 4.15 and 4.16 show the illuminance values in these periods during the surveys. Except for the last two tests with partially cloudy conditions, other tests were conducted with clear sky conditions. Thus, in general, around 90% of the time the sky was clear and the remaining time, it was partially cloudy. The exterior horizontal global illuminance ranged from 18,258.5 lux to 87,763.3 lux, and the exterior vertical global illuminance ranged from 17,661.6 lux to 89,518.5 lux. In all the 30-minute periods, external lighting levels were high enough to activate the control of the blinds.

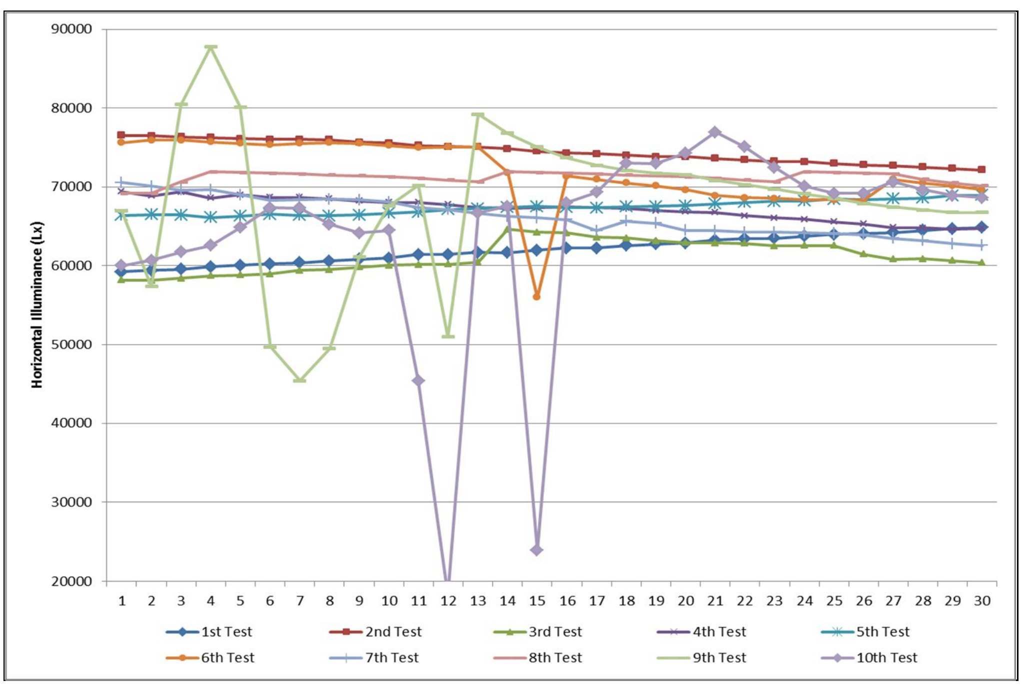


Figure 4.15. External horizontal illuminance during 30 minutes of each test

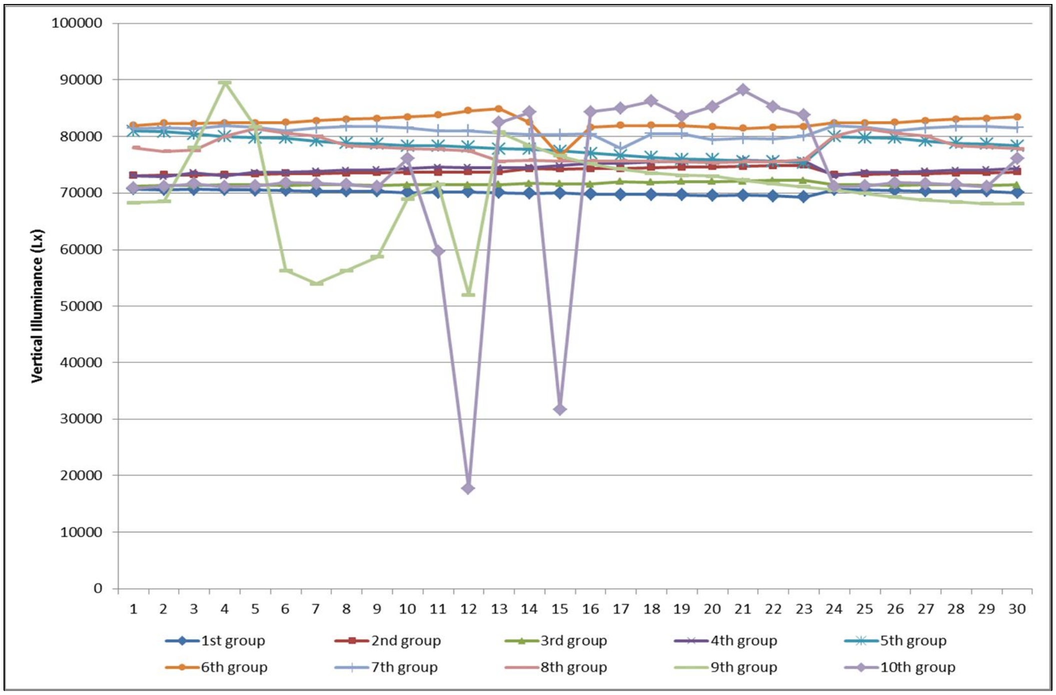


Figure 4.16. External vertical illuminance during 30 minutes of each test

4.5.2 Subject Characteristics and Attitudes

During the study period, 60 subjects underwent mockup surveys on the Riverside Campus. Of the 60 respondents, 30 were in the control group and 30 were in the experimental group. Most subjects were students or university employees of TAMU. An initial pilot test was run with seven subjects. The pilot was designed to test the procedures, questionnaires, and lab monitoring equipment. Changes were made to the questionnaires and control modes in response to lessons learned during the pilot phase. Results from the pilot phase are not included in the results of the main study.

Subjects self-reported information on their age, gender, race, eyesight, color vision deficiency, normal work/study environment, and eyes' color which we hypothesized might affect their responses to the kinetic window systems. The incidence of colorblindness was consistent with the general population and provided no other information. The remaining responses in the two groups are summarized in Table 4.8. Also, correlations between demographic variables were examined by contingency analysis, and the results are also shown in Table 4.8. As seen in Table 4.9, no statistically significant difference was found between the control group and the experimental group ($p > 0.05$). In both the experimental group and the control group, 46.7% of the subjects were female, and 53.3% were male. In the experimental group, 90.0% of the subjects were aged 20-29 years, 66.7% were Asian, 53.3% usually did not wear glasses, 53.3% normally worked or studied in rooms with a window view, and 50% had brown eyes (see Table 4.9).

Table 4.9. Comparison of demographic and normal study / work conditions of experimental and control groups

Characteristics	**Experimental Group**		**Control Group**		**Total**		χ^2 **/** p
	n	**%**	**n**	**%**	**n**	**%**	
Gender							
Female	14	46.7	14	46.7	28	46.7	χ^2=0
Male	16	53.3	16	53.3	32	53.3	p=1.0
Age group (yr)							
20-29	27	90.0	25	83.3	52	86.7	χ^2=0.96

Table 4.9. Continued

Characteristics	Experimental Group		Control Group		Total		
	n	**%**	**n**	**%**	**n**	**%**	χ^2 / ***p***
30-39	3	10.0	5	16.7	8	13.3	*p*=0.327
Ethnicity							
White	10	33.3	11	36.7	21	35.0	χ^2=0.14
Asian	20	66.7	19	63.3	39	65.0	*p*=0.705
Wear glasses							
No	14	46.7	16	53.3	30	50.0	χ^2=0.54
Yes	16	53.3	14	46.7	30	50.0	*p*=0.464
Windows view							
No	14	46.7	10	33.3	24	40.0	χ^2=2.40
Yes	16	53.3	20	66.7	36	60.0	*p*=0.121
Eyes color							
Brown	15	50.0	16	53.3	31	51.7	χ^2=1.92
Black	10	33.3	7	23.3	17	28.3	*p*=0.383
Blues and others	5	16.7	7	23.3	12	20.0	

Similar to the demographic data collection, Part II of questionnaires were conducted because we hypothesized that attitudes and sensitivity to visual factors, like glare, gloominess, etc., might affect responses to the mockup visual environment. The comparison of the subjective attitudes of the experimental and control groups is presented in Table 4.10. As seen in Table 4.10, there were no significant differences in subjects' attitudes and sensitivities on the factors related to the visual environment.

Table 4.10. Comparison of attitudes of the experimental and control groups

	Experimental group		**Control group**				
	Mean	**Std Dev**	**Mean**	**Std Dev**	**Mean dif**	**Std Err dif**	***p***
Importance of the factors in making a comfortable visual work / study environment (1 being the least important, 4 being moderately important, and 7 being the most important)							
Good lighting	6.19	0.78	6.20	1.00	-0.01	0.23	0.951
Lighting control	5.48	1.06	5.04	1.26	0.45	0.30	0.150
Windows	5.17	1.34	5.14	1.69	0.03	0.39	0.943
Windows view	4.91	1.28	5.14	1.72	-0.22	0.39	0.571
Visual privacy	5.19	1.44	4.82	1.56	0.37	0.39	0.342
Controllable shadings, blinds or sunscreens	5.17	1.15	4.89	1.60	0.28	0.36	0.443
Good room color rendering	4.86	0.98	4.30	1.62	0.56	0.35	0.111
Sensitivity to visual conditions (1 being not sensitive, 4 being moderately sensitive, and 7 being very sensitive)							
a) Glare	5.64	1.04	5.30	1.51	0.35	0.33	0.305
b) Gloominess	4.64	1.40	4.46	1.51	0.17	0.38	0.645
c) Noise	5.21	1.46	5.04	1.32	0.18	0.36	0.627
d) Visual distraction	4.95	1.26	5.03	1.36	-0.08	0.34	0.806
Preferred light levels (1 being very low, 4 being moderate, and 7 being very bright)							
	4.96	0.88	5.04	0.70	-0.08	0.21	0.708

In terms of mean values of the factors creating a visual environment, for all subjects in both groups, good lighting (6.20 ± 0.89) was the most highly ranked characteristic, and lighting control (5.26 ± 1.18) was ranked as the second most important factor, as shown in Figure 4.17. The following important factors included windows (5.15 ± 1.51), window view (5.03 ± 1.51), controllability of shades/blinds/sunscreens (5.03 ± 1.50), visual privacy (5.00 ± 1.39), and good room color rendering (4.57 ± 1.36).

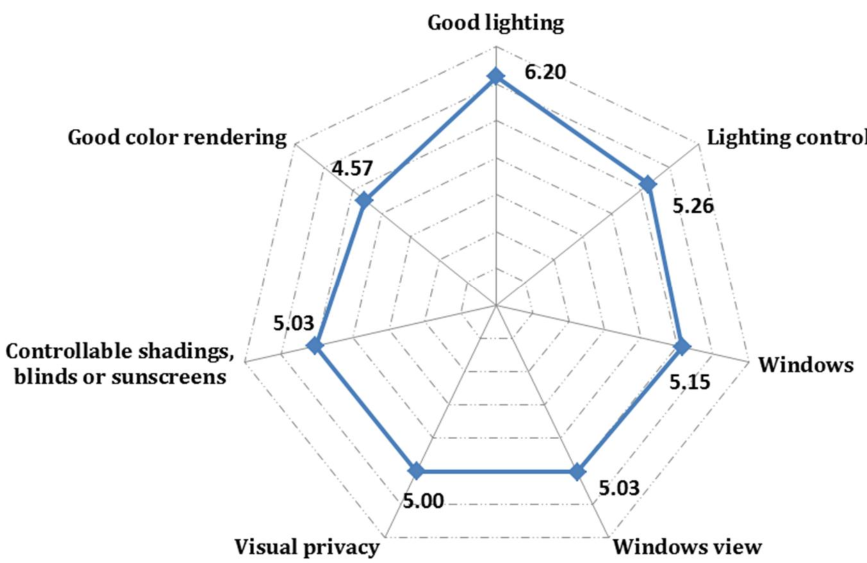


Figure 4.17. Importance of factors to create a comfortable work / study space

4.5.3 Responses to Visual Qualities

The types of tasks undertaken by the subjects in the mockup rooms are summarized in Table 4.11. Regarding the types of tasks, the largest percentage of time (46.3%) was spent on reading papers. Using a laptop was the second most frequent task (35.1%), while writing by hand (7.6%) and drawing by hand (8.0%) had similar percentages. Other specified activities were minor.

Table 4.11. Type and percentages of tasks during the study

Tasks	**Mean (%)**	**Std Dev(%)**	**Max(%)**	**Min(%)**
Reading on paper	46.3	42.8	100	0
Laptop (reading, drawing, typing)	35.1	44.6	100	0
Writing (by hand)	7.6	14.6	50	0
Drawing (by hand)	8.0	21.1	100	0
Other (please specify)	1.3	4.3	25.0	0

Note: The "other" category consisted of 6 answers: 2 talking, 2 using cellphone, 1 looking around, and 1 thinking.

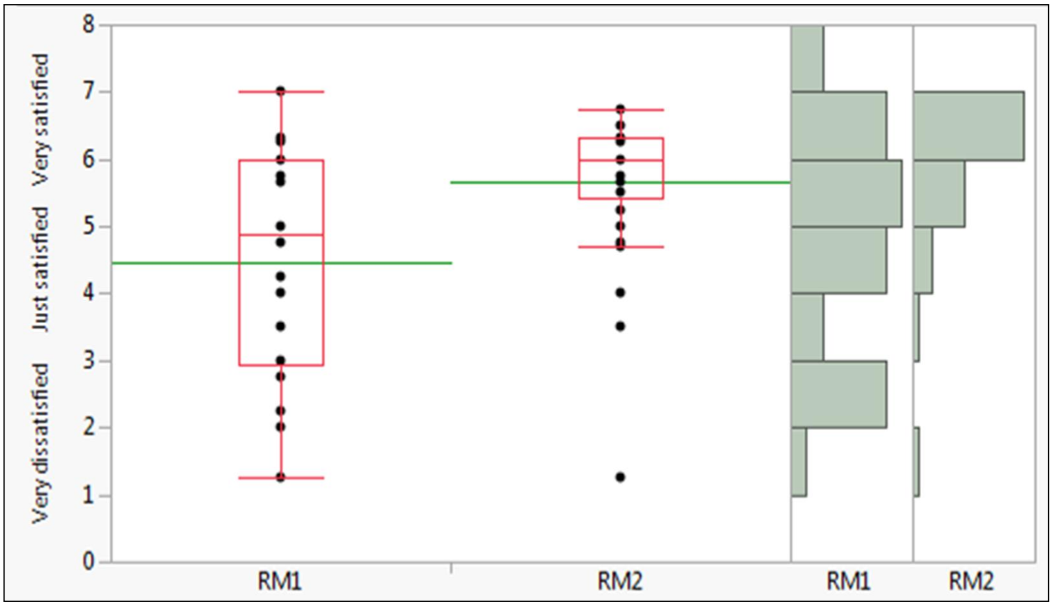
In the aforementioned analysis, the subjects in each group were comparable in demographic traits, attitudes, and sensitivity, which meant the two distributions had the same variance. We utilized an independent two-sample *t-test* (one-tailed) to analyze each question responding to visual qualities and window systems. Table 4.12 shows the intergroup comparison related to the responses to visual qualities. The only non-significant difference was associated with the responses regarding visual distractions.

Table 4.12. Comparison of subjective responses to visual qualities for both experimental and control groups

	Experimental group		Control group					
	Mean	**Std Dev**	**Mean**	**Std Dev**	**Mean dif**	**Std Err dif**	**t ratio**	***p***
Overall satisfaction (1 Very dissatisfied / 4 Just satisfied / 7 Very satisfied)	5.65	1.14	4.48	1.62	1.17	0.36	3.26	0.001*
Light level (1 Too dark / 4 Just right / 7 Too bright)	4.19	0.75	4.89	1.27	-0.71	0.27	-2.63	0.006*
Lighting distribution (1 Poorly distributed / 4 Just right / 7 Nicely distributed)	5.21	1.22	4.04	1.65	1.17	0.38	3.13	0.001*
Windows view (1 No view / 7 Clear view)	3.40	2.03	4.70	1.96	-1.30	0.51	-2.53	0.007*
Visual distraction (1 Not affected / 7 affected)	2.70	1.64	3.45	2.24	-0.74	0.51	-1.47	0.148
Glare sensation (1 Not perceptible / 4 acceptable / 7 Intolerable)	3.07	1.39	4.39	1.60	-1.32	0.39	-3.41	0.001*

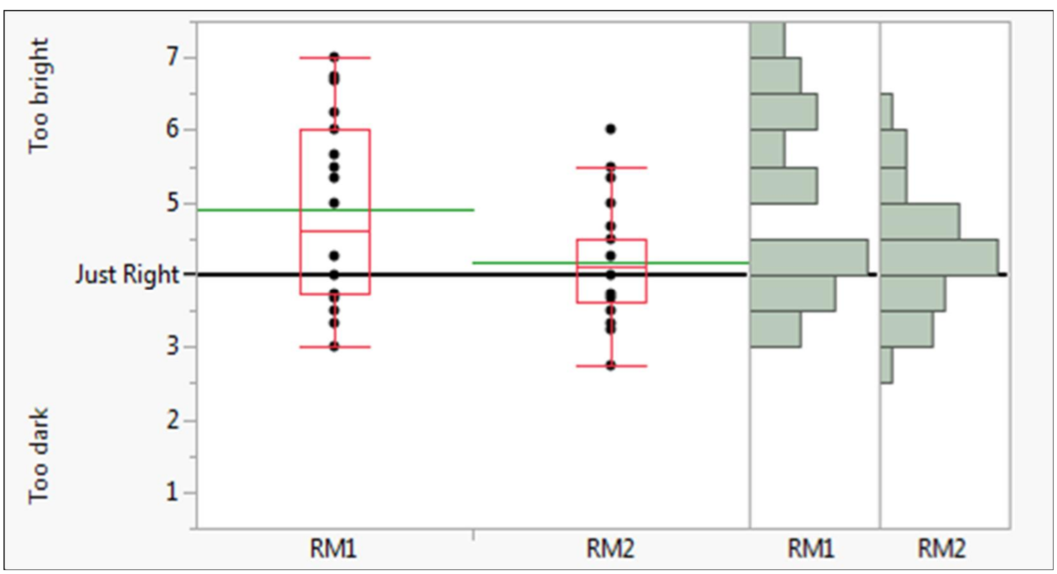
As shown in Figure 4.18, overall satisfaction with the visual qualities in the experimental group with movable blinds (5.65 ± 1.14 on a scale of 1-7, with 1 = very dissatisfied, 4 = satisfied, and 7 = very satisfied) was higher than the mean value of the control group (4.48 ± 1.62). The difference between the groups was found to be statistically significant (mean value difference is 1.17 on a scale of 1 to 7, *t* ratio is 3.26, and p=0.001).

