Transformable Tensile Façade: Performance assessment on energy, solar and daylighting

A Master's Thesis submitted for the degree of
"Master of Engineering"

supervised by

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Vienna, 15.10.2014

Affidavit

I, **SIMON K. CHIU**, hereby declare

1. that I am the sole author of the present Master's Thesis, "TRANSFORMABLE TENSILE FAÇADE: PERFORMANCE ASSESSMENT ON ENERGY, SOLAR AND DAYLIGHTING", 62 pages, bound, and that I have not used any source or tool other than those referenced or any other illicit aid or tool, and
2. that I have not prior to this date submitted this Master's Thesis as an examination paper in any form in Austria or abroad.

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Signature

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ABSTRACT

Building façade plays an important role in the overall building design. Its exclusive aesthetic appearance represents the unique DNA that the designer encodes for each building. Moreover, it significantly impacts the energy consumption of the building throughout its lifecycle. This is where the research recognizes the potential of tensile membrane façade (TMF) systems to marry geometric complexity with improved building performance. However, several obstacles exist which impede designers attempting to incorporate tensile membrane structure (TMS) system into their design. One of the fundamental problems this research explores is how designers can gauge the impact of incorporating TMF into their design despite the increased complexity in geometric and physical properties TMF add to the design. The applicable tools and means and methods to enable this process have rarely been discussed and identified in the prior research.

To address these issues, this research first reviews current efforts on façade and shading strategies to improve various aspects of building performance, followed by an introduction to the overall research method. Next a photo-goniometric lab experiment is conducted to obtain the test sample's optical properties. This experiment is followed by two case-based experiments to understand the impact of the optical property input in conjunction with the impact of different shading strategies. The impact of a transformable TMF system is also explored through a series comparative studies. Finally, this research presents the limitation and discusses future work in the conclusion.

Through the goniometric lab testing, the measured optical properties shows a slight difference from the theoretically derived results. This high resolution measurement might have a significant impact on the lighting and energy simulation performance. However, due to the limitation of the current energy simulation tools, the full Bidirectional Scattering Distribution Function (BSDF) cannot be considered and therefore the actual impact cannot be obtained at this current research stage. As a result of the low resolution intake of the energy simulation tool, only 7 angular optical values were taken into consideration during the energy simulation process.

The first case-based experiment focuses on assessing the impact of external textile shades on solar heat gain and energy consumption including the consideration of the

textile shade's optical property. There were a total of 6 shading scenarios tested in three different climate zones. Based on current simulation results, although the performance variation can be observed, the impact of the transmission (Ts) value might not be significant enough to affect the design decision making process. However, current research only tested on flat shading surfaces and excluded the potential of electrical lighting energy reduction, the actual impact of using optical properties cannot be accurately gauged based on the current results. Furthermore, the potential of textile shades to provide higher daylighting performance has yet to be considered. As a result, the incorporation of the goniometric measured Ts value or higher resolutions Ts value during the simulation process is still a research in question that is worth further exploration. When comparing different shading strategies, the results demonstrate that the control mechanism of the fabric shade has a significant impact on the performance. While the research only explored the fabric shading strategies as a flat system with one solar heat gain threshold control mechanism, the significance of the impact can already be observed. This implies higher potential with the incorporation of the dynamic system control along with the angular variation of the shading surface.

The second case-based experiment focuses on assessing the impact of a transformable tensile membrane façade system on daylighting performance. The experiment utilized a shoe-box model with four different membrane layer configurations. The results demonstrated that the system can provide nearly consistent daylighting performance throughout different times and dates if the façade's geometric variation is possible. While this study only applies a specific performing criteria on a shoebox model as an example, more substantial opportunities can be foreseen that the adaptive membrane façade system is able to accommodate occupants' needs for different occupancy zones during different times, dates and orientations. In addition, the use of the adaptive membrane façade enables appearance variation with assorted possible configurations which can broaden designers' design space with fixable and inspirational yet high performing components. This not only encourages designers to be more creative regarding the façade system but also promotes performance based design. While there are several unknowns and questions that still need to be further explored, the experiments support the vision of the research.

ABBREVIATIONS & ACRONYMS

AEC	Architecture, Engineer, and Construction
AoI	Angle of incidence
BRDF	Bi-directional Reflectance Distribution Functions
BSDF	Bidirectional Scattering Distribution Function
BTDF	Bidirectional Transmittance Distributions Function
DOE	U.S. Department of Energy
DSF	Double-Skin Façade
Ecotect	Autodesk® Ecotect® Analysis 2011
ETFE	Ethylterafluoroethylene
Excel	Microsoft® Excel® 2010
HVAC	Heating, Ventilation, and Air Conditioning
ID	Identification
LBNL	Lawrence Berkeley National Laboratory
MEP	Mechanical Electrical and Pluming
NIR	Near infrared
OBJ	Objective
Radiance	Desktop Radiance
Revit	Autodesk Revit 2013®
TMF	Tensile Membrane Façade
TMS	Tensile Membrane Structure
Ts	Transmission
Tv	Visible transmittance

CHAPTER 1 INTRODUCTION

Building façade plays an important role in the overall building design. Its exclusive aesthetic appearance represents the unique DNA that the designer encodes for each building. Moreover, it significantly impacts the energy consumption and other performance aspects of the building throughout its lifecycle (Cardoso et al. 2007). With the growing concern of sustainable design and rising demand for higher performing buildings, materials and methods that effectively reduce energy consumption and improve daylighting and thermal comfort have become an industry priority. Adopting effective façade configurations, shading strategies and their control systems to improve building performance has been the focus of various prior research (Atzeri et al. 2008, Eskin and Türkmen 2008, Wienold et al. 2011, O'Neill 2008, Wankanapon 2009). However, when designing a building that occupies a constantly changing environment, a dynamic responsive system is deemed as an opportunity to push the current boundaries of building performance. Although several attempts have demonstrated the potential of using a dynamic shading or façade system (Winstanley 2011, Baraona Pohl 2009), the rigidity and complexity of such systems have reduced their economic feasibility and raised longevity issues. This is where the research recognizes the potential of using tensile membrane façade systems to address these problems.

1.1 PROBLEM STATEMENT

Tensile membrane structures are lightweight and flexible in form, thereby enabling a wide range of dynamically unique design forms. These unique characteristics also enable tensile membrane structures to potentially be more effective towards improving building performance (i.e. thermal comfort and daylighting) than other more rigid building systems. However, due to the physical properties and geometrical complexities of the tensile membrane system, several associated obstacles arise and impede designers to incorporate tensile membrane structures into their design. Consequently, the potential of using responsive and transformable tensile membrane system to improve building performance has not been able to accurately gauged and demonstrated.

One of the fundamental obstacle this research focuses on is in regards to measuring the performance impacts and potentials of the tensile membrane system on the design. In order to incorporate this dynamic and complex component into to the design process, designers need to rely on computer simulation tools to assess and predict the performance of their design. However, the methodology to simulate the physical characteristics of a tensile membrane layer has yet to be explored within the current architectural design field. Although window shade performance can be simulated in several commonly used energy simulation tools by using their mechanical properties (Jonsson et al. 2008), the tensile membrane layer's optical properties have not yet been accurately characterized (Wankanapon 2009). It is also a question whether or not currently available tools are able to appropriately support design needs. In response to these observed gaps in current conditions, this investigation intends to explore how designers can gauge the impact of utilizing tensile membrane façade system, which significantly increases the complexity of both the geometric and physical properties of their design. Compounding the issue of complexity in both the geometric and physical properties of a design is the inclusion of determining the performance impact of a dynamic and responsive control system.

1.2 Overview of Research

1.2.1 Research Hypothesis

The research hypothesis is that the lightweight, versatile, and transformable characteristics of textile membrane based architectural envelopes can greatly enhance buildings' energy and daylighting performance by effectively controlling solar heat gain and daylight actively responding to the surrounding environmental condition.

1.2.2 Research Aims, Objectives and Questions

The overall aim of the research is to explore how designers can gauge the impacts of tensile membrane façade system, and thereby demonstrating the potential of using tensile membrane façade system to achieve higher performing design. In pursuit of this aim, the research has the following three specific objectives, which can be achieved by addressing the associated research questions:

1. **To identify the potentials and gaps of using tensile membrane façade system by investigating the existing approaches that focus on improving building performance through façade strategies.** In order to form the basis of the research hypothesis, a clear understanding of existing literature is needed regarding their approaches, effort focuses, successes and failures. To achieve this objective, the following research questions must be addressed:

   1.1 What are the limitations and successes of current efforts focusing on shading or façade strategies to improve building performance? Do the conclusions drawn from the literature can support the use of transformable tensile membrane façade system?

   There have been several efforts that focus on investigating different shading strategies and façade systems to achieve higher performance building. However, several issues still exist and have yet to be resolved. In order to support the potential of using tensile membrane façade system to overcome the problems, it is necessary to synthesize current efforts and identify their fundamental obstacles and advantages through literature review and analysis.

   1.2 How can the research undertake as the first step to overcome the shortcomings of these precedents' approaches?

   Once the benefits of using tensile membrane façade system are identified through the literature review, it is necessary to isolate the most essential obstacle that prevents designers from incorporating tensile membrane façade system into their design process. Through this investigation, the point of departure of this research can then be determined.

2. **To understand the process and effort required for designers to incorporate tensile membrane façade system during their design process with the consideration of its optical properties.** In order to assess and compare the impacts of a tensile membrane façade system, a methodology and protocol need to be established to ensure result consistency and validity. However, such methodology has yet to be predominantly explored in current architectural design

field. In addition, the necessity to considering membrane's optical property is still unconfirmed. As a result, the following research questions must be addressed:

2.1 How to assess the impact of tensile membrane system on solar heat gain, energy and daylighting?

While there have been various conventional means for designers to conduct performance analysis of their designs, the cases that involve with tensile membrane layers are considerably rare. Therefore, it is still a research in question whether existing approaches can be considered suitable to evaluate tensile membrane façade system during the design process. As a result, it is necessary for the research to understand the efforts required and limitations of current means. Thereby, the improvement suggestions can be isolated accordingly.

2.2 Is the impact of a tensile membrane layer's optical property significant enough that should be taken into consideration during the design analysis process?

One of the complexity that comes with tensile membrane layers during the performance analysis is its angular optical property. In order to understand the impact of the optical properties on the resulting energy and solar heat gain performance, a case-based experiment is needed to explore the performance variation between the scenarios with and without angular property consideration. Prior the comparative simulation can be conducted, it is also needed to accurately obtain the angular optical properties of a tensile membrane layer.

3. **To demonstrate the potential of a transformable tensile membrane façade system on daylighting performance.** The last objective of the research is to demonstrate the potential of performance improvement through the geometric variation of a tensile membrane façade system. To achieve this objective, the following research question must be addressed:

3.1 What is the impact of a transformable tensile membrane façade system on daylighting performance and where is the potential?

In order to understand the impact of a transformable tensile membrane façade, a case-based experiment is needed to explore a façade system with various interchangeable tensile membrane configurations. By conducting daylighting analysis and comparative study for each configuration during various time period, the potential of using transformable tensile membrane façade system can be revealed.

1.3 Overview of the Thesis

Based on the overall aim and the objectives of the research, the thesis is organized into seven chapters, as illustrated in Figure 1-1 below. Table 1-1 summarizes the structure of this thesis with its corresponding research objectives, questions, and research methods.

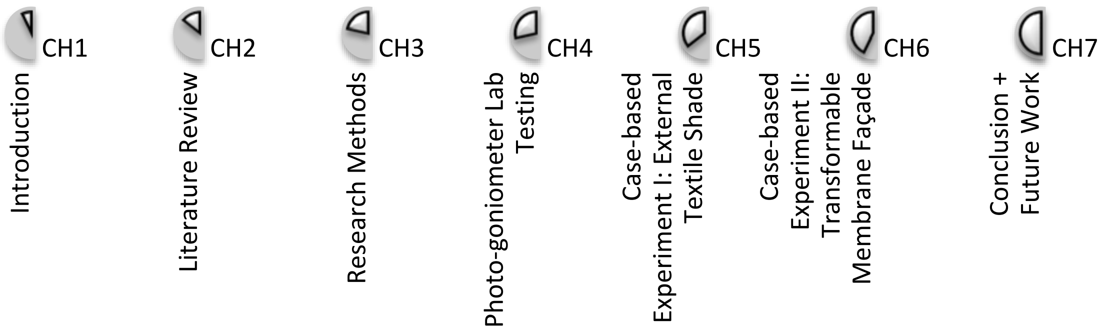


Figure 1-1: Thesis structure overview. Image by the author.

Chapter 1 provides the introduction to this research. It includes the research problem statement, research hypothesis, objectives, and questions. Chapter 2 provides the literature review, focusing on the pertinent sources in the related field. It therefore provides the foundation for the research to determine the point of departure. In addition, it serves as the basis to identify the gaps of among current efforts and position the contributions of this research. Chapter 3 outlines the adopted methodologies in this research. Chapter 4 details the background, process and results of the photo-goniometer lab testing by which the research uses to obtain the angular properties of a sample tensile membrane layer. Chapter 5 is dedicated to the first case-based experiment with the focus on exploring external textile shading strategies and their impact on solar heat gain and energy consumption. In addition, the angular properties of the tested tensile membrane layer's is included to understand its relative impact on solar heat gain and energy performance. Chapter 6 presents the second case-based experiment with the intent to explore and demonstrate the potential of using transformable membrane façade to improve daylighting performance. Finally, Chapter 7 presents the conclusions drawn from the experiment results and findings and proposals for future work.

Table 1-1: Outline of the research method and the corresponding research objective and questions. Table by the author.

Chapter	**Title**	**Research Objective**	**Research Questions**	**Research Methodology**
1	Introduction			
2	Literature Review	OBJ 1	1.1 What are the limitations and successes of current efforts focusing on shading or façade strategies to improve building performance? Do the conclusions drawn from the literature can support the use of transformable tensile membrane façade system? 1.2 How can the research undertake as the first step to overcome the shortcomings of these precedents' approaches?	Literature review
3	Research Methods		1.2 How can the research undertake as the first step to overcome the shortcomings of these precedent approaches?	Literature review
4	Photo-Goniometric Lab Testing	OBJ 2	2.1 How to assess the impact of tensile membrane system on solar heat gain, energy and daylighting? 2.2 Is the impact of a tensile membrane layer's optical property significant enough that should be taken into consideration during the design analysis process?	Photo-goniometric lab testing
5	Case-based Experiment I	OBJ 2	2.1 How to assess the impact of tensile membrane system on solar heat gain, energy and daylighting? 2.2 Is the impact of a tensile membrane layer's optical property significant enough that should be taken into consideration during the design analysis process?	IES <VE> energy simulation
6	Case-based Experiment II	OBJ 3	2.1 What criteria should be used to examine and determine the proposed framework's validity for early stage design use? 3.1 What is the impacts of a transformable tensile membrane façade system on daylighting performance and where is the potential?	Ecotect + Radiance simulation
7	Conclusion + Future Work			

CHAPTER 2 LITERATURE REVIEW

The importance of the building façade is not only related to its aesthetics but is also to the performance of the entire building (Lovell 2010). In the effort to improve building performance, utilization of shading strategies and integrated façade system has been widely deemed as an effective strategy. Considerable research has been undertaken to investigate the impact of shading strategies and façade systems on various aspects of building performance, i.e. thermal comfort, visual comfort, energy consumption, heating load, cooling load and solar heat gain. In order to isolate the potential and gaps of using tensile membrane façade (TMF) system, this research reviews the efforts focus on shading strategies and double skin façade (DSF) along with the current developments relates to tensile membrane façade (TMF) system. After examining the precedents' findings, the point of departure of this research can then be identified.

2.1 RESEARCH FOCUS ON SHADING STRATEGIES

Shading strategies have been considered as a feasible and effective means to reduce solar heat gain, glare and cooling load. However, the optimal configurations of the shading strategies to accommodate each project's unique design, façade system and location are still in need of exploration. Consequently, various efforts have been focused on this area to have better understanding regarding the optimal shading strategies for each unique condition, as well as the integration process and method. Some representative efforts that focus on exploring shading strategies include the work of Atzeri et al. (2008). Their work included an exploration of the energy performance of shading devices for thermal comfort and glare control, which concludes that the optimal shading configuration is dependent on a windows' size and orientation. The work by Eskin and Türkmen (2008) included shading and window configuration as part of the parameters to analyze annual heating and cooling energy requirements for office buildings for different climates in Turkey. The work by Wienold et al. (2011) investigated different conventional and advanced shading devices regarding their thermal and visual comfort and energy demands. David et al. (2011) assessed the thermal and visual efficiency of solar shades. The work of Kim et al. (2012) explored the advantages of an exterior shading device and suggest that optimal shadings should increase daylight levels while controlling unwanted glare and solar heat gain. The work of Bellia et al. (2013) focused on analyzing the influence of external solar shading devices on the energy requirements of a typical air-conditioned office building for Italian climates. They concluded that the solar shading devices demonstrated the highest energy efficiency for warm climates. The comparison between internal and external shade was conducted by Atzeri et al. (2014) and concluded that external systems consistently perform better than internal ones in terms of total energy consumption.

The insights drawn from the research above include that external shading is more effective in terms of overall energy reduction than other strategies. However, the optimal configuration and the effectiveness of the shading strategies are highly dependent on the climate, orientations and the control systems. As a result, another group of research not only looked into different shading strategies, but also focused on the impact of various control system integration. Some examples are O'Neill (2008) who explored the potential of an automated model-based control strategy for diffuse reflecting venetian blinds and concluded that the solar radiation control are viable to enhancing daylighting while reducing cooling loads. Mahdavi and Dervishi (2011) explored the impact of lighting and blind shade control to a building’s lighting and energy performance. Their work demonstrated the significant potential of energy reduction that can be achieved by using lighting and shading control systems. Wankanapon and Mistrick (2011) explored roller shades and automatic lighting control with solar radiation control strategies. da Silva et al. (2012) investigated the energy influence of shading control patterns and concluded that the performance is impacted significantly by occupants’ shading interaction. Automated control strategies of inside slat-type blinds are also explored by Oh et al. (2012) for visual comfort and building energy performance. Their results demonstrated a correlation between the resulting performance and the control strategies. Therefore, with proper control strategies in place, the performance of the building can be improved accordingly. While this body of research demonstrates that to use of control strategies can effectively improve building performance, their results also imply that in order to accommodate the unique climate conditions for each project location throughout daily and seasonal variations of the microclimate, a dynamic and responsive system is needed (Fox and Kemp 2009).

2.2 RESEARCH FOCUS ON DOUBLE SKIN FAÇADE

Double skin façade (DSF) systems gain their popularities among the architectural design field as a means to achieve the desired all-glass transparency aesthetics while significantly improve building performance (Hendriksen and Sørensen 2000). For this reason, DSFs have been widely applied in Europe and are blooming in North America as an effective strategy in sustainable architecture. The general principle of a DSF system is to incorporate an additional layer of glazing outside the primary glazing as a thermal buffer. It can also induces natural ventilation through the cavity space between DSF, and thereby improves the building cooling load and energy consumption (Jiru et al. 2011, Hensen et al. 2002). The reports of Heimrath et al. (2005) Poirazis (2006) provided comprehensive reviews regarding DSF's state of the art applications. Both reports indicated the potential of DSF in improving thermal, visual, and acoustical performance, and decreasing energy consumption. However, it is also suggested that the resulting performance is highly subject to the indoor and outdoor condition, as well as the integration method of the DSF system to fulfill the needs of local environment (Poirazis 2006). In addition, the relatively pricey initial build out cost is the commonly known issue, and is usually rationalized by its operational efficiency and energy saving (Poirazis 2004). Although the benefits of DSFs have been widely acknowledged, the actual behavior in operation is lack of quantifiable measurement and evidence to support design decision making (Selkowitz et al. 2003, Gratia and De Herde 2007). Therefore, several ongoing research continuingly focus on further quantifying DSFs' potential and advancing the methodology of applying DSFs. In addition, it is observed that to incorporate shading and control strategies has become a norm to achieve higher performing DSF. For example, Gratia and De Herde explored DSF's optimal operation and natural ventilation (Gratia and De Herde 2004b, a). They further investigated the influence of the position and color of shading devices on DSF (Gratia and De Herde 2007). The effort of Poirazis et al. (2008) focused on utilizing dynamic energy simulation tools to predict and optimize the energy and thermal performance of an office building in Sweden. Haase and Amato (2009) studied the effectiveness of different DSF control strategies in warm and humid climates. Kilaire (2011) applied and detailed the application process of a DSF system. The work of Evins (2011) attempted to utilize multi-objective optimization method to find the optimal configurations and the control strategies of DSF. Lastly, the work of Joe et al. (2014) focused on investigating the thermal characteristics of a cavity in a DSF and their influence on energy performance on a multi-story DSF building in Korea. In summary, these aforementioned efforts indicate their continuingly attempts to gain clarity regarding the impact of the complex DSF system. In addition, the simulation and prediction methods are also a research focus that in need of further investigation. Furthermore, the integration with the control system is an evident trends for DSF systems to be able to advance its performance and accommodate the constant changing environment and occupants needs.

2.3 RESEARCH FOCUS ON TENSILE MEMBRANE FAÇADE

In this research, the term “tensile membrane façade” (TMF) or “tensile membrane structure” (TMS) are referred to the structural systems utilize tensile membrane materials as part of the load carrying elements to sustain the overall form. The formation of the TMS highly relies on the synergy between the geometric assembly and the physical property of the tensile membrane material to distribute the tension or compression effectively. There are two primary categorization of TMS’s forms: anticlastic and synclastic, where anticlastic forms have opposing curvatures and synclastic forms curves toward the same side. Two commonly seen tensile membrane materials are 1) woven based fabrics protected by coatings, i.e. PVC and PTFE; and 2) thin-film based membrane layers, i.e. ETFE foil (Architen Landrell 2009). Attributed to the lightweight, flexible and wide-range light transmissive characteristics of tensile membrane materials, the potential of applying them as replacements for glass has been explored (Tanno 1997, Robinson-Gayle et al. 2001, Elnokaly et al. 2003, Robinson 2005). In addition, there are increasing applications using TMS as the façade system or as the second skin of the building to improve the building performance, such as the Water Cube project (Hunsberger 2006, Nadile 2008) and the MSCP Cardiff project (Base Structures Limited 2014). Although the research related to TMS is not as prevailing as the research related to shading strategies and DSFs, some research still can be found in exploring TMS’s potential. Examples are the work of Cardoso et al. (2007) that they explored the potential of the ‘smart’ ETFE cushions that allows façade’s opacities react to human touch (Cardoso et al. 2007). The research of Poirazis et al. (2009) focused on estimating the thermal and optical properties of ETFE to assist designers design analysis process by using a simplified mathematical model. It is concluded that a standardized measurement to obtain accurate and validated ETFE’s spectral properties should be the first step for the future performance analysis related to ETFE. In addition, new tools and calculations are needed in order to consider the long-wave transmissions effects, as well as a dynamic building performance simulation. The work of Gibbs et al. (2009) explored an ETFE's light transmission properties by using a light meter to measure photo-synthetically active radiation within a ETFE testing rig. Based on the conclusions drawn from current efforts, it is evidence that the quantifiable measurements regarding TMF's potential of improving building performance are significantly lacking, as well as the implementation methods, simulation tools and design analysis guidance. However, prior to the performance of TMF can be accurately gauged during the design process, the physical property of the membrane layer needs to be obtained first as it is typically unavailable.

2.4 RESEARCH FOCUS ON RESPONSIVE SYSTEM

From the prior review of current efforts, it is obvious that adopting responsive system is the trend to further advance the building performance.

> *"Since climate and occupant needs are dynamic variables, in a high performance building the façade solution must have the capacity to respond and adapt to these variable exterior conditions and to changing occupant needs. …Façade systems must be dynamic and flexible to accommodate change in the exterior environment and in occupant needs and desires, all within the context of the overall building system." Selkowitz (2001)*

In response to this need, there is a research group further investigates dynamic responsive systems. Examples are the study of Rafael (2010) used a Bioclimatic Responsive Skin (BRS) to demonstrate the applicability of the responsive system, the construction details and the control mechanism of the system. Nielsen et al. (2011) compared the performance of a dynamic solar shading system with other conventional non-dynamic ones. It is clear that dynamic solar shading dramatically improved the target performance; however, the trade-off needs to be considered among different performance aspects. Kirkegaard (2011) further extended his investigation of the responsive system to apply to the overall building envelop. Karanouh et al. (2011) applied an adaptive kinetic shading screen system on a whole glass façade. The kinetic shading system is able to provide a better occupancy comfort and lower energy consumption. However, the implementation of the kinetic shading system imposed a major challenges due to the complex kinetic mechanism, scale of the project and performance verification process. Lastly, the work of Shen et al. (2014) included the dynamic envelope components as part of a comparative study and demonstrated that the advanced control resulted in higher daylighting efficiency and glare protection when compared to an open/closed control system.