Figure 4.18 shows the subjects' responses to the lighting levels at their desks. Due to the control of blinds, certain work areas (especially the table furthest from the windows) showed lower levels of lighting in the experimental group relative to the levels in the control group. The difference between the two groups was significant (p=0.006). However, as seen in Figure 4.18, the mean value (4.19 ± 0.75) for lighting levels in the experimental group was closer to the value of "Just Right" compared to the mean value (4.89 ± 1.27) in the control group. This means the experimental group with movable blinds offered more appropriate lighting, according to the subjects.



Note: RM1 was the control group, and RM2 was the experimental group

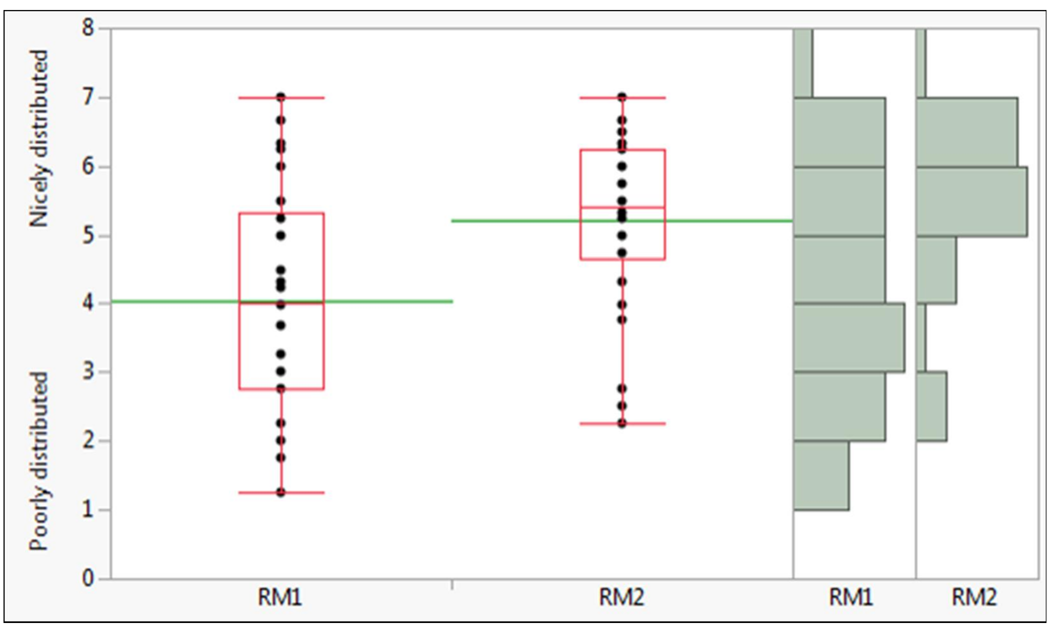
Figure 4.18. Overall satisfaction with visual qualities by the two groups



Note: RM1 was the control group, and RM2 was the experimental group

Figure 4.19. Responses to lighting levels in the two groups

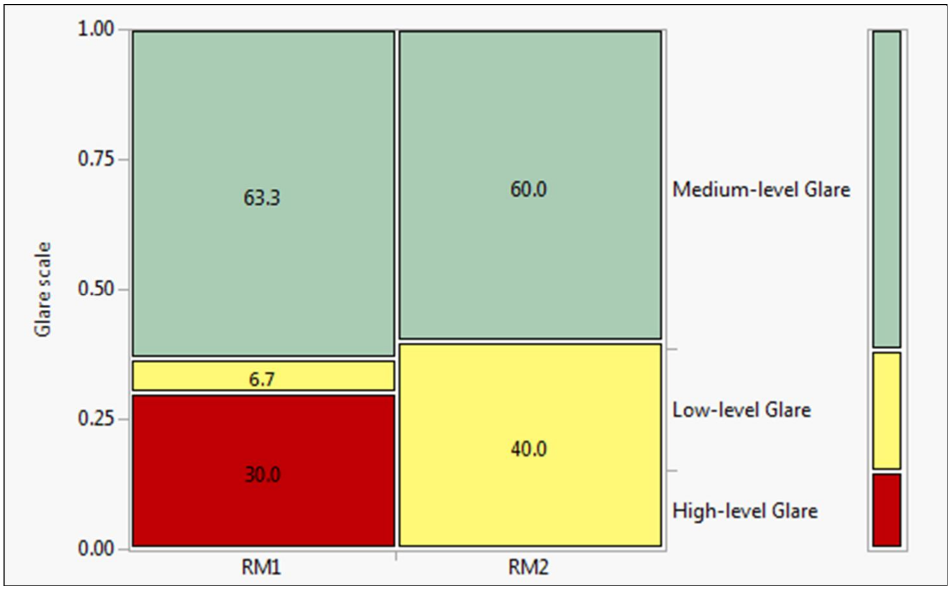
Furthermore, there was a significant difference ($p = 0.001$) in the responses to the lighting distribution between two rooms, as seen in Figure 4.20. Relative to the responses in the control group, the subjects in the experimental group reported better distributed lighting environment (mean difference is 1.17 on a scale of 1-7). The average response for window views in the experimental group was 3.40 ± 2.03 that was significantly lower than the value in the other group (4.70 ± 1.96). This significant difference (-1.30 on a scale of 1-7 with *p*-value 0.007) largely stemmed from the use of movable blinds. In order to avoid glare problems, users in the experimental groups usually closed blinds and in turn the window views were reduced.



Note: RM1 was the control group, and RM2 was the experimental group

Figure 4.20. Responses to lighting distribution in the two groups

Lastly, it was found that the use of movable blinds in the experimental group achieved significantly lower values (mean difference = -1.32, $p = 0.001$) in responding to glare sensations compared to the values collected from the control group. Regarding the mean values of each group, they ranged from 3.07 to 4.39 on a scale of 1 = “not perceptible” to 7 = “intolerable”. Thus, the mean values of the two rooms were around or under the “acceptable” glare level. However, this comparison of differences may not reveal differences in the data distribution of the two groups. So, I grouped the responses into three levels according to the Likert scales: Low-level Glare (1 = Non perceptible to 2.4 = Perceptible), Medium-level Glare (2.5 to 5.4 referring to Acceptable), and High-level Glare (5.5 = Uncomfortable to 7 = Intolerable). As seen in Figure 4.21, 30% of control group subjects (RM1) reported high-level values with uncomfortable or intolerable glare conditions, and only 6.7% of subjects in this group were within low-level glare range. Comparably, in the experimental group of RM2, there were no responses of uncomfortable or intolerable glare issues. Clearly, the controllable movable blinds offered glare protection to the subjects in RM2.



Note: RM1 was the control group, and RM2 was the experimental group

Figure 4.21. Mosaic plot of glare sensation at the three levels of glare for both groups

In terms of glare sensation, subjects also identified the sources of glare, if the glare problems were perceptible to them. Figure 4.22 shows the selections of the two groups. “Light from windows” was the most frequent source for glare problems in both rooms, but the number of selections in the control group was higher than other source choices. The sources of “Wall surfaces” and “Desk surfaces” in RM1 comprised the second highest selection rate. We also found that the experimental group with movable blinds showed a high selection rate for “Reflected glare of blinds.” This might be because that movement of the blinds created glare problems for the subjects. Also, highly reflective blind materials were used in this mockup study, which may have increased the glare problems.

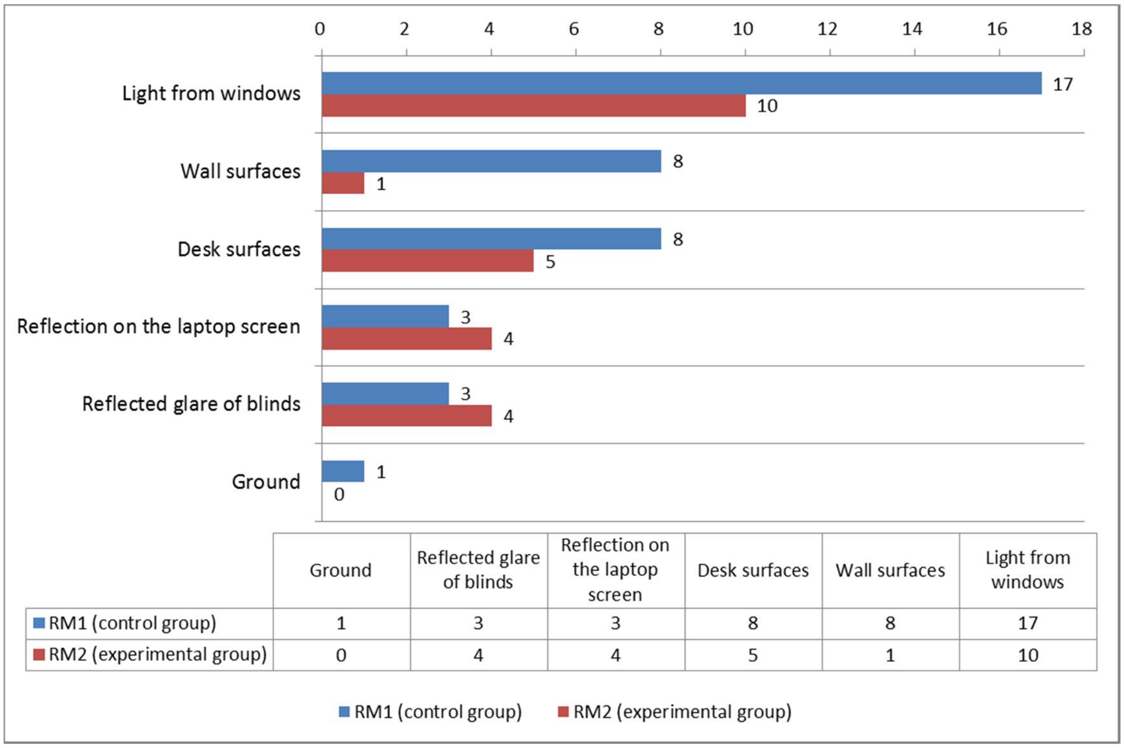


Figure 4.22. Sources of glare in the two rooms

4.5.4 Responses to Window Blind Systems

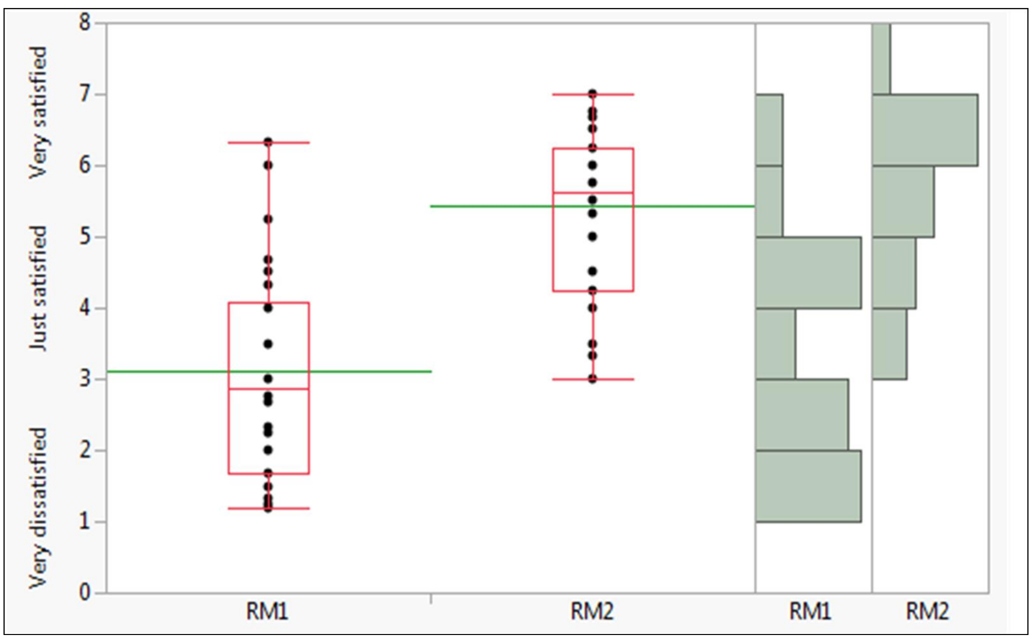
In Part III of the questionnaire, I measured subjective satisfaction with the attributes of the window blinds, including appearance, glare control, noise control, overall satisfaction, and other. Subjects were also asked to indicate their reasons for adjusting the blinds (in the experimental group) or planning to adjust the blinds (in the control group). Table 4.13 shows the intergroup comparison related to the satisfaction with window blinds and the results of the *t-tests* of the samples in the two groups. There were no significant differences (p=0.139) in terms of the rating on the appearance of windows and blinds in the two groups, but the experimental group obtained higher values in this item (mean difference was 0.62 on a scale of 1 to 7). Similarly, another non-significant factor was related to the responses to "Noise control." We hypothesized that the movable blinds might have generated some noise because of their movement, but the results did not reveal statistically significant differences (p=0.301) in the two rooms.

Table 4.13. Comparison between groups of subjective satisfaction with blinds

	Experimental group		Control group		Mean	Std Err	t	
	Mean	Std Dev	Mean	Std Dev	dif	dif	ratio	*p*
Appearance	4.61	1.38	3.99	1.79	0.62	0.41	1.50	0.139
Glare control	5.42	1.19	3.11	1.52	2.31	0.35	6.56	<0.0001*
Noise control	5.10	1.33	4.88	1.83	0.21	0.41	0.53	0.301
Overall satisfaction	5.62	1.03	3.74	1.66	1.89	0.36	5.28	<0.0001*

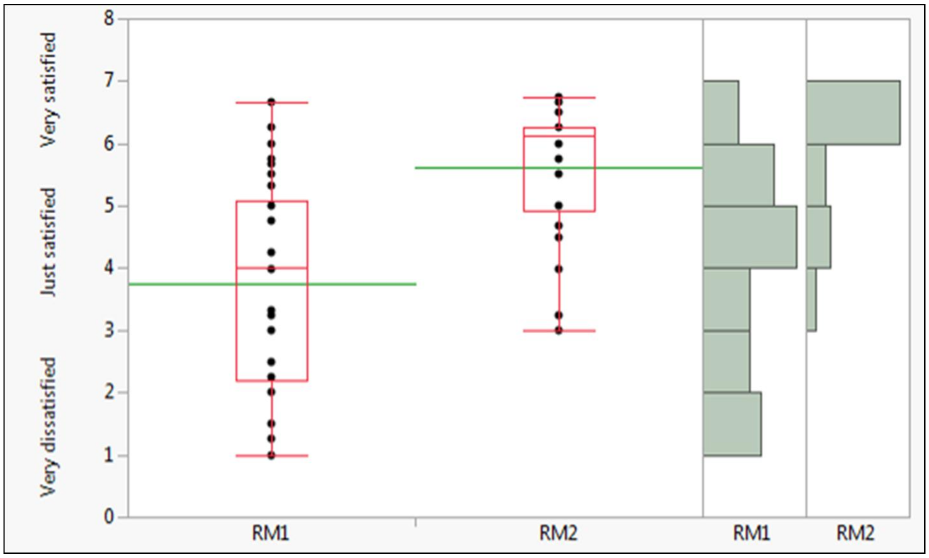
Note: the scale of each question is 1-7, with 1 = very dissatisfied, 4 = just satisfied, and 7 = very satisfied.

As seen in Figures 4.23 and 4.24, the responses to "Glare control" and "Overall satisfaction" of the blinds in RM2 (the experimental group) were significantly different ($p < 0.0001$) relative to RM1 (the control group). This was due to the different types of window blinds between the two rooms. I preset optimal angles (related to heating loads, cooling loads, lighting loads, and window views) of the blinds in RM1 with static conditions, but the subjects in this control group provided dissatisfied responses to the glare control (3.11 ± 1.52, 4 is "just satisfied" on the Likert scale) and the overall satisfaction (3.74 ± 1.66) with the blinds. On the contrary, the controllability of the blinds in RM2 offered greater effects to the experimental group. The mean values of the glare control and the overall satisfaction were 5.42 ± 1.19 and 5.62 ± 1.03 respectively.



Note: RM1 was the control group, and RM2 was the experimental group

Figure 4.23. Satisfaction with glare control of the blinds in the two rooms



Note: RM1 was the control group, and RM2 was the experimental group

Figure 4.24. Overall satisfaction with the blinds in the two rooms

In addition, the questionnaire had one question related to the electric lights, which was "Did you want to turn on the electrical lights during last 30 minutes?" Due to the clear or partial cloudy weather conditions that I chose for the mockup surveys, during the whole study, only two subjects in the experimental group and one subject in the control group reported that they wanted to turn on the lights. All three subjects were sitting at Desk 3, which was furthest from the windows.

Regarding the blind control behaviors, the responses differed between the two groups. In the control group, the subjects were unable to adjust the blinds, so the question was whether they wanted to control the blinds. In the experimental group, the subjects were able to control the blinds. So, the question was whether they adjusted the blinds. The optimal angles were present to RM1 in the beginning of the surveys, and RM2 had automatic settings for different orientations and time. On the basis of these two settings of blind systems, it was found that 22 subjects in the control group wanted to adjust the blinds, and 16 subjects in the experimental group adjusted the blinds during the surveys.

Figure 4.25 shows the percentage distribution of the reasons why they wanted to adjust or did adjust the blinds in each group. The reasons included "Reduce sunlight glare from windows," "Reduce lighting contrast on the desk," "Reduce the overall brightness," "Increase visual privacy," "Reduce solar heat," "Reduce outside visual stimulus," and "Other." Regarding the specific reasons of "Other," four items referred to "Increase the brightness" and three items to "Reduce the reflective glare from the blinds." In general, around 60.6% of the reasons to adjust the blinds in the control group were to reduce sunlight glare from windows. Similarly, in the experimental group, the selection of "Reduce sunlight glare from windows" was also the most frequently identified factor (33.3%). Therefore, the real-time automatic settings of slat angles dramatically reduced glare problems from windows. However, as subjects manually adjusted the blinds, the positions of the slats in RM2 were often nearly closed, which resulted in lessening the lighting levels in Desk 3 (the furthest location from the windows).