This “interactive architecture” concept is not only widely acknowledged in the academic research field (Razaz 2010, Loonen et al. 2014, Loonen et al. 2011), but also attempted to be applied in several professional designs, i.e. the Institut du Monde Arabe (Winstanley 2011) and the Phare Tower (Baraona Pohl 2009). While the concept of intelligent, responsive, dynamic façade system is not new, it brings a greater challenge to the architectural design and engineering field in terms of equipping the ability to specify a reliable system, as well as predicting the system’s performance during the design process (Selkowitz et al. 2003). Several rigid and highly mechanically-complex system applications were found to be not feasible to build, and have unbearable maintainence and operating costs. As a result, the systems were forced to shut down or to forgo the original design intent (Khoo et al. 2011). In order to create a feasible responsive system, research has started to explore the opportunity of utilizing light weight operable “soft skin” façades (Khoo et al. 2011, Khan 2009). This leads to the pursuit of utilizing membrane fabric structure as the overall goal of this research since it presents the most potential due to its light weight and flexible nature.

2.5 GAP ANALYSIS AND POINT OF DEPARTURE

With the advancement of tensile membrane material, the performance of the tensile membrane facade is considered more environmental friendly in terms of thermal, lighting performance when compared to a conventional glass façade (Gibbs et al. 2009, Robinson 2005, Architen Landrell 2014). In addition, some tensile membrane facade can be fully recycled thereby increasing their contribution to a sustainable design solution. It can withstand wind, sun and fire (Richards 2010, Zhao et al. 2010). Due to the characteristics of light weight tensile fabrics, designers have the opportunity to explore their creativity while creating high energy performance buildings. Some well-known light weight tensile membrane projects marrying geometric complexity with improved performance are the Eden Project (Eden Project 2014), Unileverhaus (Riddle 2010), and Media-TIC building (Architecture Today 2010). While these projects successfully showcase the opportunities of lightweight membrane structures, there are still several challenges which preclude the incorporation of tensile fabric structures into a responsive system. One of the fundamental problems this research explores is how designers can gauge the impact of incorporating fabric structures into their design despite the increased complexity in geometric and physical properties fabric structures add to the design. Compounding the issue of complexity in both the geometric and physical properties of a design is the inclusion of determining the performance impact of a dynamic and responsive control system. The applicable tools and means and methods to enable this process have rarely been discussed and identified in the prior research.

To address this fundamental issue, this research focuses on first tackling the impact of utilizing the actual physical properties of the tensile membrane on performance simulations as the first step. By using case-based experiments following typical design analysis process, the limitations of current tools and processes can be revealed. Through comparative studies the benefit of the tensile membrane shade and the inclusion of geometric variation can be further confirmed.

CHAPTER 3 RESEARCH METHODOLOGY

The overall research methodology and process adopted in this research can be grouped into four research methods: 1. Literature Review – which focuses on surveying the current efforts and precedents that have attempted to explore façade configurations to improve building performance; 2. Photo-goniometric Lab Testing – which utilizes the photo-goniometer lab in Lawrence Berkeley National Laboratory (LBNL) (LBNL 2009) to conduct photo-goniometric measurement for obtaining the tested fabric's angular optical properties.; 3. Case-based Experiment I: External Textile Shade – which is designed to understand the potential of external textile shade by comparing its thermal and energy performance with different shading design strategies as well as those strategies in different climate conditions.; 4. Case-based Experiment II: Transformable Membrane Façade – which utilizes Desktop Radiance (LBNL 2000) and Autodesk® Ecotect® Analysis 2011 (Ecotect) (Autodesk 2014) as the simulation tools to obtain the daylighting performance. A general description of each research method is introduced as follows:

3.1 LITERATURE REVIEW

The literature review of this research focuses on surveying the current efforts and precedents that have attempted to explore façade configurations to improve building performance. The primary purposes of the review is listed as following:

1. By reviewing current efforts that explored façade configurations to improve building performance, understanding of the potential means and limitations is increased, allowing for situating the potential of using tensile membrane façade.

2. By reviewing precedents' predictions and recommendations based on their findings, the research hypothesis can initially be examined and supported.

3. By reviewing the precedents that applied responsive system or membrane façade performance analysis, the limitations of their approaches can be identified and improved upon, thereby the point of departure of the research can be determined. In addition, the contribution of the research can be identified.

4. By reviewing the efforts that have adopted the optical properties into their performance analysis, the research is able to understand the means and methods to measuring the optical properties of the test sample.

It should be noted that the literature review is conducted throughout the research and has been updated continuously during the research period

3.2 PHOTO-GONIOMETRIC LAB TESTING

In order to incorporate this dynamic and complex tensile membrane component into to the design process, designers need to rely on computer simulation tools to assess and predict their design. However, existing research that compares fabric shade with other shading strategies rarely considers the angular optical properties of the fabric (Wankanapon 2009, Wankanapon and Mistrick 2011, Yao 2014) despite these properties being considered relevant to the analysis results (Kohler 2012, Grobe et al. 2010, Jonsson et al. 2008, Ward et al. 2011). As it is still not the norm to incorporate the physical characteristics of fabric within the current architectural design field during the simulation process, an appropriate way for designers to simulate fabric added complex glazing systems need to be investigated. Furthermore, it is also important to understand whether the physical property input of the fabric is significant enough to impact the simulation results. Therefore, prior to analyze a tensile membrane system, this research first utilizes the photo-goniometer lab in Lawrence Berkeley National Laboratory (LBNL) (LBNL 2009) to conduct photo-goniometric measurement for obtaining the tested fabric's angular optical properties. This tested results can then be incorporated into the latter case-based experiment and further understand its impact on the resulting performance. The detailed testing process can be found in Chapter 4.

3.3 EXTERNAL TEXTILE SHADE CASE-BASED EXPERIMENT

After the photo-goniometric lab testing, the first case-based experiment is designed to understand the potential of external textile shade by comparing its thermal and energy performance with different shading design strategies as well as those strategies in different climate conditions. The significance of the impact introduced by the fabric shade's optical properties are also explored. In addition, due to the lack of existing guideline to perform design analysis involves with textile shades' optical properties, this case-based experiment applies a conventional means to understand the restrictions found in current process and tools. IES <VE> (IES 2014) is selected as the simulation tool due to its ability to conduct both whole building energy analysis and solar heat gain analysis (Bambardekar and Poerschke 2009). Furthermore, it allows the user to specify and incorporate the different angular transmission (Ts) properties into the simulation. The detailed experiment design of the case-based experiment can be found in Chapter 5.

3.4 TRANSFORMABLE MEMBRANE FAÇADE CASE-BASED EXPERIMENT

In order to support the potential of introducing geometric variation to membrane layers, a transformable membrane façade system is explored. While the intended goal is to include extensive performance aspects into consideration, daylighting is selected as the initial attempt to proof of concept. In this case-based experiment, Desktop Radiance (LBNL 2000) and Autodesk® Ecotect® Analysis 2011 (Ecotect) (Autodesk 2014) are utilized as the simulation tools to obtain the daylighting performance. By measuring the daylighting performance for each variation of a transformable membrane façade on different time and dates, the performance of each façade configuration can be revealed and compared. In addition, the potential of the performance improvement from the interchangeable façade can be observed. The in-depth process and the scenario design for the second case-based experiment are presented in Chapter 6.

CHAPTER 4 PHOTO-GONIOMETER LAB TESTING

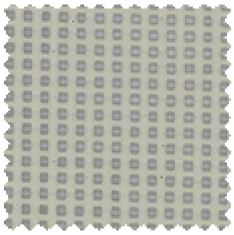
In order to simulate the impact of building openings on the building's lighting and thermal performance, it is necessary to predict the light entering and exiting the building envelope. For typical glazing, the method to obtain these spectral data, i.e. transmission and reflection, is straightforward and can be calculated from accepted equations (Karlsson and Roos 2000). However, when there are fabric shades involved, the angular properties of the light coming through an opening can no longer be obtained via a simple formula due to the fabric's light redirecting and/or diffusing characteristics. While these characteristics of fabric are where the potential for fabric shades to improve lighting and thermal performance derive from, they complicate the predictions of lighting behavior as it requires additional angular behavior measurement beyond the necessary spectral transmittance and reflectance (Kohler 2012). As a result, before the research can utilize a simulation tool to predict the impact of fabric shades, the angular properties of fabrics need to be obtained first. Unfortunately, there are no angular properties immediately available in fabric product specifications in the current marketplace. Therefore, the first step of the research is to obtain the angular properties of the specimen fabric via a photo-goniometer lab testing.

4.1 SPECIMEN BRIEF

The selected specimen is Serge Ferrari's Stamisol® FT 381-3109, which is a high-quality PVC-coated polyester open fabric that is pre-tensioned during coating (Industrias BEC 2014). The technical specification from the manufacture is summarized in Table 4-1. The available transmission and reflection data are measurements from normal-incidence without other angular considerations.

Table 4-1: Technical specifications of Stamisol® FT 381-3109 (Ferrari , Industrias BEC 2014). Table by the author.

Property Name	Property value
Color 3109:	light grey /silver
Material:	PVC coated polyester
Use:	Exterior / interior
Yarn:	1100 Dtex PET HT
Weight:	17.7 oz/yd² (600 g/m²)
Thickness:	0.043 in (1.1 mm)
Tensile Strength	741/741 lbs/2in (330/330 daN/5cm)
(wrap/weft):	146/146 lbs/2in (65/65 daN/5cm)
Tear resistance	-
(wrap/weft):	-22°F a + 158°F (-30°C a + 70°C)
Water penetration	ASTM E84, NFPA 701, M1/NFP 92-507, B1/DIN, 4102-1,
resistance:	BS 7837, VKF 5.3
Temperature resistance:	B-s2,do/EN 13501-1
Flame retardancy:	29 (Is the % of solar radiation which goes through the fabric.)
Euroclass:	36 (Is the % of solar radiation which reflects on the fabric.)
Transmission (Ts):	35 (Is the % of solar radiation that the fabric absorbs.)
Relexion (Rs):	29 (Is the % of visible light which goes through the fabric
Absorption (As):	screen.)
Visible transmission (Tv):	



4.2 PHOTO-GONIOMETER LAB TESTING METHOD & PROCESS

Typically, the angular properties of a complex system, such as fabrics, can be described by a Bi-directional Scattering Distribution Function (BSDF) (Kohler 2012). A BSDF is a mathematical function that describes how light coming from a certain direction is transmitted and reflected in other directions. A material's BSDF is defined by using both sides' reflection and transmittance properties. Hence, a BSDF is a combination of 2 Bi-directional Transmittance Distributions Functions (BTDFs) and 2 Bi-directional Reflectance Distribution Functions (BRDFs). The bidirectional transmittance,$\tau(\theta_o, \varphi_o; \theta_i, \varphi_i)$, (or reflectance, $\rho(\theta_o, \varphi_o; \theta_i, \varphi_i)$) of a component or a system is defined as the formula (1) (Papamichael et al. 1988):

$$\tau(\theta_o, \varphi_o; \theta_i, \varphi_i)\big(or\ \rho(\theta_o, \varphi_o; \theta_i, \varphi_i)\big) = \frac{dL_o(\theta_o, \varphi_o)}{dE_i(\theta_i, \varphi_i)}\,[sr^{-1}]\ (1)$$

Where

(θ_i, φ_i) are the polar coordinates, as shown in Figure 4-1, of the incoming light flux [°]

(θ_o, φ_o) are the polar coordinates, as shown in Figure 4-1, of the outgoing light flux [°]

$dL_o(\theta_o, \varphi_o)$ is the luminance of the outgoing transmitted or reflected luminance