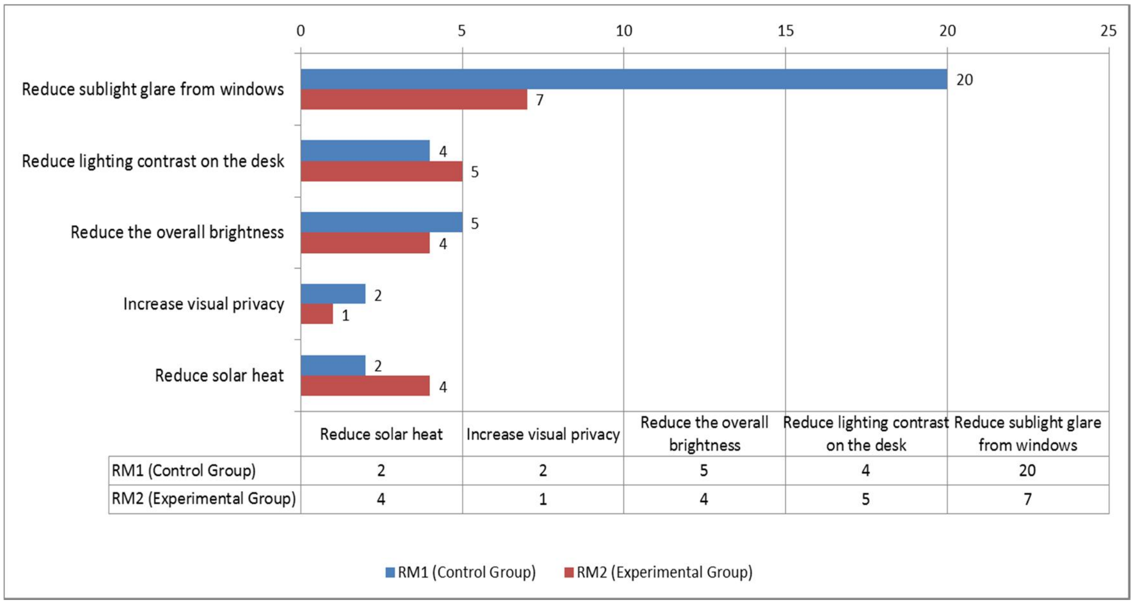


Figure 4.25. Reasons to adjust blinds in the two rooms

4.6 Chapter Summary

In this chapter, a series of subjective surveys were conducted to obtain appraisals of the kinetic window technology, and satisfaction with the visual work/study environment. Basically, this chapter examined the effects on human factors of AKE. Sixty subjects were randomly assigned into RM1 (the control group) or RM2 (the experimental group). Then, each survey had three subjects in each room, and the six subjects studied or worked with different blind systems: external static blinds with optimal angles or kinetic external Venetian blinds, under identical external environmental conditions. With regard to the types of tasks the participants undertook, the main percentage of time (46.3%) was spent reading papers. Using laptops was the second most common task (35.1%), and writing by hand (7.6%) and drawing by hand

(8.0%) had similar percentages. Subjects were asked to fill out questionnaires after having spent 30 minutes exposed to the scenarios.

The entire mockup survey was conducted between the end of September and early October 2013. By rotating the room, the time periods selected in this study had low solar positions ranging from 31.1º to 40.3º. These low solar altitude angles created uncomfortable visual conditions with high probabilities of glare. Around 90% of the time the sky was clear, and the remaining time the sky was partially cloudy. The horizontal illuminance ranged from 18,258.5 lux to 87,763.3 lux, and the vertical illuminance ranged from 17,661.6 lux to 89,518.5 lux. During these chosen 30-minute periods, the external lighting levels were high enough to be able to activate automatic movements of the blinds of RM2. The main findings are as follows:

1) A contingency analysis was conducted on the subjects' characteristics, attitudes, and sensitivities to visual factors. No statistically significant differences ($p > 0.05$) were found between the control group and the experimental group. In addition, good lighting was the most highly ranked characteristic for making a comfortable visual work/study environment, and lighting control was ranked as the second most important factor.
2) With respect to the visual qualities of the two groups, I utilized an independent two-sample *t-test* (one-tailed) to analyze each question. The overall satisfaction of the visual qualities in the experimental group (5.65 ± 1.14) with movable blinds (RM2) was statistically higher than the mean value

of the control group (4.48 ± 1.62), and the difference between the groups was found to be statistically significant (*p*=0.001). On particular questions, the subjects' responses to the lighting levels at their desks (*p*=0.006) and lighting distributions (*p*=0.007) in the two groups had significant differences. The mean values of these answers in the experimental group were closer to the lighting conditions "Just right" and "Nicely distributed." The use of movable blinds in the experimental group achieved significantly lower values (*p*=0.001) in responding to glare sensations compared to the values collected from the control group. In terms of the sources of glare, "Light from windows" was most frequently selected for creating glare problems in both rooms. In this part, the only non-significant difference concerned visual distractions.

3) With respect to the satisfaction with blind systems, the responses to "Glare control" and "Overall satisfaction" of the blinds in RM2 (the experimental group) were found to be significant ($p < 0.0001$) relative to RM1 (the control group). There was no significant difference (*p*= 0.139) in terms of the rating of the appearance of windows and blinds in the two groups. In addition, we hypothesized that the movable blinds might generate some noise because of their movements, but the results did not reveal statistically significant differences (*p*=0.301) in the two rooms. Regarding the reasons why they wanted to adjust or did adjust the blinds in each group, the selection of "Reduce sunlight glare from windows" was most commonly chosen in two groups. Therefore, the real-time automatic settings of slat angles dramatically

offered good glare protection related to windows. However, as subjects manually adjusted the blinds, the positions of the slats in RM2 were often nearly closed, which resulted in lessening the lighting levels at Desk 3 (the furthest location from the windows).

Lastly, the solar locations ranged from 31.1º to 40.3º and the solar elevation altitudes ranged from -25º to 30º in this study (see Table 4.24). Although the surveys and the tests were conducted in Bryan, TX the survey results are applicable to other locations with similar solar positions. Table 4.25 presents similar solar positions in Houston, San Francisco, Baltimore, and Chicago. Figure 4.26 shows the solar paths of these four locations where is highlighted the periods with similar sun positions.

Table 4.14 Basic information about solar positions in this study

Location	**College Station**	
Solar altitude a_t	31.1º~40.5º	
Solar elevation azimuth a_z	-25º ~ 30 º	
Solar profile angles a_p	32.8º~41.2º	
Selected orientation	115º (Southeast)	240º (Southwest)
Time	9:50~10:30	15:50~16:30
Date	September 23rd to October 4th 2013	

Table 4.15. Basic information about solar positions in this study

	Houston	**San Francisco**	**Baltimore**	**Chicago**
Month	Nov.21st ~ Jan.21st	Oct.21st ~Sep.21st	Oct.21st ~Nov.21st & Jan. 21st ~ Feb. 21st	Oct.15th ~Nov.15th & Feb.5th~ Mar.5th
Solar Time	10:30~13:30	10:30~13:30	10:45~13:45	10:45~13:45

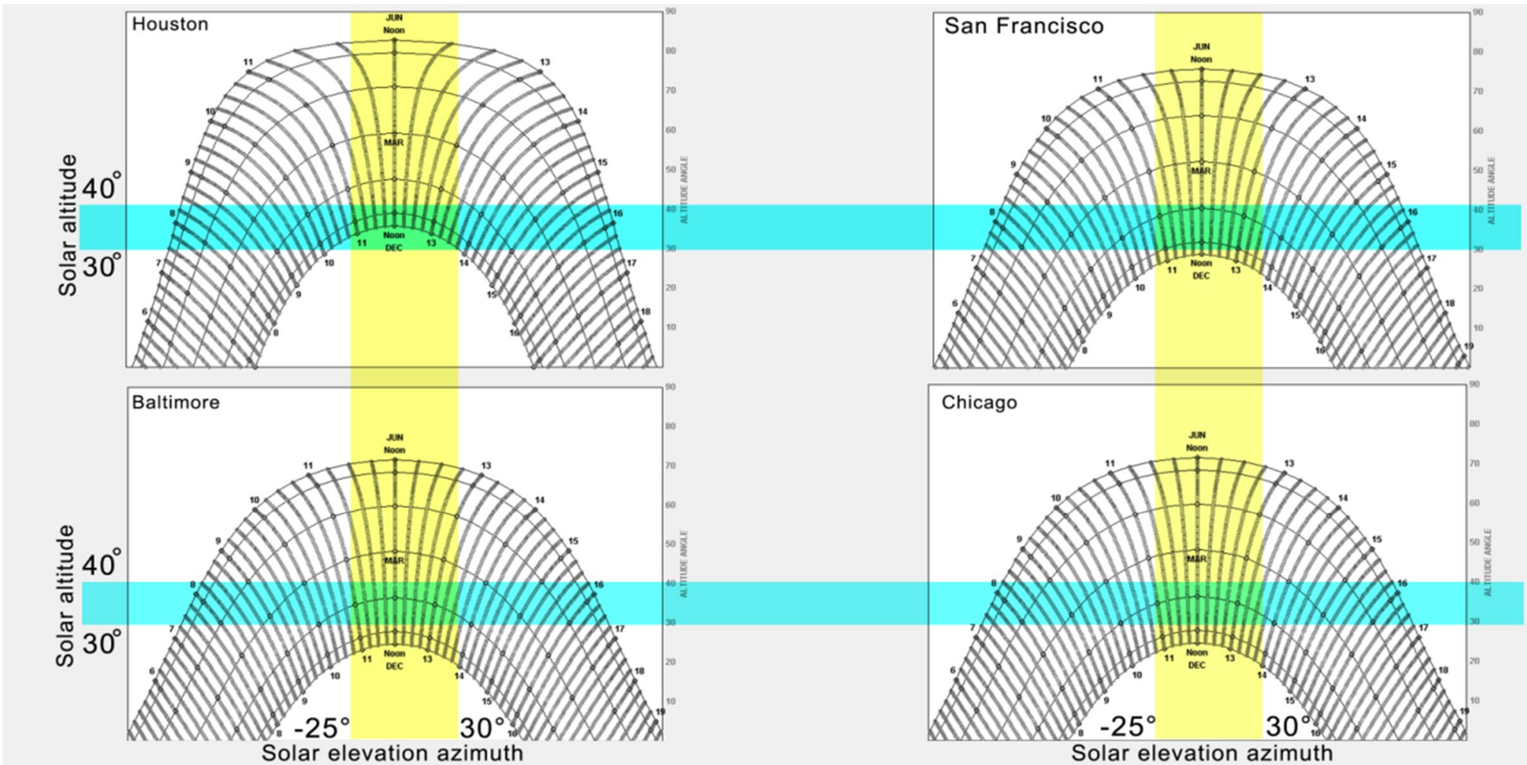


Figure 4.26. Solar path for the four cities with similar solar positions to this study

CHAPTER V

CONCLUSION

Current energy efficient design strategies and technologies of building envelopes have led to significant building energy savings. However, for some climatic conditions, the conventional building envelopes with static properties may not be an optimal solution. In Chapter I, we hypothesized that AKE with dynamic properties responding to the climatic environment and occupants' needs may enhance the building performance related to energy and indoor environmental comfort under certain climatic conditions. Through parametric energy simulation and mockup surveys and tests, Chapter III and IV demonstrated the applicability range and features of AKE technologies and their beneficial effects on energy and indoor comfort as well. In this final chapter, the main findings are summarized, and some potential contributions and challenges of AKE applications are discussed. Also, the limitations of this study and the remaining future works are addressed.

5.1 Concluding Remarks

To achieve the aforementioned research objectives in section 1.2, the following main achievements were obtained:

1) **Categorization and Characteristics of AKE Implementation:** In recent years an increasing number of kinetic architecture examples have been built. However, among these cases, only few of them can be classified as being climatic responsive. Based on the climate-responsive characteristics of these AKE technologies, we grouped the design cases (built, or experimental) into

three categories: Solar-responsive, Air-flow-responsive, and others (Appendix C). It was found that because solar energy (solar radiation and daylight) tends to be climate specific and has certain conflicting circumstances for buildings, most design cases are about solar-responsive AKE.

2) **Parametric Energy Simulation Methods:** Combined with the parametric simulation approach of *jEPlus*, Energy Management System (EMS) of *EnergyPlus* offered an effective approach to model and simulate kinetic envelopes with variable properties. Some particular built-in features of *EnergyPlus*, like "Variable Thermal Conductivity" and "Movable Blinds," were also effective to create an AKE model.

3) **Energy Savings of AKE:** Compared to Baseline Models, Advanced Models, and Ultra Models, Kinetic Models with AKE technologies significantly reduced heating and cooling loads and peak demands of buildings, even relative to future highly-insulated glazing and walls, in the heating-dominated climate, the cooling-dominated climate, and the mixed-climate. On the baseline of ASHRAE 90.1-2010 Energy Standard, the PNNL prototypical office building with proposed AKE properties can significantly reduce building site energy uses for the four climates. Also, the site energy use intensity of kinetic-integrated models for the four climates demonstrated those proposed dynamic characteristics can produce high potentials to achieve net-zero energy.

4) **Effects on Energy Savings of AKE Assemblies:** In the four cities, kinetic windows played a more significant role in saving energy than the other kinetic components, and the savings were around two times as large as the savings of the highly-insulated glazing. However, compared to the highly-insulated opaque assemblies, variable thermal properties of AKE were more appropriate to the cooling-dominated climate because the highly-insulated opaque assemblies performed better in saving heating loads. Lastly, with respect to the effects of movable blinds, it was found that only cooling-dominated climate installations could obtain the energy savings by setting up movable blinds. In the mixed-climate and the heating-dominated climate, incorporation of blinds failed to save energy because the resulting winter energy and lighting loads outweighed the summer cooling energy savings.

5) **Impacts on Human Factors:** movable external Venetian blinds were used as a test case to illustrate how kinetic envelopes affect indoor comfort levels to occupants. Mockup survey results showed that overall satisfaction with the visual qualities associated with movable blinds was statistically higher (p=0.001) than the levels related to optimal static blinds. Similar trends were also found in the subjective responses to "Lighting Levels (p=0.006), Lighting Distributions (p=0.001), and Glare Sensation (p=0.001). Meanwhile, compared to static blinds, the movement of the blinds in RM2 reduced the satisfaction level on window views (p=0.007). With respect to the subjective

acceptance of external movable blinds, subjects reported higher levels (p<0.0001) on Overall Satisfaction and Glare Protections than the subjects in rooms with static blinds.

5.2 Potential Contributions

5.2.1 Net-zero Energy Buildings

As mentioned in the first chapter, the optical and thermal properties of the building façade act as an important climate-moderating function. This study demonstrated that kinetic building envelopes may provide the appropriate thermal, lighting, and air exchanges, necessary for improving the indoor conditions, even compared to the optimal static settings or future highly-insulated building envelopes. To achieve zero-energy building (ZEB), the National Renewable Energy Laboratory (NREL) (Long, Torcellini, Judkoff, Crawley, & Ryan, 2007) assessed the energy performance for commercial buildings based on technologies that were projected to be available in 20 years. NREL noted that the EUI could be as little as 40.3 kBtu/ft^2·yr. Figure 5.1 shows the EUI values of different standards or current "net-zero energy" buildings. Compared to these EUI values, Kinetic Models in this study achieved lower levels (ranging from 17.2 KBtu/ft^2·yr to 20.8 KBtu/ft^2·yr). In the coming decades, the kinetic building envelopes can be dramatically reshaped by combining the results of research building-integrated renewable energy technologies, efficient mechanical systems, advanced sensors and controls. Therefore, these kinetic properties of AKE in this study may not be available currently, it still shows a promising potential for future net-zero energy buildings.

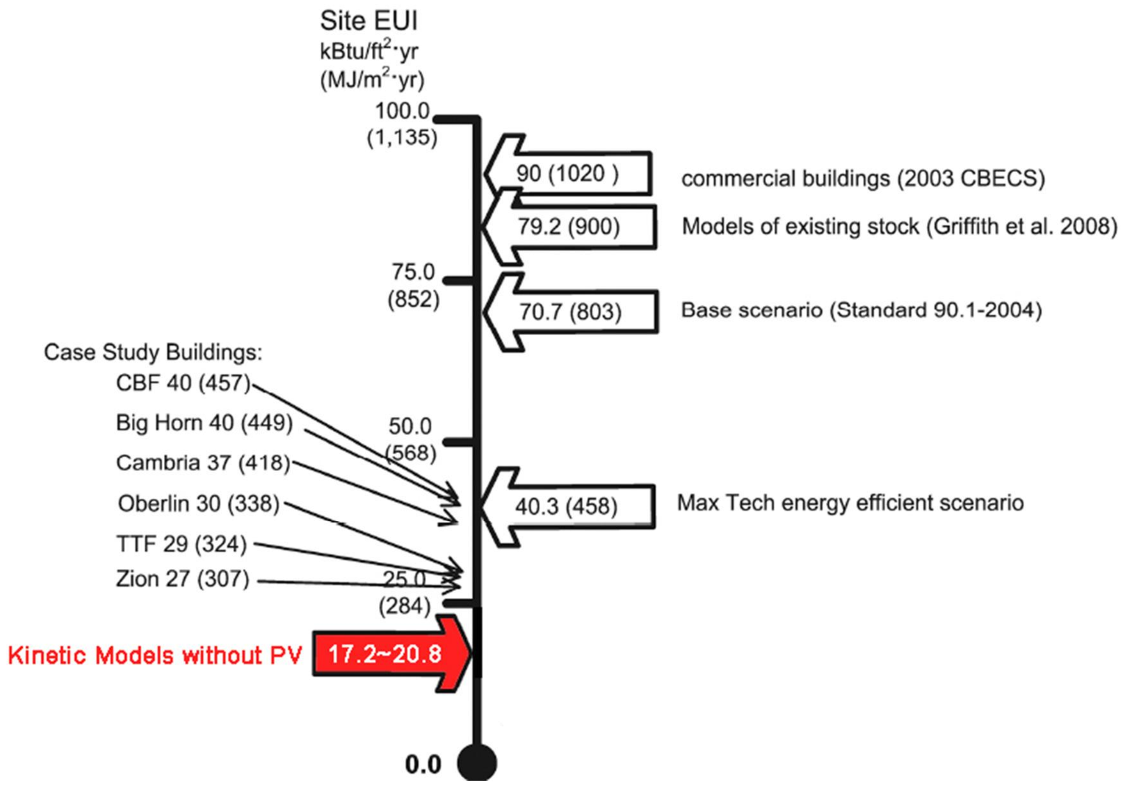


Figure 5.1. Comparisons of average EUI at the various levels based on the NREL's report

5.2.2 Renewable Energy Generation by Kinetic Technology

According to the definitions of Net-Zero Energy by the U.S. Department of Energy, zero energy buildings should generate as much energy on-site through renewable sources as it uses. NREL (Long, Torcellini, Judkoff, Crawley, & Ryan, 2007) predicted that the widespread installation of rooftop PV could produce an average 28.1 kBtu/ft2•yr for commercial buildings. However, as discussed in Chapter II, there are currently some examples related to movable BIPVs, and these kinetic properties may improve the energy generation in most climates relative to the static BIPVs. So, if certain kinetic renewable energy systems (e.g., PV, wind turbines) can be integrated into buildings, buildings with kinetic envelopes and energy generating systems could not only achieve net-zero energy but also produce more energy than they consume.