$dE_i(\theta_i, \varphi_i)$ is the incident illuminance of the material

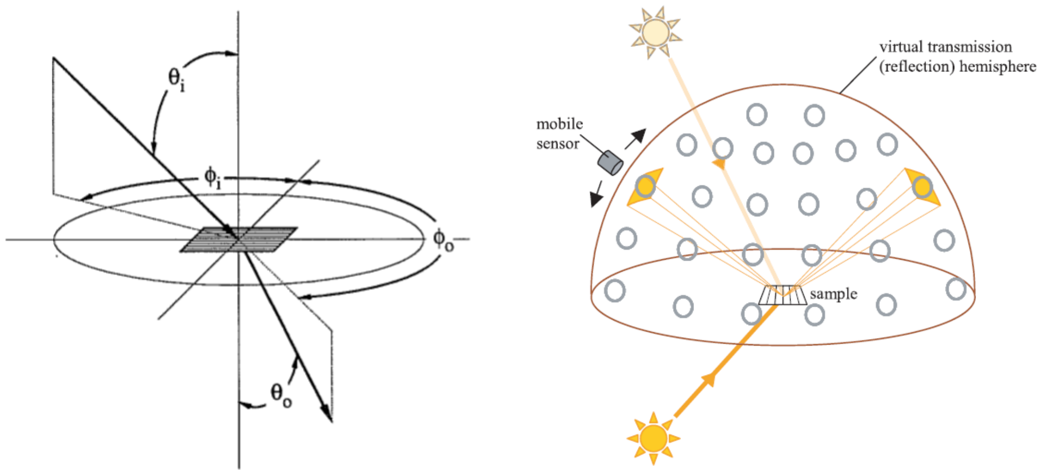


Figure 4-1: (Left) Coordinate system for bidirectional measurement. Image from (Papamichael et al. 1988); (Right) Detection principle for conventional photo-goniometers: the photo-sensor moves along the virtual hemisphere to measure the reflection and transmission properties of the specimen. Image from (Andersen 2004)

These directions can be measured by a photo-goniometer through a discrete hemisphere that is composed of a number of patches. The detection principle is illustrated on the right of Figure 4-1. A hemisphere composed of 145 patches is typically used in the windows and daylighting research field (Mitchell et al. 2008, Kohler 2012, LBNL 2009, Tregenza 1987), as shown in Figure 4-2. The figure also presents a sample visualization of the BSDF results obtained through testing the specimen. BSDF has been used for lighting performance and solar heat gain simulation, however, it is rarely been adopted into the whole building energy simulation process. The process of obtaining a complete bi-directional scattering distribution function (BSDF) that can be used in simulation programs is detailed in (Jonsson et al. 2008). In summary, as much optical information as possible is first collected from the sample. Then a scattering model is fitted to the experimental results which is used to generate the BSDF. For this research, the photo-goniometer testing was conducted at the Windows Group Complex Glazing Lab of the Lawrence Berkeley National Laboratory (LBNL) with a total measuring duration of approximately 4.5 hours excluding the post data processing. The lab testing procedure can be summarized as the following 3 steps:

1. Spectral measurements at near normal angle of incidence
   Prior to conducting goniometric measurements, the research first measures the spectral properties at near normal angle of incidence to understand and distinguish the characteristics of the front and back of the fabric. For this step, a Perkin-Elmer Lambda 950 spectrophotometer fitted with a 150 mm integrating sphere was used for measurement of total and diffuse reflectance. The reflectance was measured at every 5 nm from 300 nm to 2500 nm. Integrated solar reflectance was calculated using the ASTM E891-87 AM1.5 solar spectrum. Integrated visible value was calculated using CIE D65 standard illuminant and the y of the CIE 1931 2° Standard Observer.

2. Goniometric measurements
   Angle-resolved measurements were carried out using a Photo-goniometer II (pgII) instrument, as illustrated in Figure 4-3. The instrument is manufactured and special made by the Pab Advanced Technologies Ltd based on LBNL's specifications (LBNL 2009). It uses a calibrated white light source and filtered detectors to obtain the BSDF values in the solar wavelength range. As described previously, a single BSDF value is given using four angle indices obtained for each combination of incidents and outgoing angle pairs (θ, φ). The measurement uses the Klem's 145 patch coordinate system which has 9 theta bands with varying number of phi value for each band. A normal light source for each patch is measured through the 145 patch's incident, reflected and transmitted light. This results in a total of 145 x 145 unique BSDF value for each wavelength band. Two type wavelength light sources are measured for both front and back of the tested sample: (1) the visible wavelength using CIE D65 standard illuminant; (2) the near infrared (NIR) wavelength is using the ISO8859-1.

3. Comparative study of theoretical and measured results & post data analysis.
   Lastly, the research conducted a comparative study of the results derived from the calculations versus the results from the measurement. This comparative study serves as a reference to evaluate whether the physical measurement can be replaced with the established calculation method by Kotey (2009).

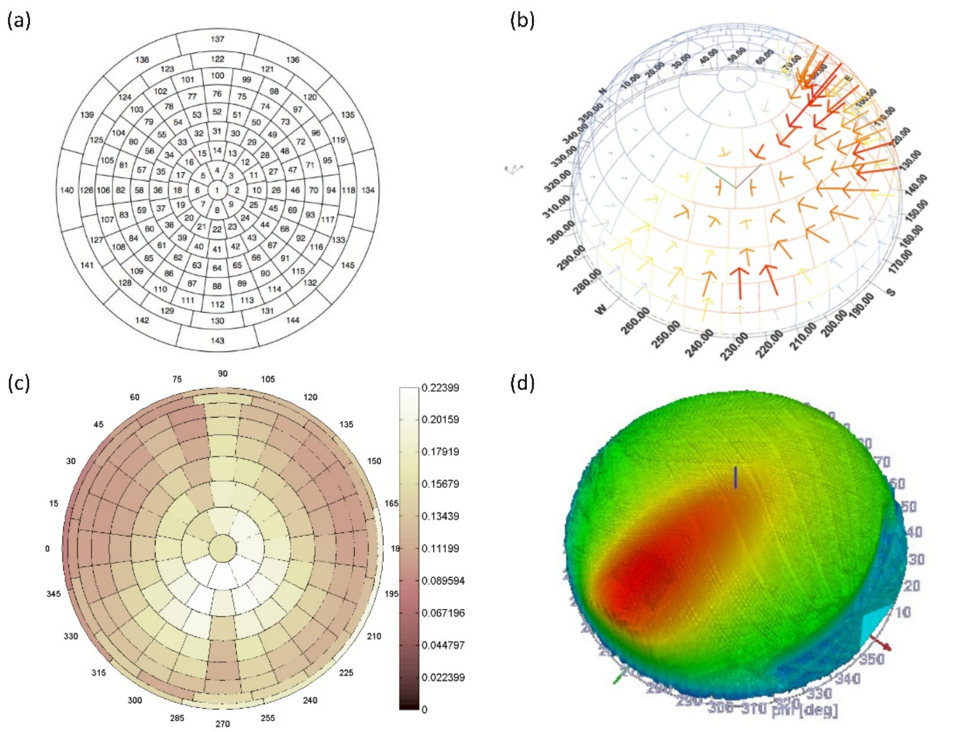


Figure 4-2: (a) Illustration of the Klems 145 – patch hemispherical basis with numbered subdivisions Image from (Ward et al. 2011). (b) Illustration of the recording light incident direction for each patch. Image from (Roudsari 2014). (c) and (d) are samples of the data visualization: projection of the color-coded results on virtual hemisphere (Left); mountain plot (Right). Images extracted from the research's LBNL experiment report.

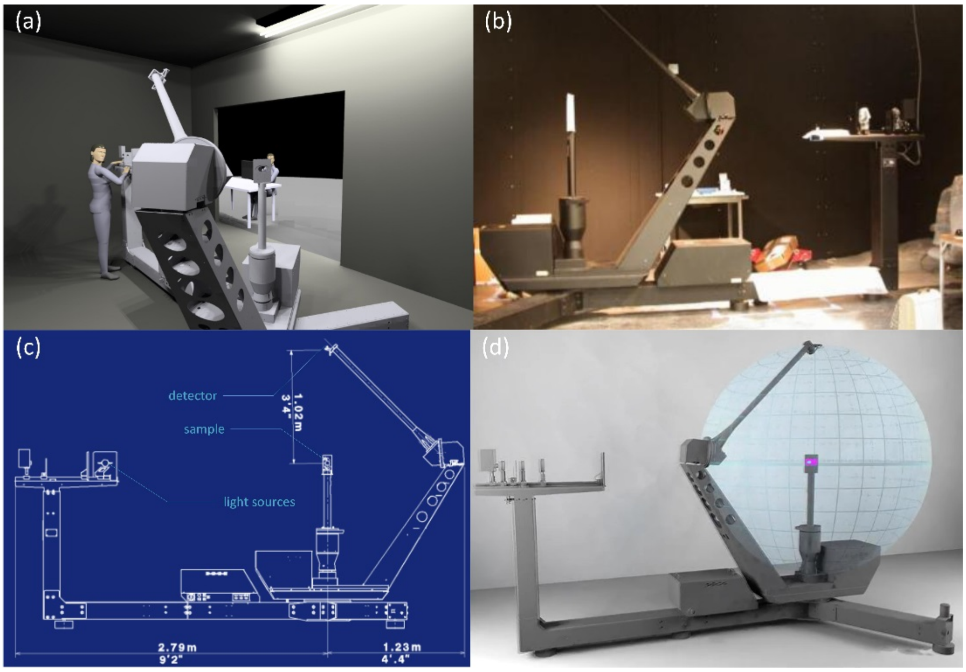


Figure 4-3: Images of the Pab Ltd Photo-goniometer II (pgII). (a) Rendering of the instrument; (b) pgII set up in LBNL; (c) instrument dimension; (d) measuring illustrations. Images from (LBNL 2009, pab Ltd 2014)

4.3 PHOTO-GONIOMETER LAB TESTING RESULT

4.3.1 SPECTRAL MEASUREMENTS

The results of the spectral measurement are illustrated in Figure 4-4. Observing the results of the front surface, low diffuse transmittance indicates that the transmittance is dominated by the openness of the weave. The silver color does not have a significant specular component which should result in minimal reflected glare. The back surface has a transmittance that is identical to the front side. The reflectance is slightly higher in the visible at the cost of lower NIR reflectance.

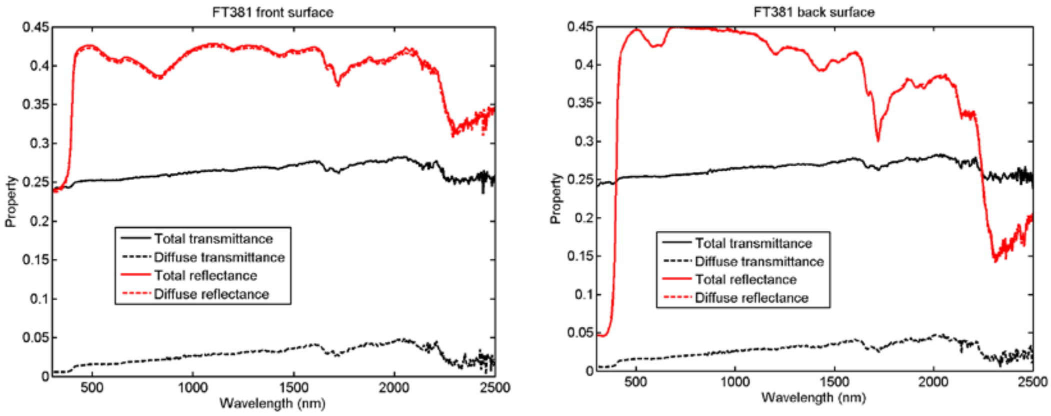


Figure 4-4: Spectral measurement results of the front and back of the test sample: (Left) measured transmittance and reflectance for the silver colored front surface of the material; (Right) measured transmittance and reflectance for the silver colored back surface of the material. Images extracted from the research's LBNL experiment report.