5.2.3 Environmental Satisfaction and Productivity

Many studies (e.g., Gensler, 2006; Uzee, 1999; Leaman and Bordass, 1993; Williams *et al.* 1985) have noted that the environmental satisfaction is playing a major role in boosting human productivities (ranging from 0.5% to 10%) and improving organizational performance. Clements-Croome (2000) stated that staff costs are 100 to 200 times as much as the cost of operating building environmental systems, so, 0.5 to 1% increases in productivities can off-set the costs on installation and running these environmental systems. This study demonstrated that the integration of AKE technologies may dramatically improve the satisfaction on visual qualities (around 26% rises of the overall satisfaction level on visual qualities in this mockup surveys). Thus, spending money on improving working environment by utilizing AKE technologies could still be cost effective, because a small rise in productivities can contribute a great deal to the overall profitability.

5.2.4 Smart Buildings and Occupant Controls

Our surveys revealed that the controllability of kinetic building envelope systems was desirable. As the development of indoor environment system operation and management, sensor- and data-processing for smart buildings and mobile network controls, AKE will be not only a net-zero energy function of its original climatic responsiveness but an interactive interface between users and buildings. Therefore, the study on AKE may revolutionize visions and approaches of architects and engineers toward future smart buildings, interactive architectural aesthetics, and occupant responsive controls.

5.3 Limitations of the Study

5.3.1 Limitations in Energy Simulation

Firstly, the following kinetic parameters were selected in this study: variable insulation of walls, variable insulation of roofs, dynamic glazing U-factors, dynamic SHGC of windows, and movable blinds. The dynamic properties of the envelope assemblies were theoretically proposed and analyzed. So, the values for the relative energy reduction were based on artificial boundary conditions and may not be achieved currently.

Secondly, the study is limited in terms of its generalizability to all kinetic building envelopes. Except for the aforementioned kinetic functions, there are currently also other kinetic features related to AKE, for example, sliding walls and retractable roofs. There kinetic properties may have different impacts on energy use. Thus, the results of this energy simulation study cannot be generalized to other types of kinetic envelopes.

Thirdly, the building typology in this study is limited to one-floor office building. The NREL's report (Long, Torcellini, Judkoff, Crawley, & Ryan, 2007) stated that single-story buildings are the most likely to achieve net zero energy consumption relative to multi-story buildings. Also, compared to hospitals, office buildings, and food service establishments, non-refrigerated warehouses, vacant, religious worship, and educational buildings may get a better chance of achieving zero energy because they do not have high plug and process loads. So, kinetic properties in different functions and forms of buildings may have different impacts on energy uses. Consider, for instance, residential buildings that may have lower heat gains from inside equipment and people relative to office buildings. Thus, the variable insulation of opaque assemblies in residential buildings may not reduce cooling loads as many as these kinetic properties in office buildings.

5.3.2 Limitations in Mockup Surveys

Firstly, most of these kinetic properties in the simulation study are still in experimental stages. Current kinetic insulated envelopes in the real world do not meet our proposed kinetic properties of envelopes during the simulation study. Only external movable Vernation blinds were adopted as a representative kinetic technology in our mockup surveys. The findings of the surveys, therefore, don't address the comparisons with other building components of kinetic envelopes.

Secondly, the results of the mockup tests and surveys were limited to the blinds used in the mockup structure. For example, the blinds used in this study had specular reflection that might affect the human responses related to glare sensation and controls.

Thirdly, the distribution analysis of subjects' age shows nearly all participants in this study were under 30 years old. Similarly, the subjects in this study were White and Asian. Therefore, the human responses of this study were limited to subjects of these two ethnicities and backgrounds.

5.4 Future Work

In this study, only some characteristics of kinetic envelopes were tested and evaluated with energy simulations and mockup surveys. Based on the findings and the methods of this study, future research might include:

1) **Other building types and forms:** One-floor prototypical office building was selected as a case in this study, so the environmental systems, equipment, schedule, and other settings of the office typology affected the final results. Other building types, such as healthcare, commercial and residential buildings may have different input parameters in evaluating energy uses. Also, the building size and forms were constrained at this stage, which may be crucial to the results. So, integrating the dynamic geometric settings into the evaluations of AKE would be of another interest.
2) **Comprehensive and integrated simulation approach**: In this study, the techniques of *EnergyPlus* and *jEPlus* were utilized and expanded to allow the evaluations on the specific kinetic properties. However, the process of using these approaches for this study was still complex and isolated. Some built-in functions worked for the dynamic properties, but they were not specifically designed for AKE. Some errors and limitations were often met during the modeling and simulating process. One of the future works is to experiment and integrate all functions for other dynamic materials and systems into one platform or one simplified workflow.
3) **Optimization approach of AKE parameters**: During the course of the

energy simulation study, I proposed variations for each envelope parameter and then conducted the comparison with other referenced models. Although *jEPlus* was used for a series of parametric simulation runs to find out the "optimal settings" for the kinetic envelopes, real optimization for a broader range of parameter variations is still needed. Some existing research explored different algorithms (e.g., Genetic Algorithm) for optimization of building forms, shadings, and physical properties. Most of these studies are to finalize the optimal properties for the static situation rather than kinetic states in different seasons or days. Therefore, the optimization method and tests of AKE are another category for the future research.

4) **Lifecycle analysis:** It is critical to consider its entire life cycle before utilizing these emerging technologies. This includes upstream impacts (e.g., raw smart materials acquisition, manufacturing, and shipping), using impacts (e.g., installations, energy performance, effects on human factors, and maintenance), and downstream impacts (e.g., removal and waste management). Especially, regarding the impacts of the use of AKE, attention to gains and costs are required for well-balanced trade-offs. At this time, the inherent economic challenges may hamper the application of AKE. On one hand, these emerging technologies require more initial costs than CEE. On the other hand, AKE still consumes some energy to adjust itself from one state to another one. The amount of energy needed and associated operational and maintenance costs might be larger than the gains on energy savings and

human factors. Therefore, the impacts of operating AKE are the significant part to the lifecycle assessment. The future work may embrace aspects spanning from economics through design to functionality.

5.5 Closing

Integrating kinetic properties into building envelopes may lead to innovative design approaches in how architects and engineers create buildings to respond to climatic conditions and occupant needs. This research demonstrated the benefits of AKE on energy and occupant satisfaction under certain conditions relative to CEE with “best” or even “future” envelope properties. With the advent of new AKE technologies, the techniques and the results in this study can serve as a reference point for future research on applicability and optimization of kinetic building envelopes toward net-zero energy buildings and indoor comfort.

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APPENDIX A

QUESTIONNAIRES

PART I: BACKGROUND INFORMATION

I-1 What is your gender?

a) Male

b) Female

I-2 How old are you?

a) Less than 20

b) 20 - 29

c) 30 - 39

d) 40 - 49

e) 50 - 59

f) 60 or over

I-3 What is your race?

a) White

b) Black or African American

c) American Indian or Alaska Native

d) Asian

e) Native Hawaiian or Other Pacific Islander

f) Some Other Race

I-4 Do you wear glasses when doing study/office works?

a) No

b) Yes

I-5 Are you color blind?

a) No

b) Yes, Red-Green / Blue-Yellow (please choose one).

c) I am not sure.

I-6-1 Where you normally work/study, do you have a view of a window while working/studying?

a) No

b) Yes

I-6-2 If yes, do you have a scenic view?

a) No

b) Yes

I-7 What color are your eyes?

a) Brown

b) Black

c) Blue and others

----------- End of Part I ----------

PART II: ATTITUDINAL SURVEY

II-1 Please assign a rating for the importance of the following items in making a comfortable visual environment, with 1 being the least important and 7 being the most important.

Unimportant Moderately Important Very Important

1 2 3 4 5 6 7

a) Good lighting

|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|

b) Lighting control (adjust lighting levels)

|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|

c) Windows (glazing type, shapes, and others)

|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|

d) Windows view

|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|

e) Privacy

|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|

f) No noise

|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|

g) Controllable shadings, blinds or sunscreens

|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|

h) Good room color rendering

|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|

i) Other (specify)

|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|

II-2 Please assign a rating for your sensitivity to the following items, with 1 being not sensitive, 4 being moderately sensitive, and 7 being very sensitive.

Least Sensitive **Moderately Sensitive** **Very Sensitive**

a) Glare

|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|

b) Gloominess

|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|

c) Noise

|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|

d) Visual distraction

|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|

II-3 When you perform your work / study tasks, what is your preferred light level in your workspace?

Very Low **Moderate** **Very Bright**

Light level

|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|

----------- End of Part II ----------

RM1 PART III: HUMAN RESPONSES TO THIS MOCK-UP ROOM VISUAL QUALITIES

III-1 During the last 30 minutes, what percentage of your time was spent on each of the following tasks?

a) Reading on paper _____%

b) Laptop (reading, drawing, typing) _____%

c) Writing (by hand) _____%

d) Drawing (by hand) _____%

e) Other (please specify) ______________ _____%

III-2 In which desk did you sit? (Use labels on the desk)

a) No. 1

b) No. 2

c) No. 3

III-3 Please assign a rating for the following visual qualities of <u>your working area.</u>

a) Overall satisfaction of the visual qualities

Very Dissatisfied Just Satisfied Very Satisfied

1 2 3 4 5 6 7

|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|

b) Light level

Too Dark Just Right Too Bright

|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|

c) Lighting distribution

Poorly Distributed Nicely Distributed

|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|

d) Windows view

No views Clear view

|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|

e) Visual distraction (window systems including glazing, blinds and views; except for rotations)

Not affected Affected

|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|

f) Glare sensation

Not perceptible Perceptible Acceptable Uncomfortable Intolerable

|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|

If you perceived glare sensation while in the room, please indicate the source of the glare. (Please check all that apply)

a) Windows

b) Wall surfaces

c) Desk surfaces

d) Reflections on the laptop screen

e) Reflected glare from blinds

f) Other (please specify)____________________

III-4 Please assign a rating or your satisfaction with the following attributes of the <u>window blind systems</u>.

Very Dissatisfied Just Satisfied Very Satisfied

1 2 3 4 5 6 7

a) Window (including blinds) appearance

|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|

b) Glare control

|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|

c) Noise control

|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|

d) Overall satisfaction of the blinds

|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|

e) Other (please specify) ___________________

|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|

III-6-1 Did you want to turn on the electrical lights during last 30 minutes?

a) Yes

b) No

III-6-2 If yes, when did you want to turn on the lights?

a) During the first 10 minutes

b) During the second 10 minutes

c) During the third 10 minutes

III-7-1 Did you want to control the window blinds (adjust the slats angles and / or lift the blinds) during last 30 minutes?

a) Yes

b) No

III-7-2 If yes, please choose the reasons why you wanted to adjust window blinds in last 30 minutes.

a) To reduce glare from daylight/sunlight

b) To reduce lighting contrast on the desk

c) To reduce the overall brightness

d) To increase visual privacy

e) To reduce the heat from the sun

f) To decrease the level of visual stimulus from the outside

g) Other (please specify) ___________________

III-8 Please add any additional comments (e.g., window operation, blinds, lighting, visibility, comfort, etc.) about this test in the space.

RM2 PART III: HUMAN RESPONSES TO THIS MOCK-UP ROOM VISUAL QUALITIES

III-1 During the last 30 minutes, what percentage of your time was spent on each of the following tasks?

a) Reading on paper _____%

b) Laptop (reading, drawing, typing) _____%

c) Writing (by hand) _____%

d) Drawing (by hand) _____%

e) Other (please specify) _______________ _____%

III-2 In which desk did you sit? (Use labels on the desk)

a) No. 1

b) No. 2

c) No. 3

III-3 Please assign a rating for the following visual qualities of <u>your working area.</u>

a) Overall satisfaction of the visual qualities

Very Dissatisfied Just Satisfied Very Satisfied

1 2 3 4 5 6 7

|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|

b) Light level

Too Dark Just Right Too Bright

|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|

c) Lighting distribution

Poorly Distributed Nicely Distributed

|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|

d) Windows view

No views Clear view

|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|

e) Visual distraction (window systems including glazing, blinds and views; except for rotations)

Not affected Affected

|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|

f) Glare sensation

Not perceptible Perceptible Acceptable Uncomfortable Intolerable

|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|

If you perceived glare sensation while in the room, please indicate the source of the glare. (Please check all that apply)

a) Windows

b) Wall surfaces

c) Desk surfaces

d) Reflections on the laptop screen

e) Reflected glare from blinds

f) Other (please specify)____________________

III-4 Please assign a rating or your satisfaction with the following attributes of the <u>window blind systems</u>.

Very Dissatisfied Just Satisfied Very Satisfied

1 2 3 4 5 6 7

a) Window (including blinds) appearance

|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|

b) Glare control

|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|

c) Noise control

|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|

d) Overall satisfaction of the blinds

|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|

e) Other (please specify) ___________________

|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|

III-6-1 Did you want to turn on the electrical lights during last 30 minutes?

a) Yes

b) No

III-6-2 If yes, when did you want to turn on the lights?

a) During the first 10 minutes

b) During the second 10 minutes

c) During the third 10 minutes

III-7-1 Did you control the window blinds during last 30 minutes?

a) Yes

b) No

III-7-2 If yes, please choose the reasons why you adjusted window blinds in last 30 minutes.

a) To reduce glare from daylight/sunlight

b) To reduce lighting contrast on the desk

c) To reduce the overall brightness

d) To increase visual privacy

e) To reduce the heat from the sun

f) To decrease the level of visual stimulus from the outside

g) Other (please specify) ___________________

III-8 Please add any additional comments (e.g., window operation, blinds, lighting, visibility, comfort, etc.) about this test in the space.

----------- End of Part III ----------

APPENDIX B

DATALOGGER AND CALIBRATIONS

B.1 Datalogger and Devices

In the mockup test of this study, the data related to indoor lighting environment, exterior lighting conditions, wind speed, etc. were collected. So, I utilized the CR1000 datalogger and a series of sensors to set up our data-acquisition system. The CR1000 is manufactured by Campbell Scientific (CS) and is widely used in a broad range of of fields including the building environment. The CR1000 datalogger consists of a measurement and control module and a wiring panel, and it needs an external CPU, keyboard, and monitor for controling it. The CS LoggerNet 5.0 software was used for editing and collecting data. Table B.1 shows all devices that I used in the mockup tests.

Table B.1. Devices for calibration

Devices/programs name	Type	Purpose	Number
Datalogger	CR1000	Data acquisition system	1
Multiplexer	AM16/32B	Increase the number of sensor channels	1
LI-COR Photometric Sensor	LI-210SA	Collect illuminance data	27
Dell Server with monitor	Windows 7 64 bits	Control the datalogger and data storage of the datalogger	1
Loggernet	5.0	Programming, communication, and data retrieval between dataloggers and a PC	1
Chroma Meter	CL-200	Calibration of LI-COR sensors	1

The multiplexer was also made by CS and it was the type of AM16/32, which allowed 16 more groups of four lines (a total of 64 lines). With this device it increased the number of sensors that we can connect to the CR1000. In our research, we used 28 LI-COR Photometric Sensor, so that the 14 groups of the multiplexer AM16/32B were occupied.

The LI-COR LI-210 Photometric Sensor was utilized to measure illuminance levels in lux. The millivolt adapter connected to the BNC connector of the sensor, and the wire leads of the adapter were connected to the datalogger. Therefore, the sensor output was millivolts rather than lux, so the converting process was using "Ohms Law" (Voltage = Current * Resistance). Twenty-four sensors were distributed on six desks to collect indoor illumination data, and other two sensors were located outdoor to collect the exterior global horizontal and vertical illuminance. In addition, we set up two movable LI-210 sensors with the cameras for assessing the vertical illuminance at the eye level of subjects during the mockup tests.

Figure B.1. Connections of the datalogger, sensors, and a laptop

B.2 Calibrations for LI-210 Sensors

In this study, I used Loggernet 5.0, CR1000 Datalogger, Minolta CL-200 Light Meter, and compact fluorescent lamps to calibrate the LI-210 sensors.

1) Set up the Calibration Environment and Structures

The first step is to set up a stable and uniform lighting environment with adjustable lighting levels for the calibration. We utilized the photography room of TAMU's College of Architecture and created a lighting scenario including three groups of 6-compact fluorescent lamps with softbox and adjustable stands. The light source's color temperature ranged between 5000 - 5500K, and the illuminance on the work plane ranged 200~2000lux. By adjusting the height of the stands or turn on / off certain lamps, we could achieved different levels of lighting with a stable lighting conditions.

Figure B.2. The lighting environment setting up for calibration

In addition to the lights, in order to give relatively stable and uniform lighting conditions to 32 sensors, we designed a structure to hold 32 LI-COR sensors. This way, we could calibrate all sensors simultaneously under similar lighting conditions. Then, we connected these sensors to the CR1000 datalogger and the datalogger to a laptop via a USB port.

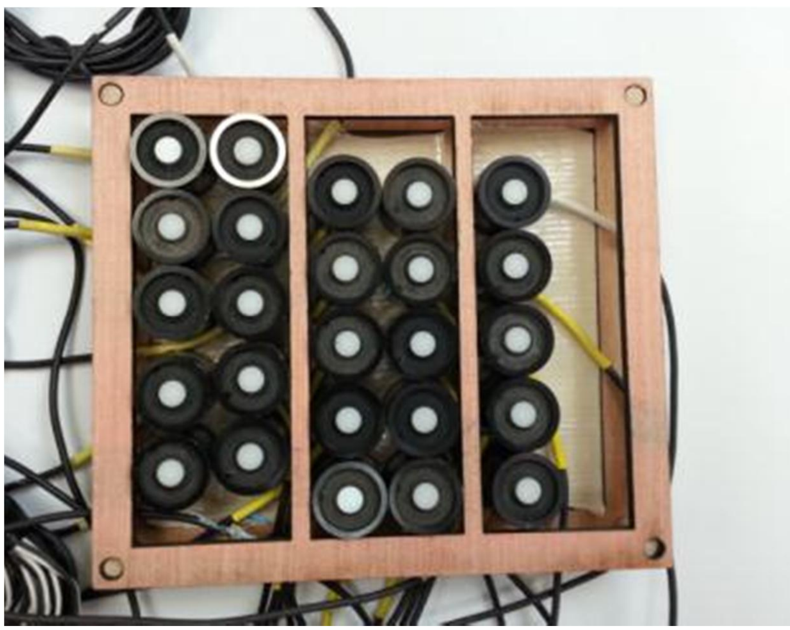


Figure B.3. Specific structure designed for holding up to 32 LI-COR sensors

To connect the LI-COR sensors to the CR1000 datalogger, it requires to connect properly the millivolt wires. The green or red lead should be connected to the positive (or high) terminal on the datalogger, and the blue or red lead should be connected to the negative (or low) terminal on the datalogger. We did not connect the ground terminal and the low terminal for each sensor although materialist was suggested this connection to minimize noises. All sensors were connected to the multiplexer that was connected to the CR1000 datalogger.