4.3.2 GONIOMETRIC MEASUREMENTS

There are a total of 84,100 value points recorded during the goniometric measurements (2 (visible & NIR) x 2 (front & back) x145 x 145). The overall characteristics of the test sample can be observed and visualized in Figure 4-5 and Figure 4-6. Figure 4-5 presents the transmittance and reflectance results from the visible wavelength measurement for both front and back of the test sample during normal and 50° angle of incidence (AoI). The full experiment results can be found in Appendix B. Similar to the previous observation, the front and back of the test sample possess near identical optical properties. In addition, there is an observable impact in the transmittance and reflectance properties between the different angles of incidence. Figure 4-6 uses a logarithmic scale mountain plot to illustrate the transmittance and reflectance properties at 60° AoI. The transmittance plot, Figure 4-6 (a), shows that the specular component dominates and that even the small diffuse component is also fairly specular. With lower angles of incidence the difference between specular and diffuse is even more pronounced. The data indicates that light is able to transmit through the test sample almost evenly diffused except a small spike area. In addition the light reflected before and after transmittance is also fairly diffused.

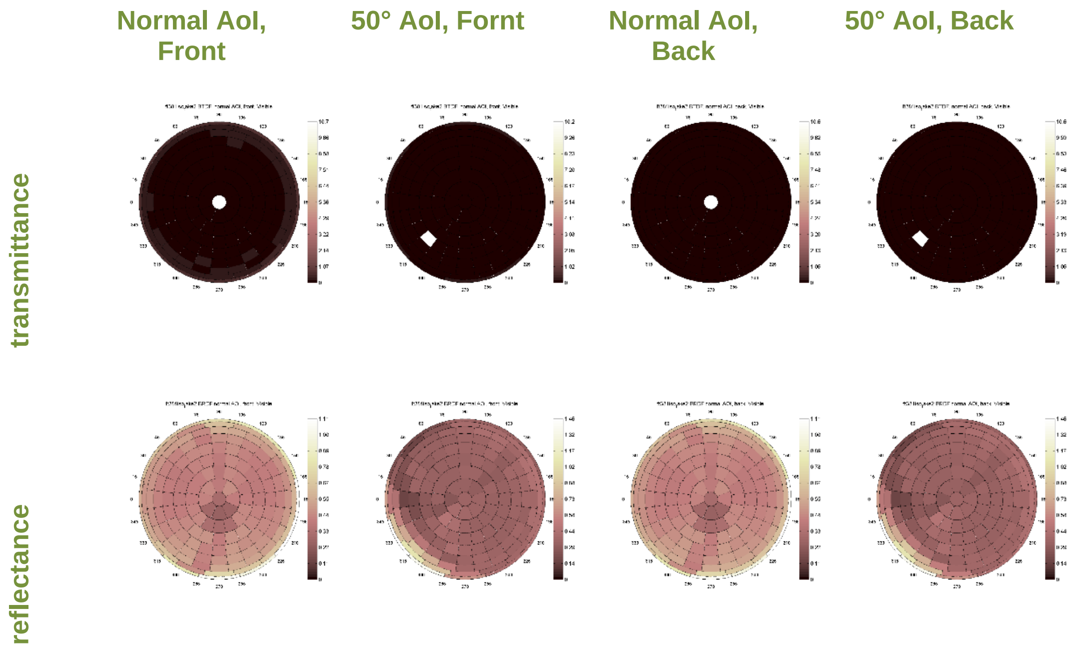


Figure 4-5: Optical overview of the test sample: illustrating the visible wavelength measurements of the reflectance and transmittance data. Images extracted from the research’s LBNL experiment report.

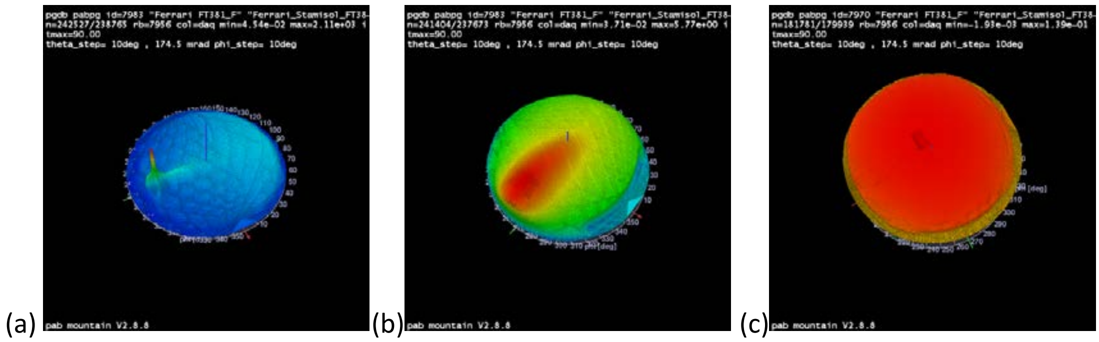


Figure 4-6: The mountain plots of the test sample’s BSDF data at 60 degree angle of incidence. (a) Transmittance of the test sample; (b) Reflectance of the front side of the test sample; (c) Reflectance of the back side of the test sample. Images extracted from the research’s LBNL experiment report.

4.3.3 COMPARISON BETWEEN GONIOMETRIC MEASUREMENT AND THEORETIC-DERIVED RESULTS

In order to understand the impact of the photo-goniometric measurement, another approach to obtain the sample's angular properties was explored. The prior research of Kotey (2009) developed a method to obtain angular properties of shade fabrics based on the properties at the normal angle of incidence. This research adopts his method and extrapolates the collected spectral measurements of the test sample, as shown in Figure 4-7 (a) and (b). When comparing the derived results with the results of the goniometric measurement, Figure 4-7 (c) and (d), there is an observable difference. The values at 0 and 70 degrees are close to Kotey's model but the path between them has dramatic variation. This indicates that when attempting to use the extrapolated properties for further daylighting or energy simulation, there might be inaccuracies due to the false representation of the actual condition. If the impact is significant, either a goniometric measured value is needed, or a more accurate extrapolating model needs to be established. Either way the potential significance of the impact of the angular properties difference requires further research to confirm.

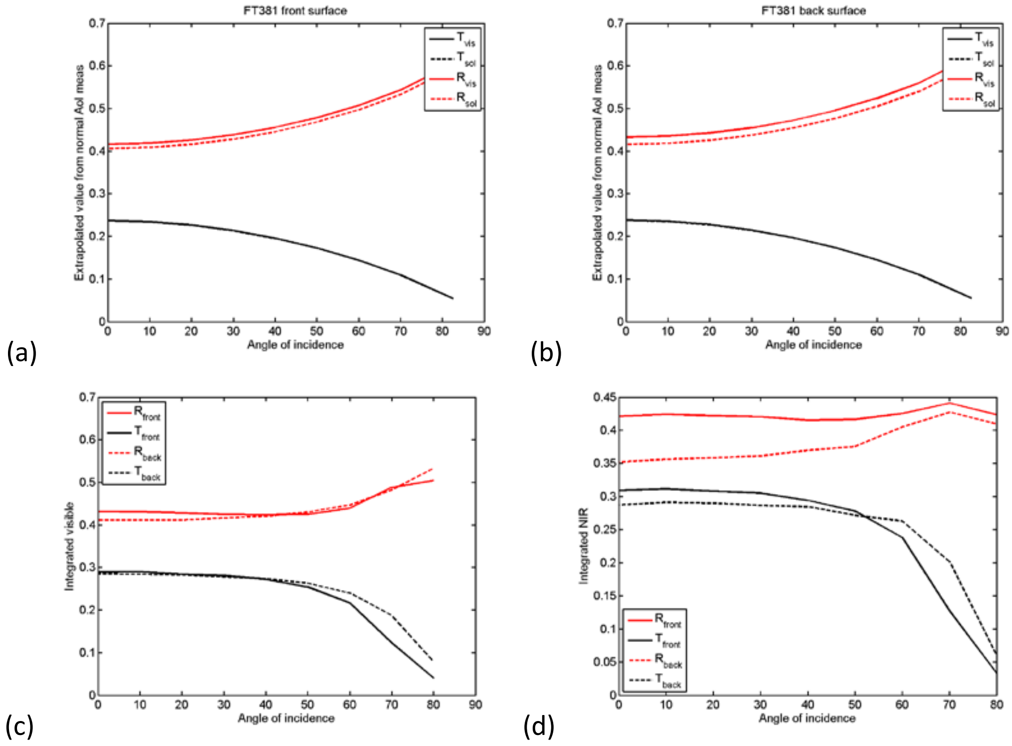


Figure 4-7: Test sample's optical angular properties comparison between the extrapolated results and goniometric measurement. (a) and (b) are the sample's optical properties extrapolated from normal angle means which are measured via spectral measurement. (c) and (d) are the sample's optical properties measured via goniometric measurement. Images extracted from the research's LBNL experiment report.

4.3.4 FROM GONIOMETRIC MEASUREMENT TO ENERGY SIMULATION INPUT

The final step of this experiment is to extrapolate the measured results for energy simulation use. This is where the limitations of the selected energy simulation program are revealed despite being deemed the most suitable one for the study. No currently available energy simulation tools are capable of utilizing the full BSDF (which can be considered as a limitation of currently available energy simulation tools on the whole). However, a more relevant question is whether the resolution of the full BSDF properties is considered too high to be practically adopted during the simulation process, especially if the simulation is intended to assist design decision making during the design process. Nonetheless, this is another research in question that is worth future exploration. For the purpose of this research, the resolution of optical angular properties is determined by the selected energy simulation program. The selected simulation program, IES <VE>, is only capable to consider 7 sun angle transmission factors in 15° increments from perpendicular. As a result, the extrapolated input for later simulation is listed in Table 4-2:Extrapolated transmission input for energy simulation. Though there is the concern that the resolution of the energy simulation input cannot represent the entire BSDF measurement, the impact on the simulation results can still be observed. However, due to the unavailability of this detailed information, any disparities caused by the input resolution that might occur during the simulation are not considered. This concern, however, is outside of the current research scope and will be included for future work.

Table 4-2: Extrapolated transmission input for energy simulation. Table by the author.

Incidence Angle	0°	15°	30°	45°	60°	75°	90°
Transmission factor	0.24	0.23	0.21	0.18	0.14	0.09	0.01

CHAPTER 5 CASE-BASED EXPERIMENT I: EXTERNAL TEXTILE SHADE

After obtaining the fabric's physical properties, this research proceeds to evaluate the impact of the fabric shade on the building's solar gain and energy consumption through IES <VS> simulation. There are three observation objectives:

1. The performance difference due to the physical property input of the fabric;
2. The performance difference due to the different shading strategies;
3. The performance difference due to the building site for the same strategies.

The two observed performances are:

1. The solar gain of the East, South and West façade on the fifth floor of the tested building: measured in kBtu
2. Monthly and annually of the whole building's total building system energy consumption and its breakdown, i.e. chiller, boiler and auxiliary energy: measured in MBtu/month and MBtu/yr.

While the shading strategies can impact the electrical lighting energy consumption if diming sensor control is considered in the simulation process, it should be noted that this research exclude the electrical lighting control as part of the simulation to better understand the impact of total system energy consumption alone.

5.1 CASE-BASED EXPERIMENT I: EXPERIMENTAL DESIGN

The experimental project is a 300ft x 300ft 6 floors steel frame office building with a 115ft x 115ft courtyard, as illustrated in Figure 5-1. The floor height for each floor is 15ft. The envelope design of the building can be categorized in three major configurations:

1. Level 1: The configuration of the first level envelope is composed of insulated metal panels with an array of 3'x14' glazing openings. The total glazing area ratio of the first floor is 20%.
2. Level 2: The second level envelope is glazed from 2.5 to 7.5ft. This leads to a 41% glazing area ratio.
3. Level 3-6: The top three levels are fully glazed with only 1' spandrel band that covers each floor slab. This results in 14' glazing height for each 15' floor. The glazing area ratio is 93.3%.

The design of the first two levels are inset from the floors above. As a result, the adopted glazing types for the first two levels have less solar protection when compared with the glazing type of the upper four levels. The project has a lobby feature that spans 145 ft of the south side of the first two levels. The lobby is glazed on both sides with laminated structural glazing, as shown on the right of the Figure 5-1. On the North side, the building bridges over one-third of the central area leaving Levels 1 & 2 completely unenclosed.

The fully glazed design of the upper four levels is where there is potential for using external solar protection to improve the building performance. As a result, this case is deemed as an ideal test case for the research. The project information and the thermal properties of the building envelope are summarized in Table 5-1.