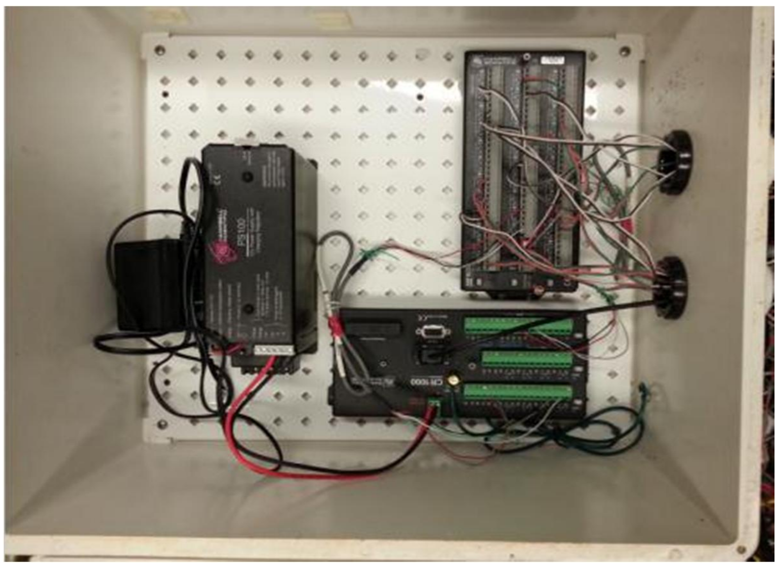


Figure B.4. Set up of datalogger with multiplexer

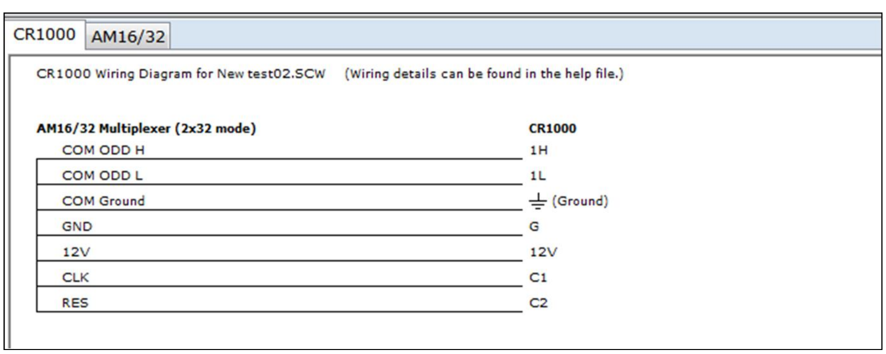


Figure B.5. Wiring diagram for connecting AM16/32 to CR1000

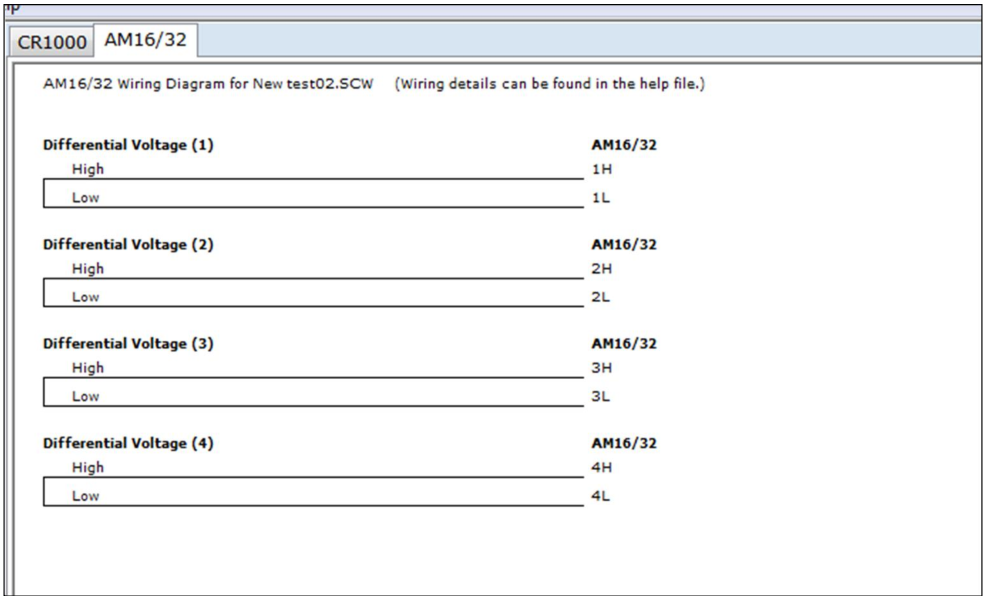


Figure B.6. Wiring diagram for connecting the LI-COR sensors to AM16/32

To connect a laptop with the CR1000, we conducted the following steps:

Figure B.7. Setup-1 for the CR1000 datalogger

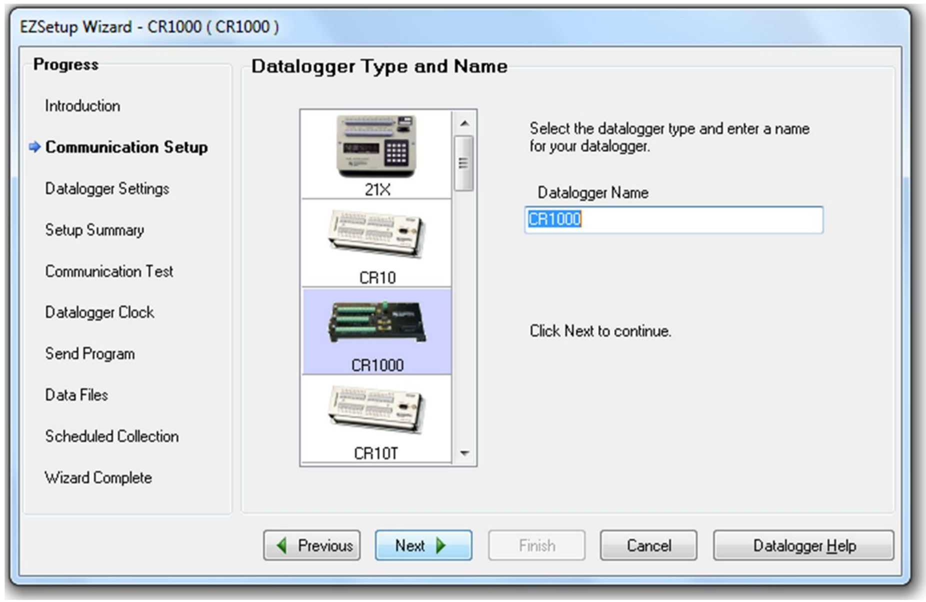


Figure B.8. Setup-2 for the CR1000 datalogger

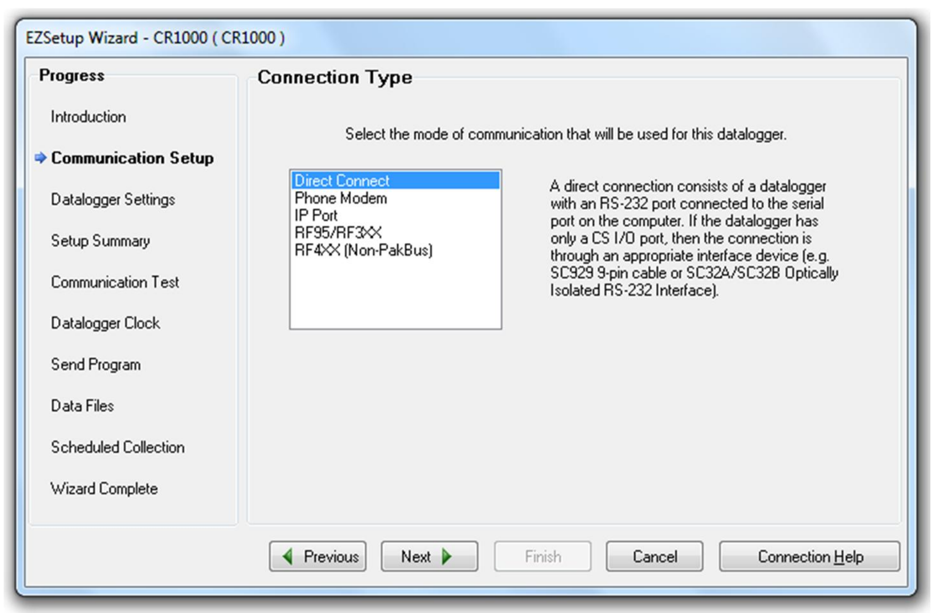


Figure B.9. Setup-3 for the CR1000 datalogger

We selected the mode of "Direct Connect" to conduct the connection between the datalogger and the laptop by using USB. We need to find out the COM port name that is occupied by the USB.

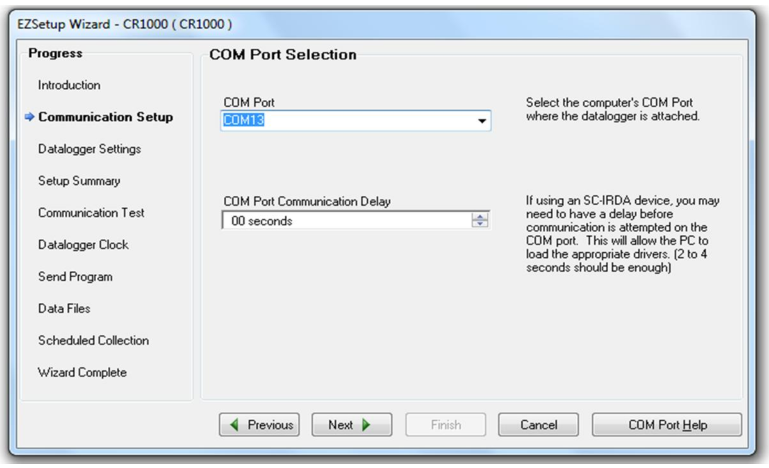


Figure B.10. Setup-4 for the CR1000 datalogger

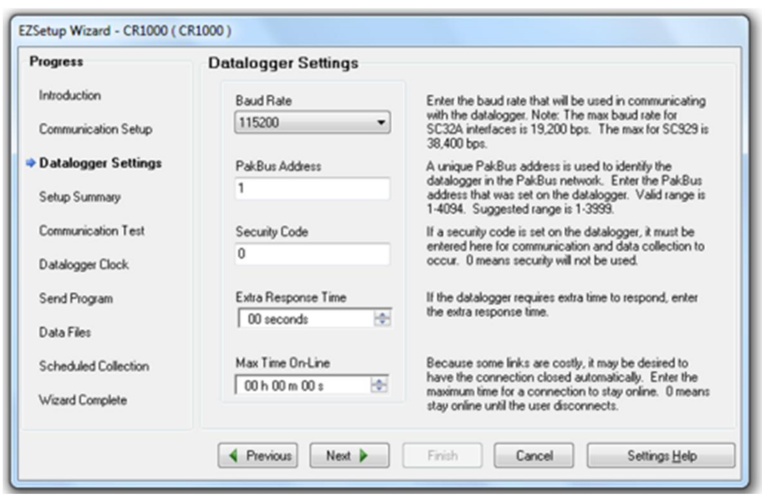


Figure B.11. Setup-5 for the CR1000 datalogger

2) Create a Calibration Program by Using the CRBasic Program

The CRBasic program is one of the functions in the LoggerNet package, and it is used to create a program to control and operate the data collection by using the datalogger. LoggerNet has some built-in programs (called short cut) for different usages and the users can create datalogger programs quickly and easily by using a wizard-like interface. These built-in programs support the most commonly sensors such as solar radiation sensors, temperature and humidity sensors, etc. However, it does not have specific programs for lighting sensors. Thus, we used "Differential Voltage" to set up a short cut program and then edited it in the CRBasic program. In the above options, we chose 0 to 2.5mV for the LI-COR sensors because the voltage values from the LI-COR sensors were within this scale. We kept the defaults for other settings. The following figures show the steps of using the CRBasic program.

- Open LoggerNet and Select Short Cut.

Figure B.11. Step-1 for creating a calibration program

- Set up a New Program.

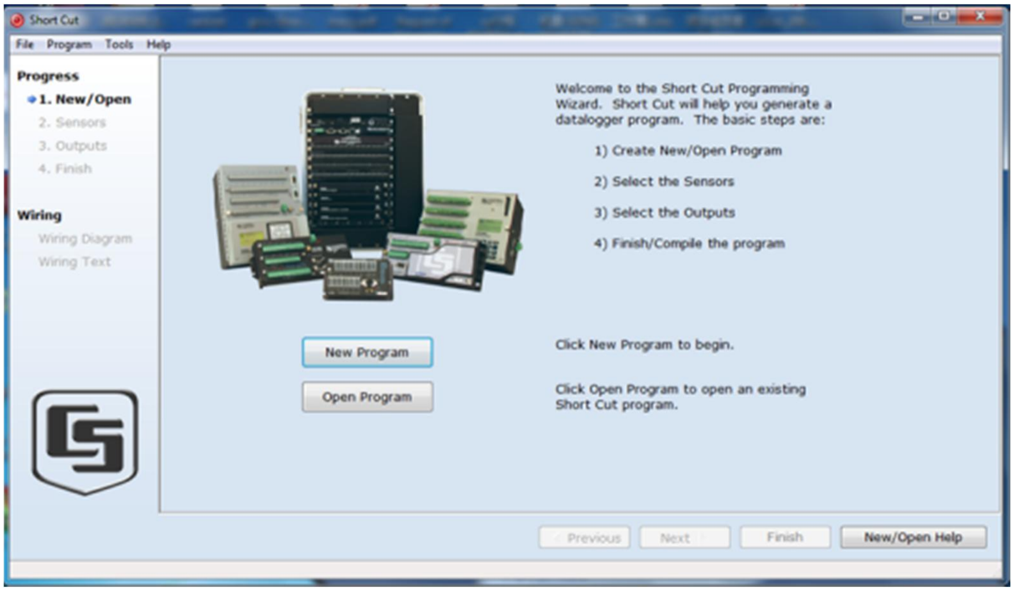


Figure B.12. Step-2 for creating a calibration program

- Input the scan interval time. Regarding the multiplexer, the minimum scan interval is 30 seconds. Also, you could edit these values later in the CRBasic program.

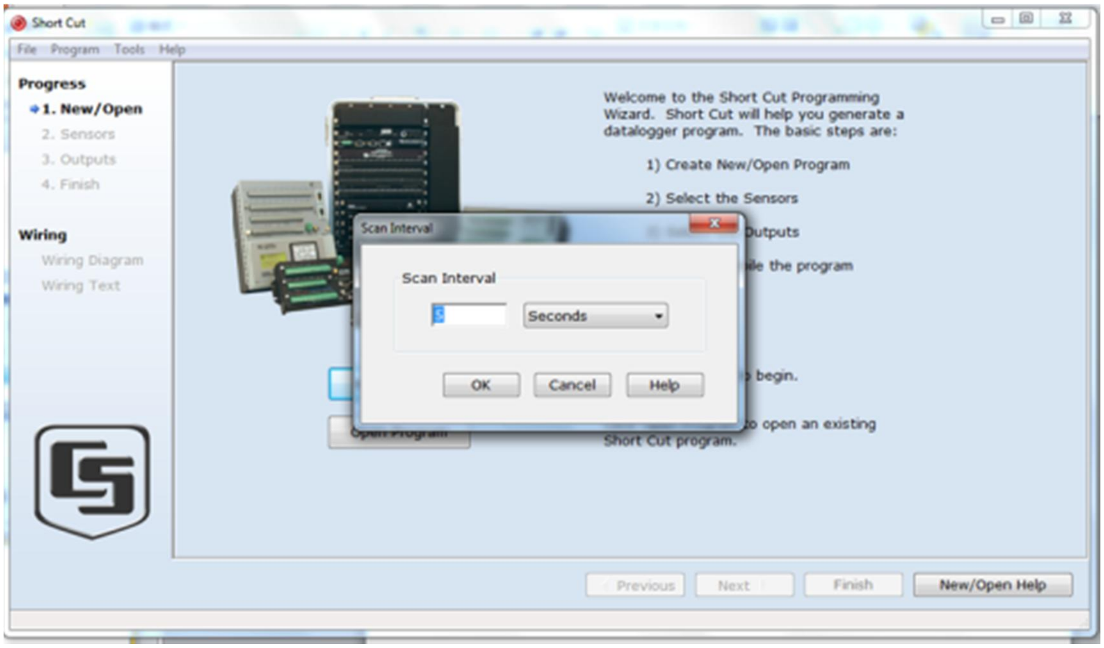


Figure B.13. Step-3 for creating a calibration program

- For the data collection of lighting sensors, you should select "Differential Voltage" under the folder of Generic Measurement. Input the numbers of the lighting sensors connected to the datalogger.