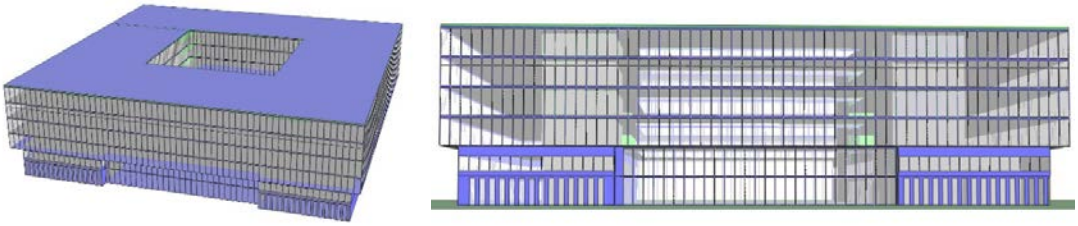


Figure 5-1: (Left) South east perspective view of the test case. (Right) South elevation view of the test case. Model and Images courtesy of Rudolph Marnich.

Table 5-1: Project and project construction summary. Table by the author.

Project	Envelope thermal property (U-value, Btu/h·ft²·°F)
Project site: 300ft x 300ft (91m x 91m) Floor Number: 6 Total Floor Area: Approx. 504,000 sf Construction Type: Steel Frame Glazing Area Ratio: Average 71.8% 1. Level 1: 20% 2. Level 2: 41% 3. Level 3-6: 93.3%	Roof: 0.044 (std. roof) Wall: 1. Spandrel: .108 2. Metal panel: .080 (1st level) Glazing: 1. Lobby: .105 (clear laminated) 2. Level 1: .304 (Dark Viracon V3-2M) 3. Level 2: .304 (clear Viracon V13-2M) 4. Level 3-6: .348 (low-e double glazed) 5. Interior: .703 Floor: 1. Typical floor: .389 (carpeted) 2. Ground floor: .044 (std. floor)

To fulfill the research objectives, there are a total for six simulation scenarios run for the test building in three different climate zone.

1. No shade: this simulation scenario serves as the benchmark scenario and does not include any shading strategies.
2. 2’ Horiz.: This simulation scenario applies 2 ft exterior horizontal shades for the top 4 levels of the building. The rigid shades are placed at 10ft height for East, South, and West exterior perimeter facades, and on the East, North, and West courtyard-facing facades. The North exterior perimeter wall is left unshaded.
3. NS 2’ Horiz. + EW 2’ Fin: Similar to the scenario 2, this simulation scenario applies exterior rigid shades for the top 3 levels of the building. However, for this scenario, the horizontal shades are only placed on the South façade and North side of the courtyard. For the East and West perimeters and courtyard, 2’ fins are placed on every other vertical mullion.
4. Oper. fixed Ts Stamisol® FT381 ctrl@ 158.5: This simulation scenario places Stamisol® FT381 on the East, South, and West exterior perimeter glazing, and on the East, North, and West courtyard-facing glazing for the top 4 levels. The shading control mechanism is to control the operable shade at the threshold of 158.5 Btu/hr/ft² (500 W/m²). When the solar energy reaches to the assigned threshold value, shades are deployed as “full-down” position. When the solar energy is below the threshold, shades are designated as full-up condition. Regarding the transmission value (Ts) in this scenario, the fixed Ts value is used as provided by the manufacture without considering the fabric’s angular optical properties.
5. Oper. fixed Ts Stamisol® FT381 ctrl@ 79.25: This simulation scenario is identical to scenario 4 with the only difference being that the operable threshold is set to 79.25 Btu/hr/ft² (250 W/m²).
6. Oper. LBNL Ts Stamisol® FT381 ctrl@ 158.5: This simulation scenario is identical to scenario 4 except that the Ts value in this scenario is replaced with the one obtained from the photo-goniometer lab testing.

Table 5-2 below is the experimental metrics that summarizes the designed simulation run to the associated observation focus and the recorded performance.

Table 5-2: Simulation run metrics of the research. There are a total of 6 simulation scenarios designed in this research for each site location. Table by the author.

		Observation Objectives			**Measured Performance**		**Tested Climate Zone**		
ID	Simulation Scenario	Obj1: Ts input	Obj2: Shading strategies	Obj3: different climate zone	Solar Gain (kBtu)	Building Energy Consumption(MBtu)	Los Angeles	Chicago	Abu Dhabi
SC01	no shade		X	X	X	X	X	X	X
SC02	2’ horiz.		X	X	X	X	X	X	X
SC03	NS 2’ horiz. + EW 2’fin		X	X	X	X	X	X	X
SC04	oper. fixed Ts Stamisol® FT381 ctrl@ 158.5	x	X	X	X	X	X	X	X
SC05	oper. fixed Ts Stamisol® FT381 ctrl@79.25		X	X		X	X	X	X
SC06	oper. LBNL Ts Stamisol® FT381 ctrl@ 158.5	X		X		X	X	X	X

5.2 CASE-BASED EXPERIMENT I: SIMULATION RESULTS & INTERPRETATIONS

This research first presents the visualization form of the overall results, then further discusses the research results based on each objective's observation focus. Figure 5-2 shows the monthly solar gain simulation results for four different shading strategies on the West, South and East side of the fifth floor in Los Angeles, Chicago and Abu Dhabi. In general, as long as a shading strategy is applied, the solar gain reduction can be achieve when compared to the baseline case SC01. For the South orientation, the overlapping of SC02 and SC03 is as expected since these two scenarios have the same shading configuration on the south side. When comparing annual solar gain performance using different shading strategies in Los Angeles, fabric shade performs more effectively in reducing solar gains in all three tested orientations, especially for the South orientation. However, the reduction degree varies from month to month for different orientations. In the West façade, the operable fabric shade is more effective during April to August. However, the vertical fin can have better control of the solar gain during fall and winter times. Conversely, operable fabric shade on the South façade presents more effective results than other shading strategies throughout the year with the exception of the month of June. This observation might imply that a constant high solar angle is better met with horizontal shades which can block direct sunlight better than fabric shade which still has transmittance. In addition, the high solar angle might cast less direct sunlight on the façade. When during other seasons, the rigid horizontal shade no longer served as an effective means to block direct sunlight. Regarding the East façade, fabric shade has a more consistent improvement throughout the whole year. The similar pattern can be observed in Abu Dhabi and SC04 where fabric shade strategies present significantly more effective performance on the South side of the façade. However, the results for South side of the Chicago simulation presents counter results. During the summer time, the fabric shade does not work as effectively when compared to the SC02 and SC03 shading strategies. Figure 5-3 presents the summary of the annual solar gain reduction when compared with the benchmark scenario. It demonstrates the effectiveness of applying fabric shade, SC04 for solar gain reduction especially on the South and East orientation, with the exception of the West orientation in Chicago climate. This observation confirms the findings of prior research that fabric shade is more effective to controlling heat gains in a warm climate. These results also supports the hypothesis that fabric shade with control is an effective means to control solar gain when compared to the other two tested strategies.

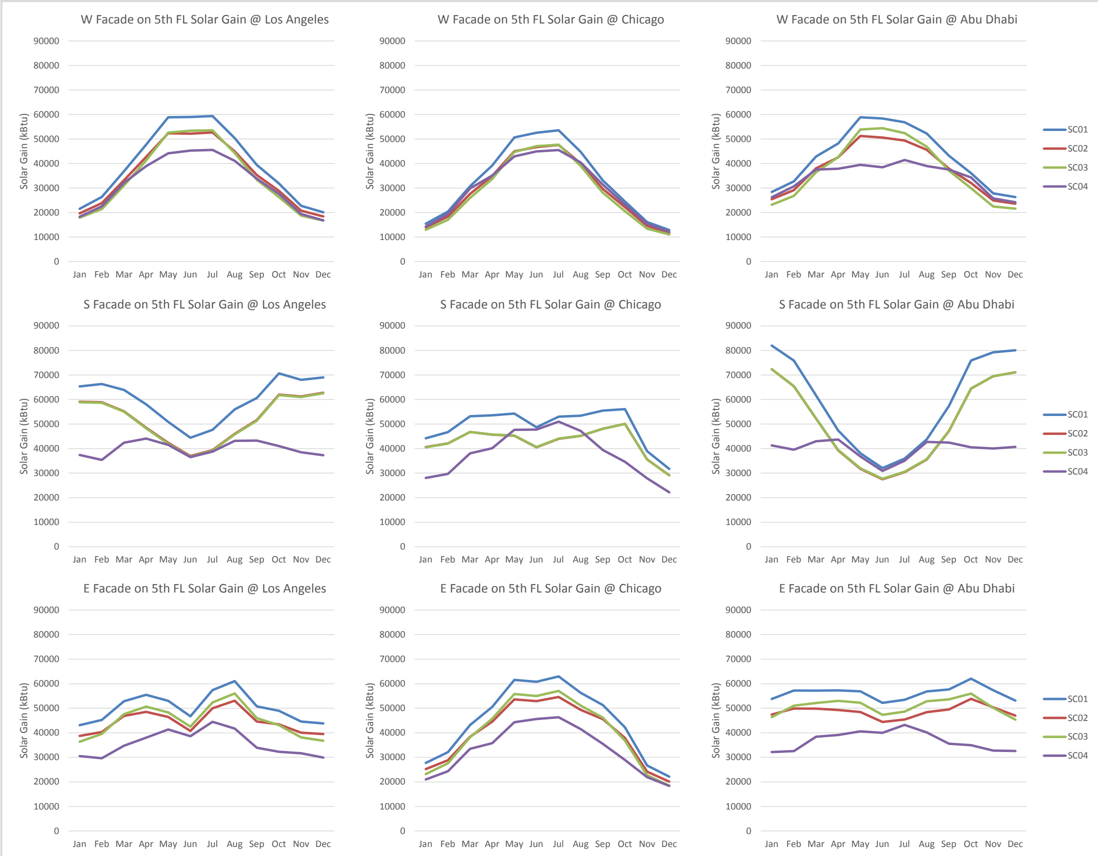


Figure 5-2: Summary of the monthly solar heat gain performance on the West, South and East side of the facade for four different shading strategies in three different climate zones. Images by the author.

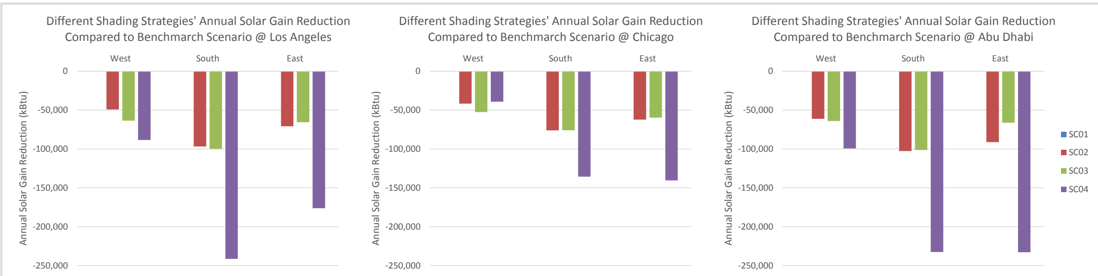


Figure 5-3: Different shading strategies' annual solar gain reduction compared to the benchmark scenario for three different climate zones. Images by the author.

Regarding the overall energy performance, the overall simulation results are illustrated in Figure 5-4. The energy consumption pattern of Los Angeles and Abu Dhabi are similar, but Abu Dhabi has higher amplitude. The boiler energy consumption for Los Angeles and Abu Dhabi seem close to zero when comparatively scaled against Chicago. The resulting pattern is understandable since only Chicago has boiler energy consumption during the cold winter time, with the accumulated total system energy consumption results having two peak point throughout the year. When comparing monthly energy reduction for different shading strategies, the improvement patterns do not have a dramatic variation with regards to solar heat gain despite some observable improvements. In general, strategies with shading all perform better in terms of total system energy consumption reduction for Los Angeles and Abu Dhabi. However, the shading strategies do not help for the Chicago climate during the winter time due to the increased heating load. While these shading strategies increase the boiler energy consumption, this increase is particularly significant. Excluding Chicago's winter condition, SC05 stands out as the most effective one capable of reducing energy consumption when compared to the other scenarios. In order to further understand the improvements made by each shading strategies, Figure 5-5 provides annual total system energy consumption comparison for all 6 scenarios in all three simulated climate zones.

Figure 5-4: Summary of the monthly total system energy, chiller, boiler and auxiliary energy consumption for 6 different shading strategies in three different climate zones. Images by the author.

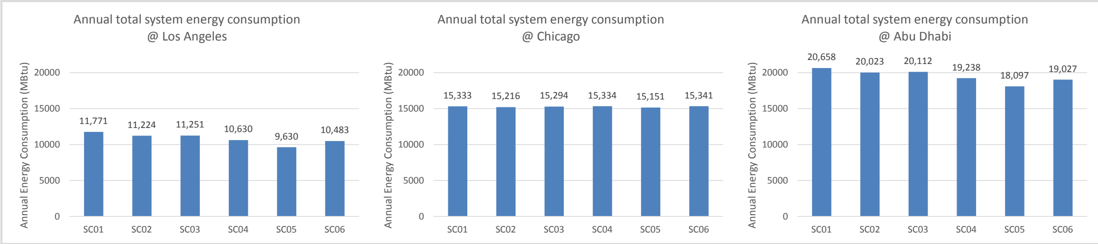


Figure 5-5: Summary of the annual total system energy comparison for 6 different shading strategies in three different climate zones. Images by the author.

In Los Angeles, when comparing against SC01 as the baseline scenario, SC04 demonstrates approximately twice the energy savings as opposed to SC02 and SC03. SC05 further doubles the energy savings when compared to SC04. A similar pattern can be observed from the results of Abu Dhabi. However, this is not the case for Chicago. In Chicago the fabric shade strategies all perform worse than the rigid shade strategies, i.e. SC02 and SC03.

To summarize the analysis results based on the research objective, the first is with regards to the impact of the Ts value. This impact can be observed through the comparison of the results for SC04 and SC06. Both scenarios have the same settings and control threshold, but SC06 uses the extrapolated value from LBNL lab testing and SC04 uses the value provided by the manufacturer. Although the resulting annual total system energy consumption have some differences, the variation is not considered very significant, as shown in Table 5-3 and Figure 5-6. For Los Angeles and Abu Dhabi, SC06 is slightly better than SC04, but SC04 is better than SC06 in Chicago. Assuming SC06 represents a more accurate results as it uses the results with higher accuracy due to consideration of difference in the angular properties, whether the difference this made is significant enough to be considered to support design decision is still unclear and requires further study.

The second research objective is to understand the impact of different shading strategies and can be observed by comparing the overall scenario runs as illustrated from Figure 5-2 to Figure 5-5. In general, fabric shade strategies with control settings perform better than the rigid shade strategies. In addition, the impact of the control strategy can be observed through the comparison of SC04 and SC05's results since both scenarios are fabric shade with different control thresholds. As shown in Table 5-3 and Figure 5-6, it is apparent that SC05's control threshold is more effective than SC04 and almost doubles the performance in all three climate zones. Furthermore, it can be observed in Chicago's result that the optimal shading strategy is varied through seasonal variation. This observation confirms the findings of prior research and highlight the need for dynamic and responsive systems to pursue higher performing results.

The last observation focus of the research is to understand the impact of different climate zones. As describe previously the results are in agreement with prior research which establishes that fabric shade is more effective in warm climates as it will increase the heating load for cold climate buildings. However, it might still worth investigating whether the use of dynamic shading strategies can improve this performance.

Table 5-3: Annual energy saving for different shading strategies when compare with the benchmark scenario. Table by the author.

			Total system energy reduction				
Scenario ID	SC01		SC02	SC03	SC04	SC05	SC06
Los Angeles	11,771	MBtu/yr	-547	-520	-1,141	-2,141	-1288
		%	-4.6%	-4.4%	-9.7%	-18.2%	-10.9%
Chicago	15,333	MBtu/yr	-117	-39	-1	-182	+8
		%	-0.8%	-0.3%	-0.1%	-1.2%	+0.5%
Abu Dhabi	20,658	MBtu/yr	-635	-546	-1,420	-2,561	-1,631
		%	-3.1%	-2.6%	-6.7%	-12.4%	-7.9%

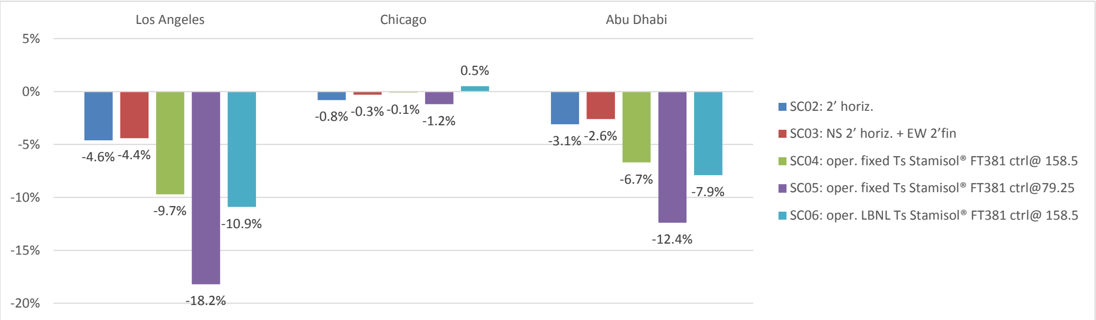


Figure 5-6: Annual energy saving for different shading strategies when compared with the benchmark scenario. Image by the author.

CHAPTER 6 CASE-BASED EXPERIMENT II: TRANSFORMABLE MEMBRANE FAÇADE

The objective of this experiment is to explore and validate the concept that using a transformable membrane façade system is able to improve building performance and encourage inspirational design synchronously. In order to achieve this objective, a shoebox model is utilized with a series of interchangeable membrane façade configurations to observe their relative daylighting performance during various time periods. By contrasting the performing results from a single configuration and multiple ones, the potential use of transformable façade to achieve higher performance can be observed and revealed.

6.1 CASE-BASED EXPERIMENT II: EXPERIMENTAL DESIGN

A 15 m x 9 m x 13.5 m shoebox model is utilized for this case-based experiment, as shown in Figure 6-1. The model is designed as a three-story building with Southeast oriented membrane facade as the outer skin 1.5 m away from the primary glazing. The floor to ceiling height is 3 m with 1.5 m utility space above. The designated daylighting analysis plane is on the second level to avoid exceptional edge conditions of the ground and top level. The ground floor, roof and two sides of the perimeter walls are extruded to encompass the edge of the membrane layer to eliminate any direct light coming through the gaps. The hypothetical site of this experiment is located at the Orly Airport, Paris, France (48.73° N, 2.4° E) using the weather data obtained from the U.S. Department of Energy (2013). Desktop Radiance (LBNL 2000) is utilized as daylighting analysis engine through the user interface of Autodesk® Ecotect® Analysis 2011 (Ecotect) (Autodesk 2014). The day lighting performance is measured and observed through the illuminance levels of each tested scenario.

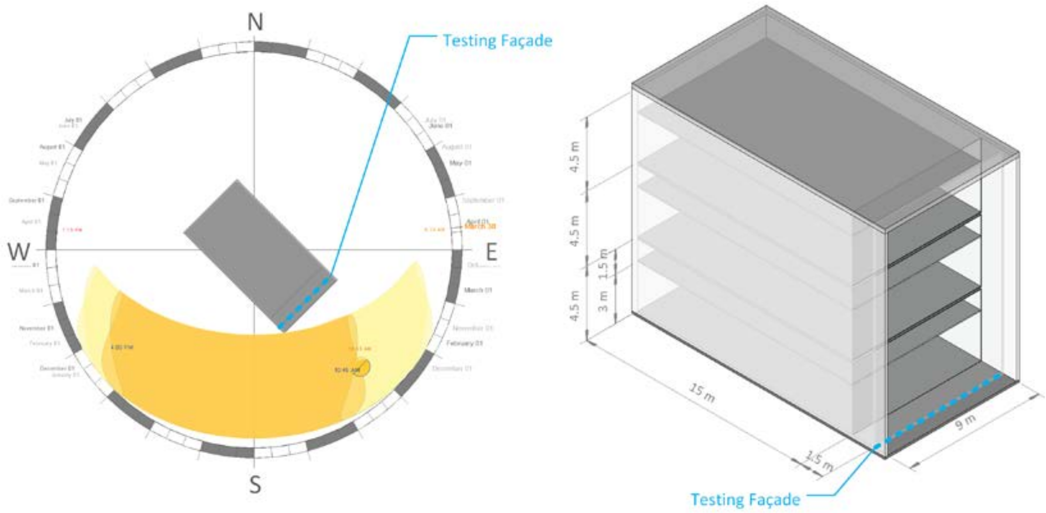


Figure 6-1: The “Shoebox” model for Case-based Experiment II. Model and images curtesy of Dr. Eve S Lin.

There are a total of 5 scenarios tested in this study, as illustrated in Figure 6-2:

1. M0 - no membrane: this scenario serves as the benchmark case which has no membrane installation.
2. M1 - flat membrane: this scenario applies a flat layer ETFE membrane as the outer skin 1.5 away from the primary glazing surface.
3. M2 - anticlastic 4pt. sail I: this scenario is an anticlastic membrane configuration composed of 24 joined four-point-sails units. Each unit is 2.25 m x 2.25 m with 0.45 m fluctuation.
4. M3 - anticlastic 4 pt. sail II: this is the second anticlastic membrane configuration. Similar to M2, the only difference is the fluctuation value changed from M2’s 0.45 m to 0.9 m.
5. M4 - synclastic pillow form: this scenario is a synclastic configuration with 12 pillow-form units. Each unit is 2.25 m x 5.5 m with 0.5 m center thickness.

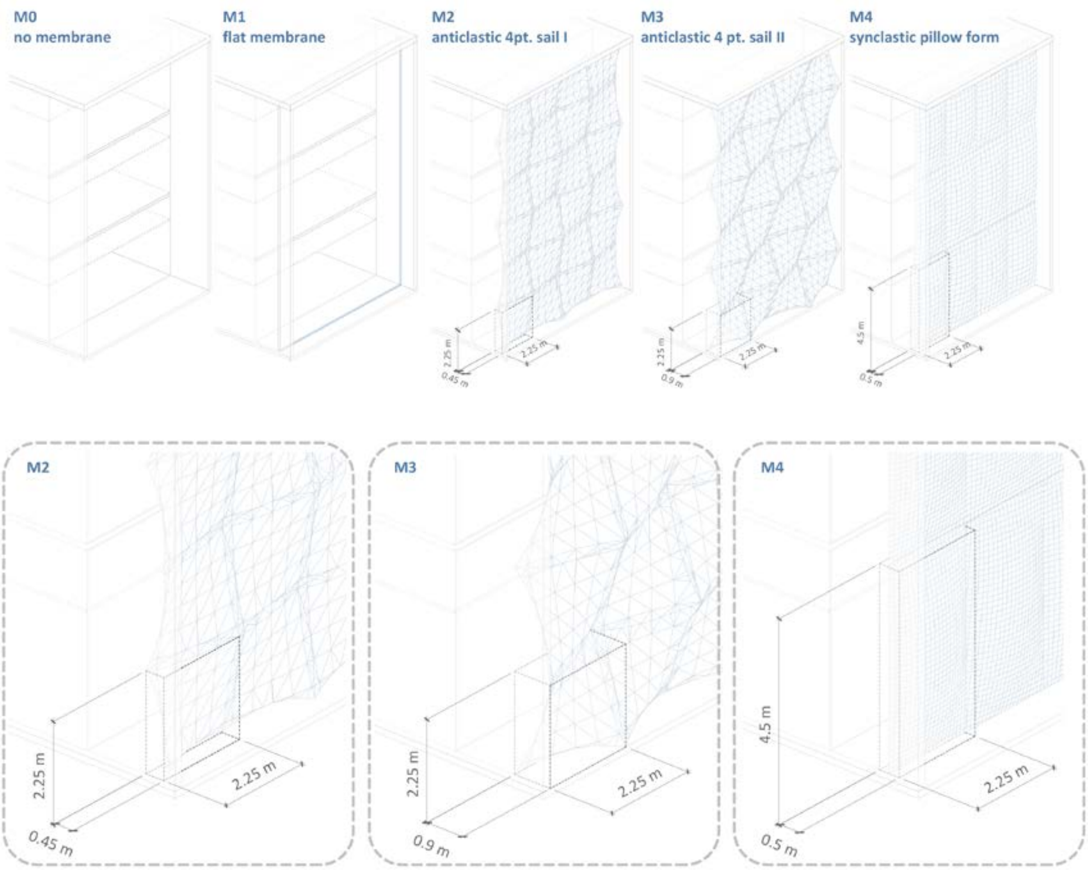


Figure 6-2: Illustration of the scenario designs of Case-based Experiment II. Illustration courtesy of Dr. Eve S. Lin.