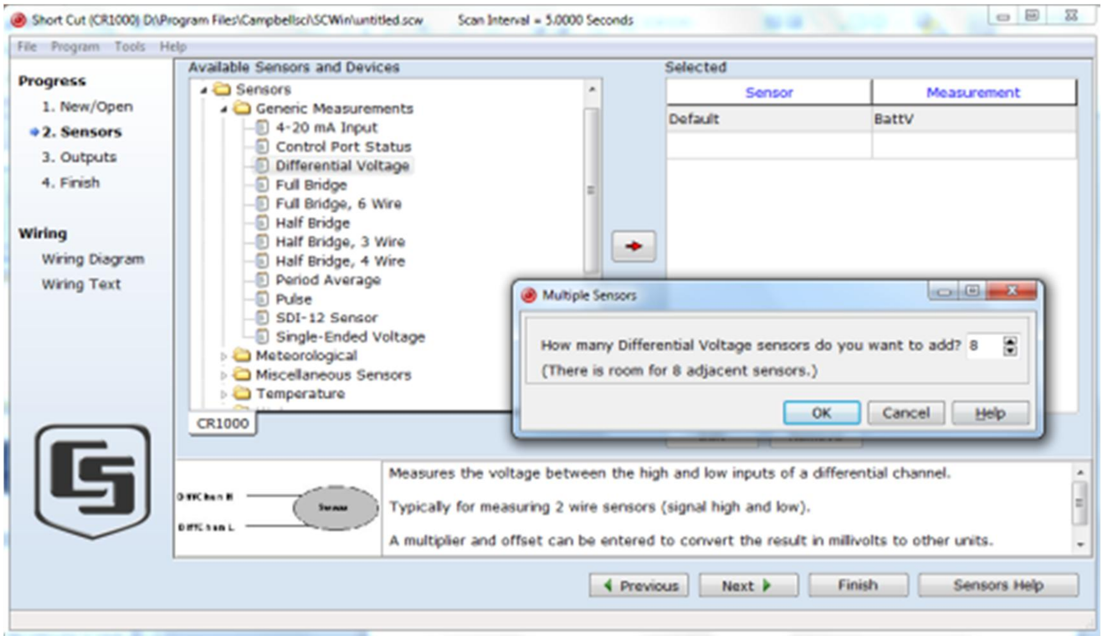


Figure B.14. Step-4 for creating a calibration program

- Some detail settings on conducting differential voltage for lighting sensors will appear. You can change the variable name and set the voltage range that should be lower than 25mv otherwise the datalogger cannot recognize the sensors' volts.

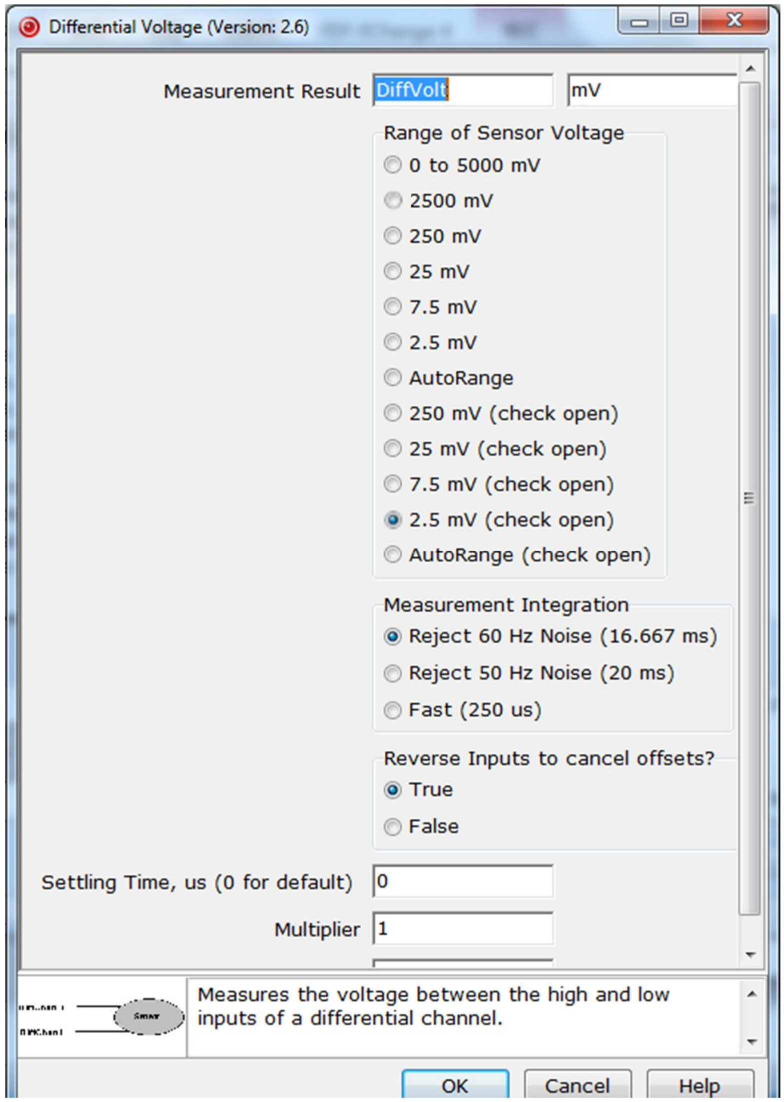


Figure B.15. Step-5 for creating a calibration program

After the shortcut was created, we opened it in the CRBasic Editor and programmed the calibration calculation. The main contents of the calibration program are shown as follows:

```
'Declare Variables and Units
Dim LCount_5
Public DiffV(32)
Units DiffV=mV
Units vtolux=lux
'Declare calibration variables
Public CalModel,KnownVar(32)
Public Mult(32), Off(32)
Public vtolux(32)
'Main Program
BeginProg
    Mult(1) = 1 : Off(1) = 0
    Mult(2) = 1 : Off(2) = 0
    ……
    Mult(31) = 1 : Off(31) = 0
    Mult(32) = 1 : Off(32) = 0
    LoadFieldCal(true)
Scan(1,Min,1,0)

'Generic Differential Voltage measurements DiffV() on the AM16/32 Multiplexer:
VoltDiff(DiffV(LCount_5),1,AutoRange,1,True,0,_60Hz,Mult(LCount_5),Off(LCount_5))
```

LCount_5=LCount_5+1

'assume the initial multiplier is 1. Thus, 1000000/ (multiplier * 604ohm) is used to convert millivolts to lux.

vtolux(1)= DiffV(1)*1000000/(1 * 604)

vtolux(2)= DiffV(2)*1000000/(1 * 604)

……

vtolux(31)= DiffV(31)*1000000/(1 * 604)

vtolux(32)= DiffV(32)*1000000/(1 * 604)

FieldCal(3,vtolux(),32,Mult(),Off(),CalModel,KnownVar(),1,1)

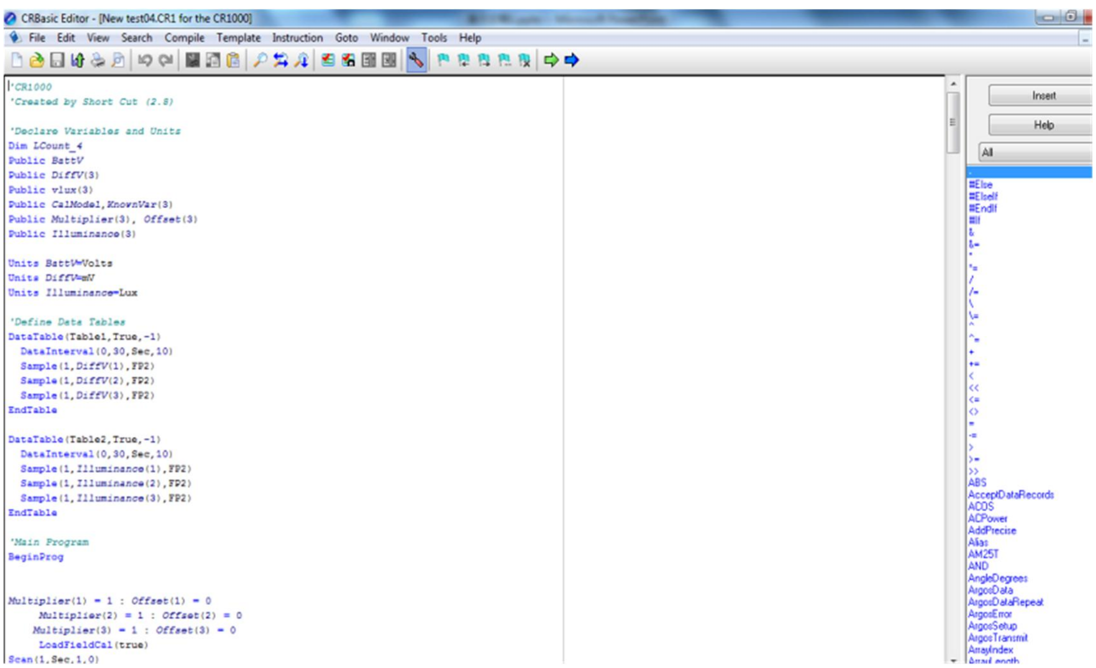


Figure B.16. Step-6 for creating a calibration program

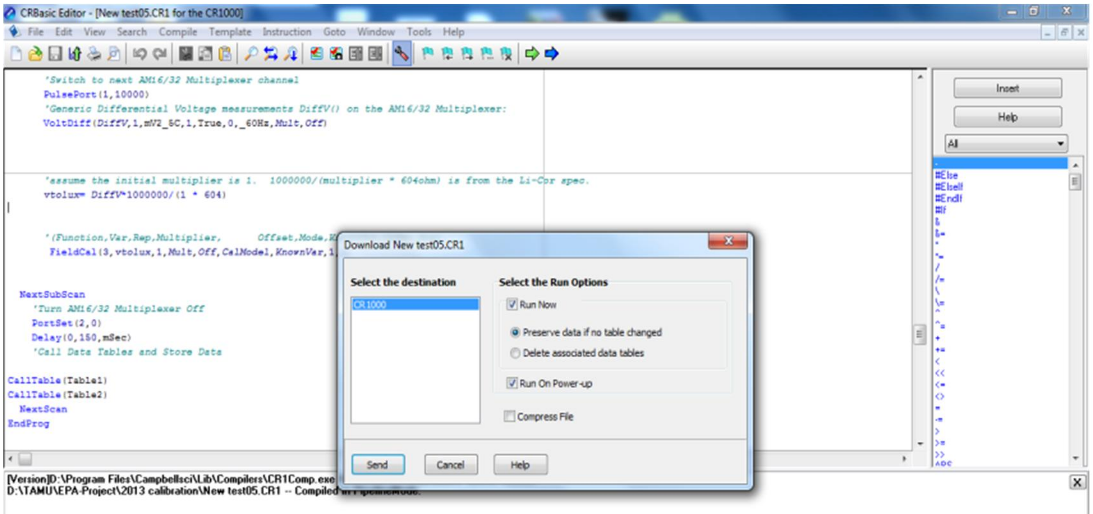


Figure B.17. Step-7 for creating a calibration program

The above figures show the main steps followed to create a calibration program. After we completed the program, we sent the program to the datalogger. We open LoggerNet and clicked “Connect” to conduct the calibration process.

Because we have already declared variables of volts generated by the LI-COR sensors as Public, we could view these real time data in the screen below (see Figure B.18). Also, the programs set the scan intervals at 30 seconds in the datalogger, so the data in this table were updated every 30 seconds.

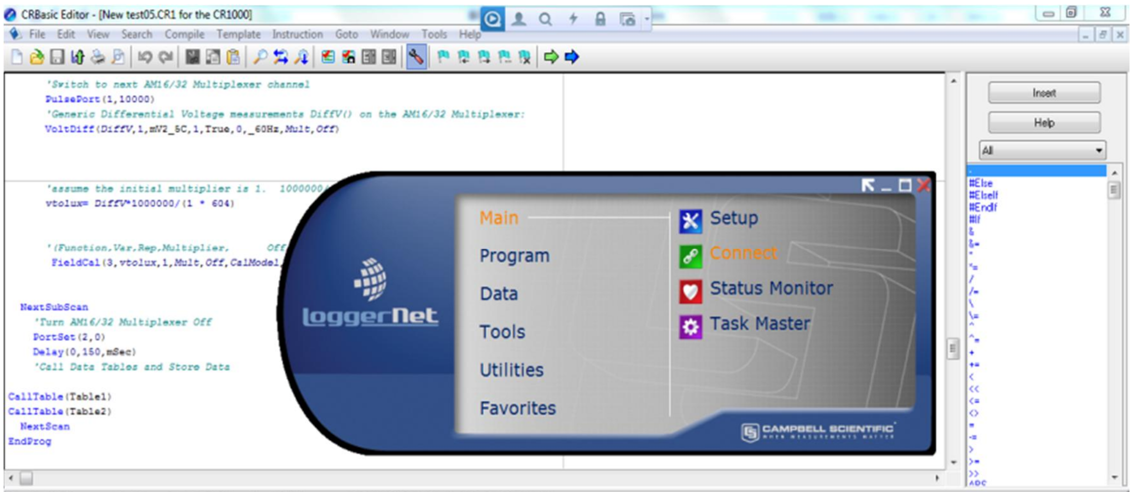


Figure B.18. Open Connect in the LoggerNet interface

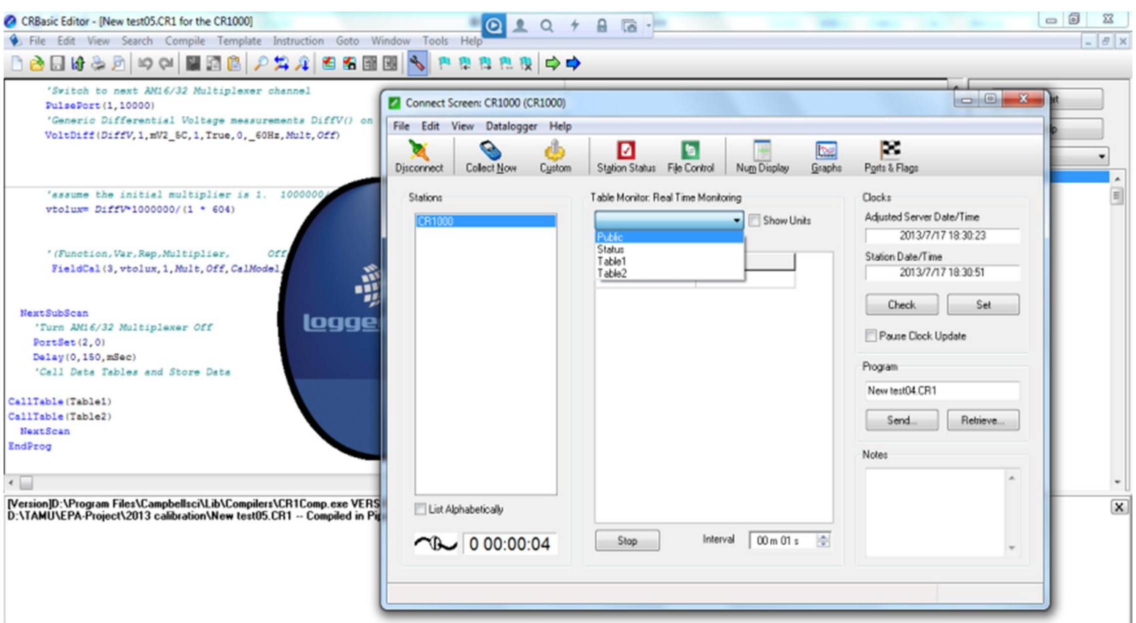


Figure B.19. Click public to view the real time data

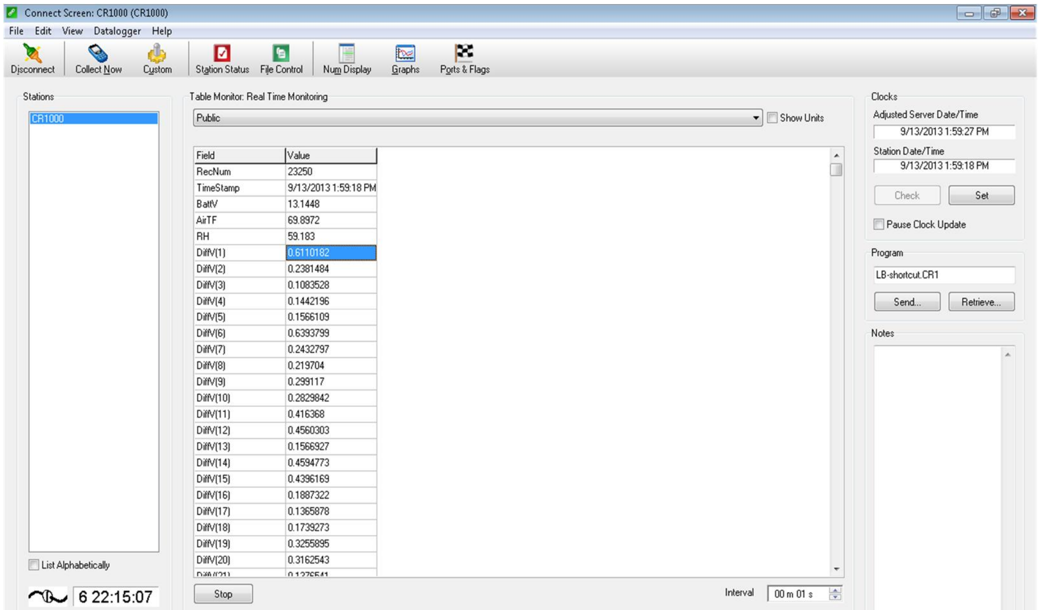


Figure B.20. The list of data of volts generated by the LI-COR sensors

The following figures show the illuminance values converted from volts.

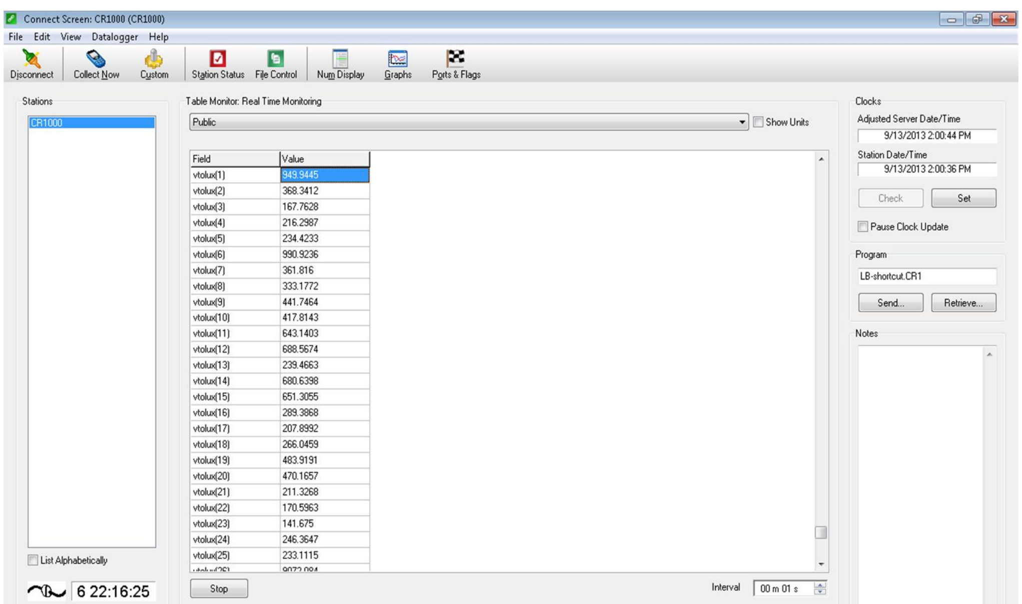


Figure B.21. The list of data of illuminance converted by the program

3) Conduct the Calibration for All Sensors by Using Light Meters

The FieldCal instruction of LoggerNet has four types of calibrations: Zeroing Calibration, Offset Calibration, Two-point Multiplier/Offset Calibration, and Two-point Multiplier Only Calibration. For our calibration process, we utilized the last method: Two-point Multiplier Only Calibration. This method accepts a linear fit approach against two different known values measured by the Light Meter in two different lighting conditions. In our calibration process, all LI-COR sensors were placed into the first condition of lighting, and we used the Light Meter to obtain the accurate real values for that lighting condition. After this, we set the known values to the datalogger program for all the sensors. Once we finished the first point calibration, the LoggerNet calibration program informed us to conduct the second point calibration that was the same process with the first point but under the different lighting conditions. After completing the calibration of the second point condition, a best fit of the two points was calculated and generated a slope value (the offset assumed to be zero). For performing this calibration mode, we need to use the number three for the calibration type in the FieldCal instruction in the CRBasic program.

We conducted calibration many times and found that the multipliers could be different in two different sensors exposed to different lighting levels. Thus, in order to maximize the accuracy of the data from these LI-COR sensors, we organized the sensors into different lighting ranges. For instance, the sensors closed to the windows might have high lighting levels (500~1500 lux) in most daytime conditions, and the sensors placed in the perimeter of the room and the rear areas of the room might have low lighting levels (50~800 lux). Also, the exterior sensors usually worked under much higher lighting levels than the interior sensors. So, all sensors were calibrated according to their own possible illuminance ranges.

The LoggerNet Calibration Wizard is the function that we used to calculate and apply the two different known lighting conditions while the program was running in the CR1000 datalogger. It provides an easy to use interface to set the sensors to the known illuminance values. The following figures show the steps on how to use this Calibration Wizard.

- Connect to the datalogger and choose the Calibration Wizard from the Connect Screen's Datalogger menu.

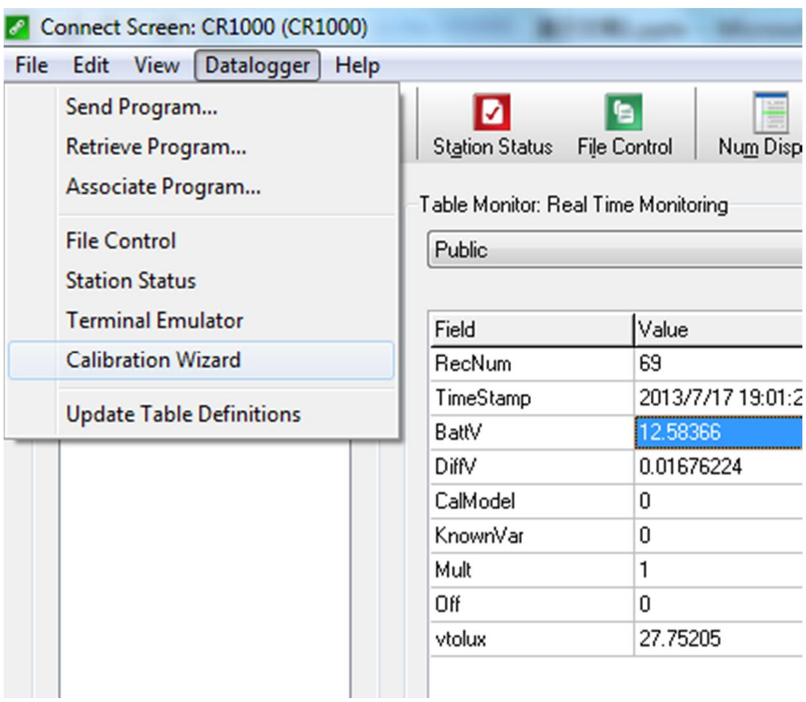


Figure B.22. Step-1 for calibration the lighting sensors

- Review the introduction and the instructions for the calibration and click Next.

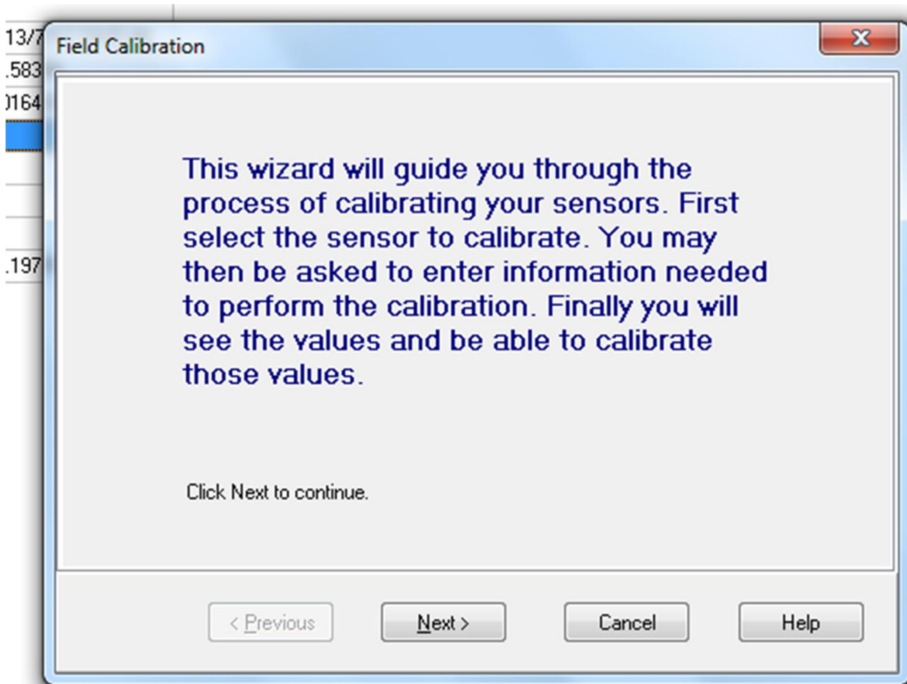


Figure B.23. Step-2 for calibration the lighting sensors

- Now choose the type of calibration (Multiplier only) then click Next.

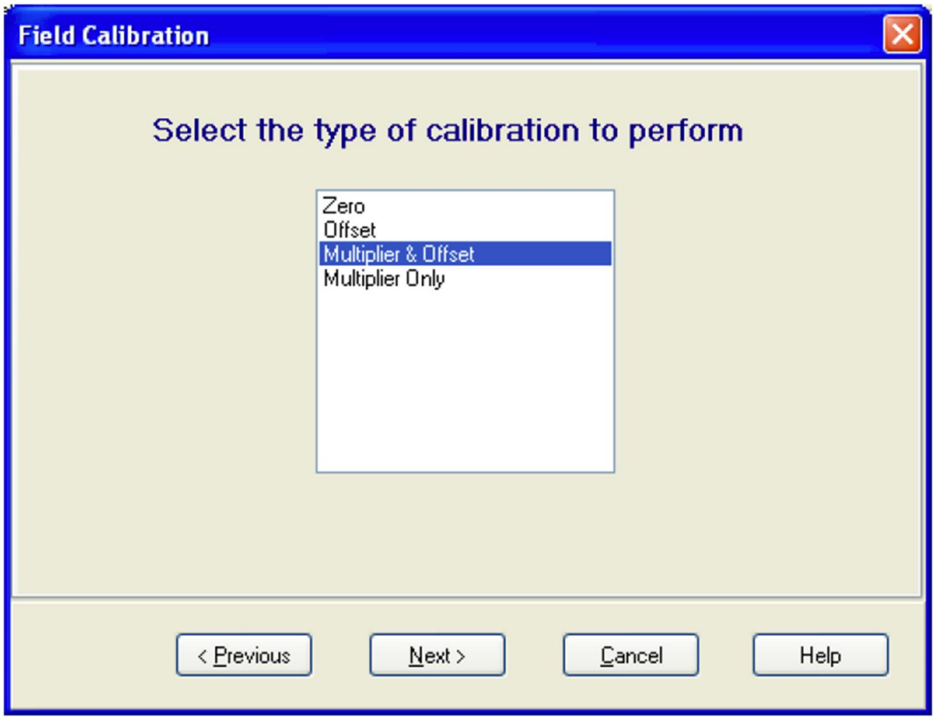


Figure B.24. Step-3 for calibration the lighting sensors

- Now place the lighting sensors into the first lighting condition and use a calibrated light meter to obtain the known value of illuminance. After this, we can enter the value into the **First calibrated value** box. Once we click **Set First Value**, the datalogger will start a calibration process and the word *Calibrating* will be visible in the **Current Value** box until that process is complete.

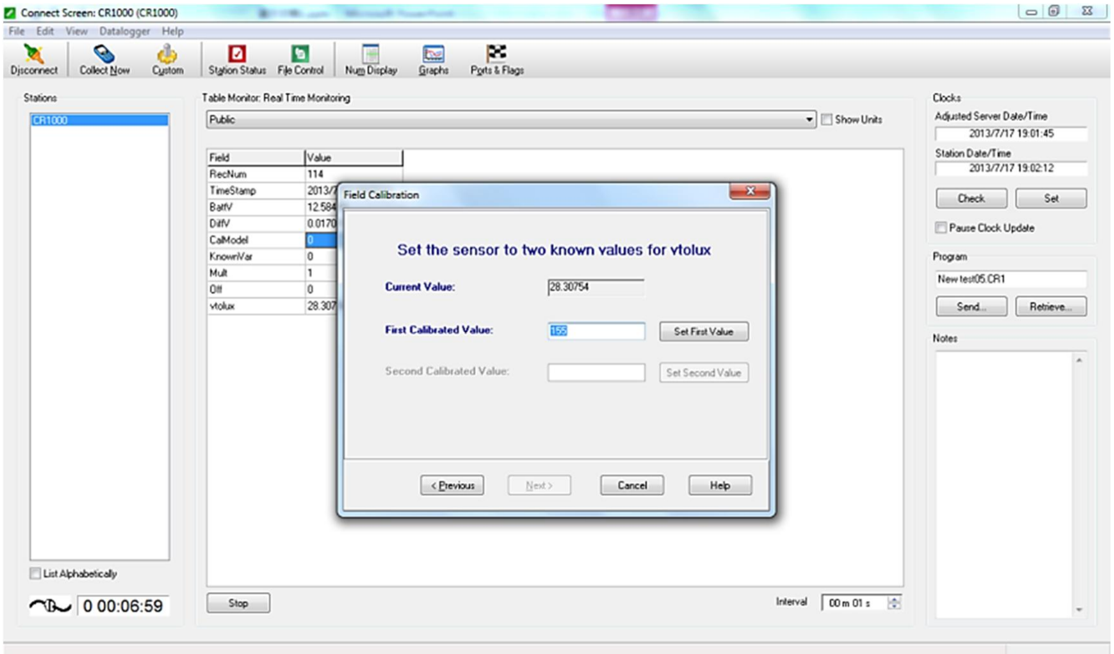


Figure B.25. Step-4 for calibration the lighting sensors

- After completing the first point calibration for all sensors, the second point calibration will appear. Place all sensors into the second lighting condition and measure the lighting level, and then input this value into the **Second calibrated value** box. Press **Set Second Value** and you will get the same word calibrating. You might get some errors messages because the multipliers cannot be calculated by the calibration program of the datalogger. You can go ahead to finish the calibration and select these values to conduct the calibration process later.

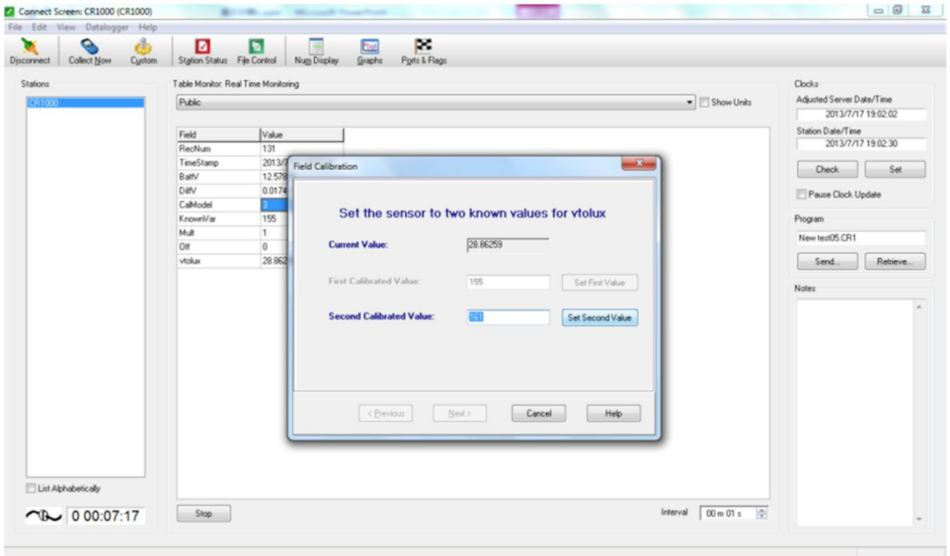


Figure B.26. Step-5 for calibration the lighting sensors

- The screen of completion will appear once you successfully get the multipliers.

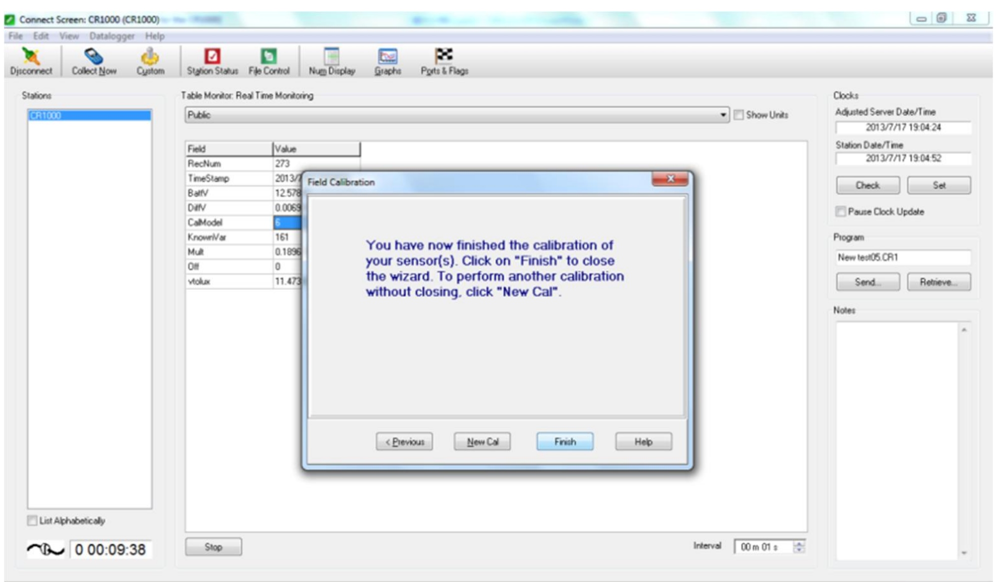


Figure B.27. Step-6 for calibration the lighting sensors

- These multiplier values are written in the calibration file and also can be reviewed in the table of “Public” of Connect Screen. In addition, you can edit these multipliers if you need to.

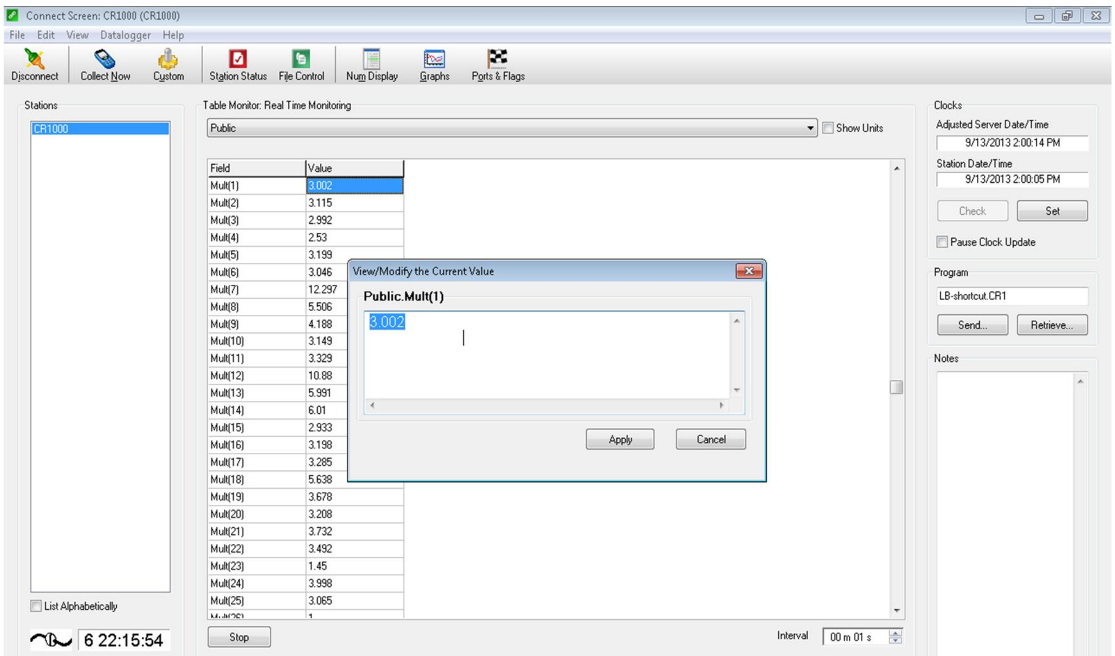


Figure B.28. Step-7 for calibration the lighting sensors

4) Analyze the Errors of All Calibrated Sensors and Document the Multipliers

We conducted a series of tests to analyze the errors of these sensors after calibration. The tests were conducted at different lighting levels ranging from 150 lux to 1,978 lux and compared them to the measured illuminance values with the Minolta light meter. The following table shows, relative to the real measurements, the errors percentages of twenty five calibrated LI-COR sensors connected to the datalogger under different lighting conditions. The relative errors ranged from 0.1% to 3.6%, so all errors percentages were less than ±5%.

Table B.2. Relative errors of 25 LI-COR sensors

Measurements	150lux	310lux	422lux	811lux	1275lux	1450lux	1978lux
PH7451B	-0.9%	0.5%	0.1%	0.9%	1.3%	0.4%	1.9%
PH7450	-0.5%	-0.1%	0.4%	1.1%	1.2%	0.9%	2.0%
PH4164	0.4%	-1.0%	-1.8%	-0.7%	-0.2%	0.1%	1.0%
PH7452	-0.5%	-0.3%	0.2%	1.0%	1.2%	0.0%	1.7%
PH7453	0.7%	2.6%	0.3%	0.9%	1.6%	2.3%	2.8%
PH7454	-0.4%	-0.3%	-0.9%	-0.1%	0.5%	0.0%	1.1%
PH4158	1.9%	-0.7%	-1.8%	-0.3%	-0.1%	1.5%	1.8%
PH4159	1.1%	0.7%	-1.1%	-0.4%	-0.5%	-0.7%	-0.5%
PH7455	-0.6%	1.5%	0.8%	1.4%	1.9%	1.4%	2.1%
PH7457	1.1%	2.1%	0.9%	1.5%	1.9%	1.6%	2.8%
PH7458	0.7%	0.7%	0.7%	1.4%	1.9%	1.4%	2.9%
PH4160	1.5%	0.5%	-1.3%	0.2%	0.7%	1.2%	2.0%
PH4161	1.0%	-2.9%	0.9%	1.9%	2.1%	1.9%	3.6%
PH4162	-0.3%	-1.5%	-1.0%	-0.3%	0.3%	0.0%	1.5%
PH7459	0.6%	1.6%	-0.8%	0.0%	0.5%	1.2%	1.8%
PH7460	-0.3%	0.8%	0.4%	1.2%	1.6%	1.0%	2.3%
PH7461	-0.7%	0.9%	0.9%	1.3%	1.8%	0.4%	2.0%
PH4163	1.9%	0.4%	-2.2%	-0.7%	-0.1%	0.8%	1.4%

Table B.2. Continued

Measurements	150lux	310lux	422lux	811lux	1275lux	1450lux	1978lux
PH7462	-2.0%	-1.1%	-1.5%	-0.8%	-0.3%	-1.1%	-0.1%
PH7463	-0.3%	1.8%	0.5%	1.2%	1.6%	0.5%	1.2%
PH7464	0.2%	2.3%	-0.6%	0.1%	0.6%	0.6%	1.5%
PH7465	-3.5%	0.6%	0.4%	0.7%	1.3%	0.1%	0.1%
PH7451A	-2.1%	-3.5%	-2.6%	-1.7%	-1.3%	-2.1%	-0.4%
PH7466	1.0%	1.7%	0.0%	0.9%	1.4%	1.9%	2.4%
PH7467	-0.5%	-1.2%	-0.5%	0.4%	0.7%	-0.3%	1.4%

Table B.3. Sensor information list for this project

Serial Number	Multiplier	Cable Length	Calibration Range	Layout numbers
Indoor sensors				
PH4157	5.441	9'6"	500~1500lux	
PH4158	5.774	9'6"	500~1500lux	15
PH4159	5.766	9'6"	500~1500lux	16
PH4160	5.615	9'6"	500~1500lux	17
PH4161	5.316	9'6"	500~1500lux	19
PH4162	6.01	9'6"	500~1500lux	14
PH4163	5.215	9'6"	500~1500lux	18
PH4164	5.614	9'6"	50~800lux	13
PH7451A	3.258	10'6"	50~800lux	20
PH7450	3.115	15'6"	50~800lux	2
PH7451B	3.002	20'6"	50~800lux	1
PH7452	2.53	20'6"	50~800lux	4
PH7453	3.199	20'6"	50~800lux	5

Table B.3. Continued

Serial Number	Multiplier	Cable Length	Calibration Range	Layout numbers
PH7455	3.046	20'6"	50~800lux	6
PH7454	4.188	20'6"	50~800lux	9
PH7457	3.149	20'6"	50~800lux	10
PH7458	3.329	20'6"	50~800lux	11
PH7459	2.933	20'6"	50~800lux	3
PH7460	3.198	20'6"	50~800lux	7
PH7461	3.285	20'6"	50~800lux	8
PH7462	3.001	20'6"	50~800lux	
PH7463	3.208	20'6"	50~800lux	12
PH7464	3.732	20'6"	50~800lux	21
Ph7465	3.492	20'6"	50~800lux	22
PH7466	3.998	20'6"	50~800lux	24
PH7467	3.065	20'6"	50~800lux	23
Movable sensors				
PH7468	3.219	30'6"	500~2000lux	
PH7469	3.211	30'6"	500~2000lux	
Outdoor sensors				
PH8291	2.85	50'6"	6000~18000lux	
PH8292	3.012	50'6"	6000~18000lux	
PH8293	2.952	50'6"	6000~18000lux	
PH8294	2.916	50'6"	6000~18000lux	

APPENDIX C

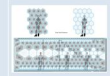
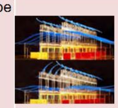
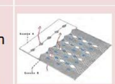
A LIST OF DESIGN OR IMPLEMENTATION EXAMPLES OF AKE

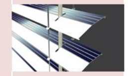
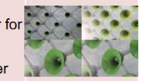
Name	Location	Architect / Researcher	Building typology	Year	Climate features	Building information	Mechanisms of AKE						Components of AKE								Movements of AKE					Remarks	Figure
							Solar-responsive			Air-flow-responsive																	
							Solar heat	Solar light	Electricity	Ventilation	Electricity	Others resources	Glazing / Translucent	Blinds / Shades / Sunscreen	Double-skins systems	Wall / opaque parts	Roof systems	BIPVs	Integrated wind turbines	Whole envelope	Rotational	Retractable	Silding	Elastic	Self-adjusting		
					Building	Level																					
Solar Drumwall House	Corrales, NM, U.S.	Steve Baer	Residence	1972	strong solar radiation (8.0 to 8.5 kWh/day)	Single floor	•									•					•					The south walls, glazed with single pane glass, have R-10 insulated, rotational reflective covers on sunny winter days and closed at night.	
Arab World Institute	Paris, France	Jean Nouvel	Exhibitions / Office	1987	—	Multiple floor, 181,850 sq ft	•	•						•								•				The traditional wooden Arab latticework screens into a glass and steel construction. The problem is overly-complex maintenance	
GSW Headquarters	Berlin, Germany	Sauerbruch Hutton Architekten	Office	1999	Prevailing wind is from the east	22-storey, 11-m wide office building				•					•						•					The louvers can fully cover the West facade	
Electrochromic Test Facility	Berkeley, CA U.S.	LBNL	Test facility	2003-2006	—	9x10-ft windowwall of 15 EC windows of 18x35-inch with a Tv of 0.60–0.05 and SHGC range of 0.42–0.09.	•	•					•												•	Compared to an low-e window (Tv-0.42, SHGC-0.22) with the same daylighting control system, the model showed annual peak cooling load reductions of 19–26% and lighting energy use savings of 48–67% when controlled for visual comfort ([35]. Schwarzenegger, 2006).	
S.F.'s new federal building	San Francisco CA, U.S.	Morphosis Architects	Office	2007	It ranges between 44-78°F, and has strong prevailing winds	345ft wide 235ft tall 65ft deep				•					•						•					One-third less energy than a typical California office building. The building uses only about 37 kBtu/sq ft (120 kWh/sq m)	
The SOUK of Aldar Central Market	Abu Dhabi, UAE	Foster + Partners	Commecial building	2010	Hot arid climate, almost year-round sunshine, little rainfall,temperature range from 50°F to 118°F.	Surrounded by three skyscrapers, the Souk is three-storey and spreads over 14,500 sq m.	•	•		•							•					•	•			The adaptive shading coverage is over 1,000 sq. m. for three courtyards. They will be open four to five months per year when outdoor temperature permits.	
Eurotheum	Frankfurt, Germany	Novotny Mähner + Associates	Residential and office mixed-usage	1999	—	100-m high and has a square 28 by 28 m plan	•	•		•									•			•				Power-operated blinds are located in the 34-cm-wide air cavity corridor. Provides natural ventilation for most of year extended or manually adjustable to shade the entire west façade.	

Office Building Halenseestraße	Berlin-Wilmersdorf, Germany	Hilde Léon, Konrad Wohlhage	Office	1996	__	The top west-facing seven stories of this ten-storey building	•	•							•							•				A automated blind was installed within the 85-cm wide, 1-storey high interstitial space.	
The laboratories of the Masdar Institute	Abu Dhabi, UAE	Foster + Partners	Laboratory	2010	__	Laboratories - Curtainwall Façade utilising inflatable ETFE cushions	•	•					•											•		It designed to provide high levels of insulation and to filter and reflect light into the street without radiating heat – they remain cool to the touch under the intense desert sun.	
EWE Arena	Oldenburg, Germany	ASP Architekten	Sports	2005	__	Circular form with 4,100 seats capacity	•	•	•									•			•					The brise soleil, that covers a segment of around 60° of the circular arena, tracks the sun at half-hour intervals in steps of 7.5°. The installed area is 240 m² which can yield of energy of 21.800 kWh/a.	
Phoenix Public Library	Phoenix, AZ, U.S.	William Bruder and DWL Architects	Library	1995	__	A total area of 280,000 sq ft with over five floors and rectangular form	•	•					•				•						•			Facades and roof are designed to control solar heat gains; building faces were conceived mindful of sun angles and sun path.	
Building Research Establishment	Garston, UK	Fielden Clegg Bradley Architects	Office	1996	__	1,350 square metres of office space	•	•						•							•					The building uses approximately 30% less energy than current best practice.	
Nordic Countries Embassies	Berlin, Germany	Berger + Parkkinen Architects	Office	1999	__	The large scale group of six buildings; the encloses as continuous element.	•	•		•				•							•					The skin has about 4000 pre-patinated copper panels with horizontal louvers at the windows. The angles at which the louvers are inclined control the amount of permeability for light, view and air.	
Madrid's City of Justice	Madrid, Spain	Foster + Partners	Office	2011	__	It consists of two distinct circular buildings for High Court (6,000 sq m shading area) and Appeals Court (2,000 sq m shading area)	•	•									•					•				The shading units occupy the central circular atrium and the eight peripheral atria as well, for minimizing unwanted solar gain, while allowing natural daylight inside.	
Bremtex Building	Oisterwijk, Netherlands	VOW architecten	Office	1996	__	Two-storey circular building	•	•						•							•					While individually adapting in response the sun, the fins take care of an optimized balance between daylight utilization and solar gains.	
Sliding House	Suffolk, UK	dRMM architects	Residence	2008	__		•	•		•										•			•			The whole enclosure including walls, windows and roofs can slide on two tracks along with the house and in turn adjust its thermal and visual properties according to seasons, weather or a remote-controlled desire to delight.	

Dynamic Tower of Dubai	Dubai, UAE	David Fisher	Residential and office mixed-usage	—	Wind and solar radiation potential to electricity	1,378 ft height with 80-floor			•		•									•	•					Each floor will rotate a maximum of 6 metres (20 ft) per minute, or one full rotation in 90 minutes. The turbines and the solar panels will be located on each rotating floors, and they can generate up to 1,200,000 kW/h energy	
DBU conference pavilion	Osnabrück, Germany	Herzog + Partner	Exhibitions / Office	2002	—	Rectangular form, two-storey loadbearing timber structure on a 10X8.1m grid.	•	•		•							•				•					The roof reduced the cost of heating and lighting. The deep area can be lit by daylight throughout the year. The air between layers can be preheated by solar and can be precooled by underground circulating water. The annual heating energy is 29 kWh/m2. which is substantially lower than the low-energy house standard.	
Das Heliotrop	Freiburg, Germany	Rolf Disch	Residence	1993	—	The cylinder-shaped building is on the one hand, heat protection triple-glazed (U value 0.5), high thermal insulation to the other side (U-value 0.12).	•	•												•	•					Exposed to the open front with its special windows to the sun for maximum energy and light is let into the house. Return on hot summer days the house of the sun's insulated back, it stays nice and cool.	
Dr. Jockisch Building	Landshut, Germany	Architecten HBH	Office	2000	—	Circular form with a diameter of 18 m and 5 floors			•									•			•					BIPV modules on the facade can be moved through motorised wheels in rails, and then can generate electrical power 10 kW.	
Gemini Haus	Weiz, Austria	ArchBüro Kaltenegger	Residence	2001	—	Two-storey circular building			•									•			•					Gemini House/Gemini Haus rotates in its entirety and the solar panels rotate independently, allowing control of the natural heating from the sun.	
Sagami bay house	Tokyo, Japan	Foster + Partners	Residence	1992	—	Single storey dwelling	•	•									•				•					The roof creates a theatre of shifting light inside, adding another dimension to the variety of light admitted by the perimeter of glass.	
Paper Art Museum A	Shizuoka, Japan	Shigeru Ban Architects	Museum	2002	—	The square floor plan is divided into three rows, and in the middle is a three storey high atrium.	•	•		•				•							•					All facades are composed of Fiberglass Reinforced Panels.By opening stacking shutters and awnings (shitomido), a spatial continuity of the interior and exterior is achieved.	

Kiefer Technic Showroom	Bad Gleichenberg, Austria	Ernst Giselbrecht + Partner	Exhibitions / Office	2007	—	The construction consists of solid brick walls,concrete ceilings and floors, and steel encased concrete columns.	•	•					•								•	•				The building presents a new facade as the day progresses, defining it as a dynamic sculpture that regulates the internal environment of the building.	
Flare Façade	Berlin, Germany	WHITEvoid interactive art and design	Exhibitions	2008	—	—		•					•							•						Each metal flake reflects the bright sky or sunlight when in vertical standby position.	
Sündreyer	Treia, Germany	SÜNDREYER GmbH	Exhibitions	2010	—	The round building with rotational roof			•							•				•						The heliotropic horizontal sun-tracking roof produces a 25% surplus of electrical energy compared to a static configuration.	
The Esplanade	Singapore	DP Architects and Michael Wilford & Partners	Exhibitions	2002	—	Cirular building form	•	•								•				•						Movable triangular sunshades admit diffuse daylight while at the same time excluding direct sunlight.	
LUMENHAUS	—	Virginia Tech	Residence	2009	—	Single floor, transportable house	•	•					•							•						Automated Eclipsis System (stainless steel sunscreen and aerogel filled translucent insulated polycarbonate panel), along the north and south façades, maximizes conservation of energy and brings diffused daylight	
Module/System Level																											
Adaptive Fritting	Boston, U.S	Hoberman Associates	Integrated glass units	2009	—	—	•	•				•									•					Utilizes a graphic pattern surface treatment, inspired by nature, in order to control heat gain and modulate light, while allowing sufficient transparency for viewing (Hoberman, 2009).	
Swindow	Japan	Tateyama aluminium Inc.	Module level	2007	—	—	•	•		•			•							•						The window starts moving when the wind blows, hence, the natural ventilation rate is a function of wind speed and direction.	
GROW	New York, U.S.	SMIT	Module level	2005-2010	—	—					•							•			•					The leaves can move around and catch the solar to generate electrical power via the sun and wind (4×7 foot strip of this can generate 85 W of solar power).	
Photochromics	—	—	Module level	1950s	—	—	•	•				•												•		Architectural implementation is pursued for a long time.Relatively high costs, sensitivity to heat and poor long-term behaviour have prevented large scale use of these systems.	

Allwetterdach	Germany	ESCO	Module level	2008	—	—	•	•		•							•				•					—	
Balloon Sun Shading	TU Delft, Netherlands	Marcel Bilow, Tillman Klein	Module level	2006	—	—	•	•					•											•		—	
Beadwall	New Mexico, USA	Zomeworks / Common Wealth Solar	Module level	1980	—	—	•	•					•												•	—	
Responsive kinetic façade	—	SOM and Sci-Arc	Module level	2008	—	—	•	•		•			•									•				A hinged glass pane and spandrel panel laminated with photovoltaic cells. Even a small six degree shift can result in a 25% reduction in the amount of solar heat gain inside the building.	
Super Cilia Skin	Massachusetts, U.S.	MIT Media Lab	Module level	2003	—	—	•	•			•								•		•					Electromagnetic energy generators make it possible to harness energy from the wind blowing over the building's exterior.	
SmartScreen	New York, U.S.	Martina Decker and Peter Yeadon	Module level	2008	—	—	•	•						•								•				The device consists of smart materials, thermo-responsive shape-memory alloys to regulate solar heat gain.	
					Conceptual	Design																					
Kinetic Roof House	—	MIT	Residence	2001	—	—	•	•		•							•				•					The kinetic roof can be opened and direct sunlight into room in the winter's daytime, and close it to keep the heat inside during the night. In summer, itf moves to a specific degree for natural ventilation but block the sunlight in a daytime, and fully opens in the night.	
AeroDimm	Vienna, Austria	Stefan Pfaffstaller	Module level	2004	—	—	•	•							•									•		Inspired by cephalopods, elastic membranes change volume between two layers of the façade to control levels of daylight and solar gains.	
Stomata Inspired Skin	Vienna, Austria	Michael Murauer	Module level	2004	—	—	•			•						•									•	A functional biomimetic translation of stomata, the openings that control the gas exchange in the leaves of plants.	
Bionic Breathing Skin	TU Delft, Netherlands	Lidia Badarnah	Module level	2007	—	—	•			•						•									•	Performs a gas exchange process which can be integrated into envelopes with the property of adaptation, based on principles abstracted from natural organisms	

Wind Shaped Building	—	Michael Jantzen	Residence	2007	—	—			•		•								•	•					The rotation of the light-weight slices generates enough electricity as it moves to light the pavilion at night.	
Blight	Belgium	Vincent Gerkens	Module level	2009	—	—	•	•	•					•				•			•				Rather than only blocking the sun's rays, the design re-envisions blinds as sun-soaking solar panels that store energy during the day and illuminate the interior at night.	
Sensitive Textile Skins	—	Philips Design Probe	Module level	2009	—	—	•	•		•		•				•									•	The membrane is used as transporter for collecting and channeling air, water and light, from the outside feeding into the inside space.	
Nano Vent Skin	—	Agustin Otegui	Existing buildings or new tower	2008	—	—			•		•							•	•		•					The outer skin absorbs sunlight photovoltaic skins transfering it to nano-fibers inside nano-wires. Each turbine on the panel generates energy. Polarized organisms are responsible for this process on every turbine's turn.	
The B&W house	—	Universidad Politécnica de Madrid|	US DOE Solar Decathlon competition	2009	—	—	•	•	•								•				•					The Roof is self-orientating to follow the sun, which gives 10.3% extra power compared to a horizontal fixed roof. The PV cells are semi-transparent.	
Jonathan Hommond house	CA, U.S.	Jonathan Hammond	Residence	1975	—	—	•										•				•					A water storing bag on the roof with operable lids which can be opened or closed enables to repond to outside solar radiation.