The geometry of the shoebox and the flat membrane is modeled directly in Ecotect. The forms of the anticlastic membranes (M2 and M3) and the synclasitc pillow (M4) are generated in Formfinder™ (Formfinder Software GmbH 2014) and Autodesk Revit 2013® (Autodesk 2013) respectively, following by imported into Ecotect through *.dxf format.

In order to isolate and compare the impact of different membrane's geometric configurations, the reflectance (R) and visible transmittance (Tv) values are assigned consistently throughout the tested scenarios, as summarized in Table 6-1. For this experiment, the Tv value of the ETFE layer adopts the test result from Gibbs et al. (2009) where the Tv value of a single layer ETFE is 0.85. While the objective of the experiment is to observe the impact of membrane layer's geometric variation, each scenario is treated as a variation of the same system that their geometric configurations are interchangeable (except the benchmark scenario M0). To this end, M1, M2 and M3 are designed as the scenarios composed of two layers of ETFE which can be inflated to form M4's pillow shape if the control strategies applied in the future. As a result, the simulated ETFE Ts value for M1~M3 is two layers of ETFE Tv value, 0.85 x 0.85 = 0.7225.

Table 6-1: Summary of the reflectance and transmittance values of Case-based Experiment II. Table by the author.

Element Type		Reflectance (R)	Visible Transmittance (Tv)
Typical Wall		0.702	
Ceiling		0.804	
Floor		0.502	
Primary Glazing			0.753
Membrane Layer	M0: no membrane		0
	M1: flat		0.7225
	M2: anticlastic 4pt. sail I		0.7225
	M3: anticlastic 4 pt. sail II		0.7225
	M4: synclastic pillow form		0.85

The illuminance analysis is done through a 2D analysis grid placed on the working plane of the 2nd level, which is 0.76m (30") above the floor plane. The grid size is 30.48 cm x 30.48 cm (1' x 1') encompassing all the interior area and the area covered by the outer layer membrane, as illustrated in Figure 6-2.

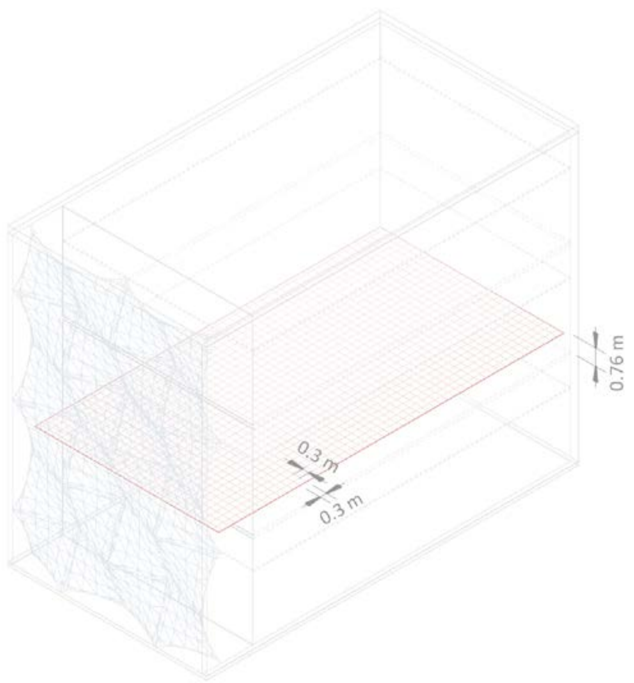


Figure 6-3: Illustration of the analysis grid placement for Case-based Experiment II. Image courtesy of Dr. Eve S. Lin.

For each scenario, an illuminance analysis is conducted respectively at 9am, 11am, 1pm, 3pm and 5pm for summer solstice, fall equinox, and winter solstice (June 21st, September 21st, and December 21st). This resulting a total of 75 simulation runs for this experiment.

Regarding daylighting performance, it is evaluated by LEED BC+D v4 through the demonstration of illuminance levels between 300 and 3,000 lux for 9 a.m. and 3 p.m., both on a clear-sky day at the equinox, for 75% or 90% or regularly occupied floor area (U.S. Green Building Council 2014). Based on this standard, it is determined by this research that the optimal illuminance performance is to demonstrate more than 75% of the area can have illuminance levels over 300 lux. In addition, in order to eliminate the excessive heat and glare introduced by daylight, when two scenarios are both designated as optimal, the scenario with less excessive illuminance (>1,200 lux) is preferred.

6.2 CASE-BASED EXPERIMENT II: SIMULATION RESULTS & INTERPRETATIONS

The collected data for each simulation run include a batch of Radiance's output files along with a color-coded image (*.bmp) that illustrates the illuminance distribution of each analysis. A consistent coloring scale, ranging from 0 lux (blue) to 1200 lux (yellow), is applied to every analysis to insure the comparability of each result, as illustrated in Figure 6-4. Based on the definition of this research, the optimal condition is the resulting image has a color ranging from burgundy (240 lux) to yellow (1200+ lux) larger than 75% of the floor area. When multiple optimal conditions exits, the image with less yellow and orange color is preferred.

Figure 6-4: The coloring and data scale for the visualization of the illuminance level distribution. Image by the author.

In order to observe the optimal membrane configuration for different times and dates, this research divides 75 illuminance distribution images into three groups based on the simulation dates: June 21st, September 21st, and December 21st. This results each group has 25 simulation runs, composed of the results from 5 different times for 5 different scenarios on the same date. For comparison purpose, each group of the results are arranged as a matrix that each column represents as a specific time, from 9am to 5pm; and each raw represents a specific scenario, from M0 to M4, as illustrated in Figure 6-5, Figure 6-6 and Figure 6-7. It can be observed that the illuminance levels for different configurations has noticeable variance in different times and dates. In general, M0 has the highest illuminance levels when comparing with other scenarios since it is the benchmark case with no ETFE layer to filter out any light. M1's results present the highest illuminance levels among the scenarios with membrane layers. M2 and M3 have relatively similar performance, but the variations are still observable. Lastly, M4 has the lowest illuminance level when compared to other configurations.

Although M1's results has the highest illuminance levels, they cannot always be designated as the optimal performance for every situation based on the definition of the experiment. This is due to their relatively high illuminance levels might compromising cooling load and visual comfort when comparing with other scenarios that involve with geometric variations. On the other hand, in certain situation, the scenarios with geometric variations present the ability to minimize excessive light but still maintain the required illuminance levels for the space. In order to isolate the optimal configuration and demonstrate the potential of geometrically-variable membrane system, the research highlights the scenario which presents the optimal illuminance performance among M1 to M4 for each simulated time based on the definition of the research, as illustrated in Figure 6-8. For the situation where none of the scenario meets the criteria, the scenario with the highest illuminance level is chosen.

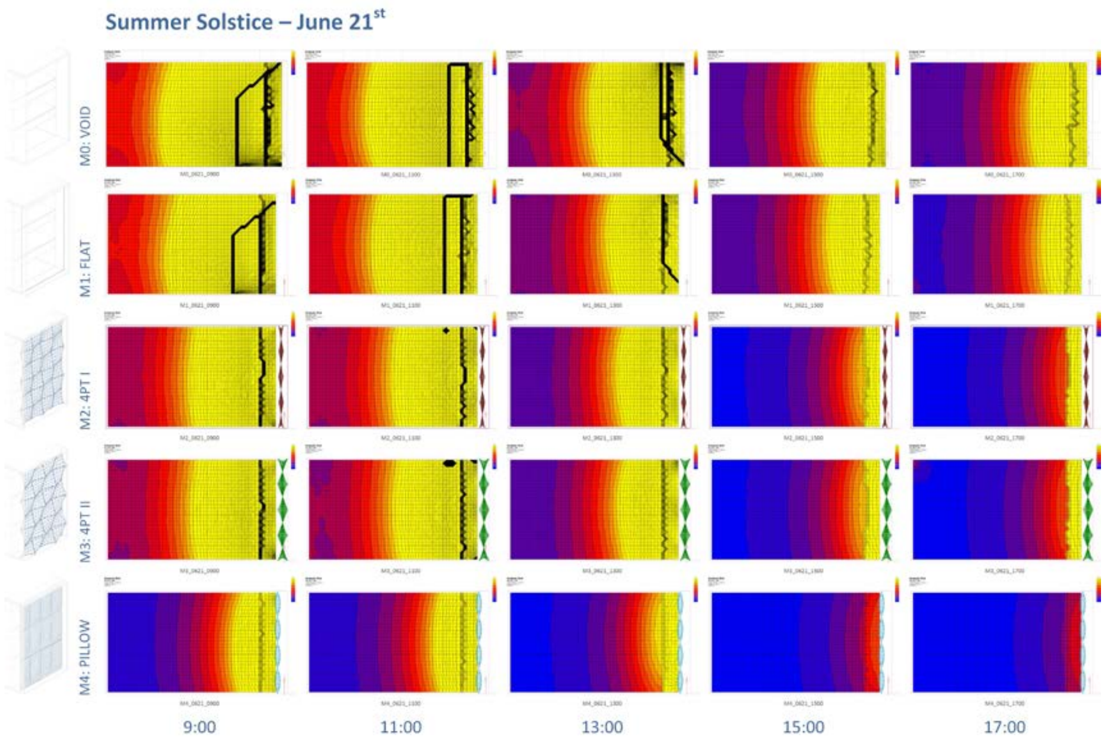


Figure 6-5: Illuminance levels distributions of all scenarios at different times on June 21st. Images by the author.

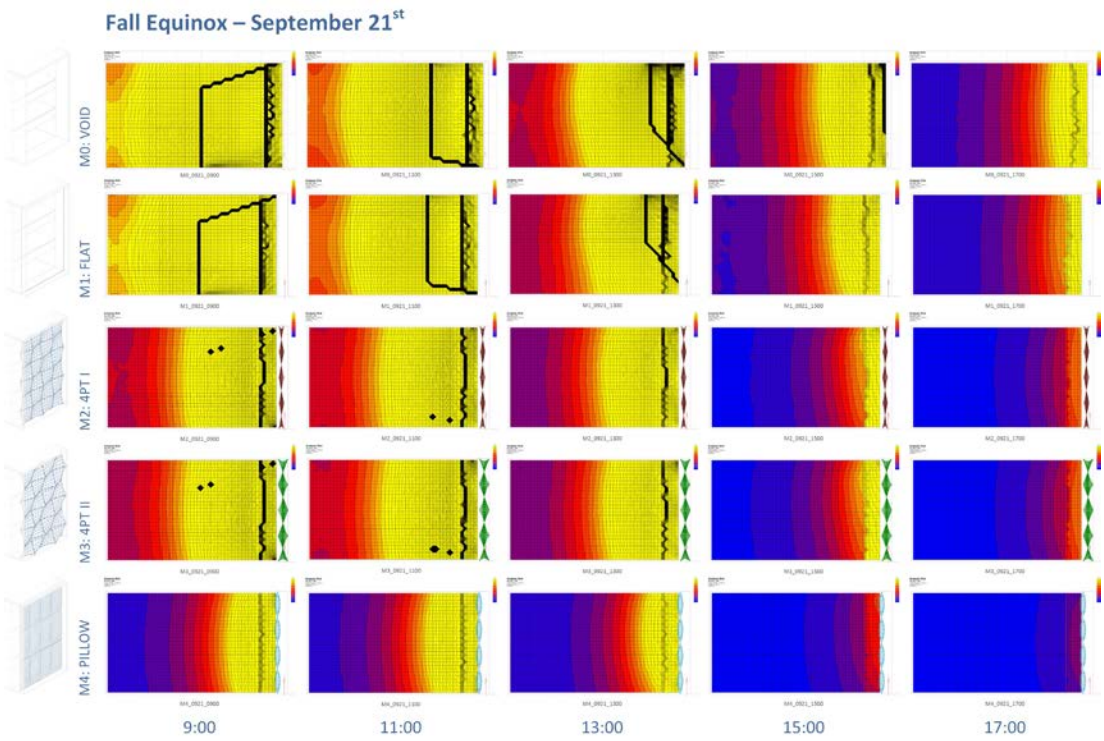


Figure 6-6: Illuminance levels distributions of all scenarios at different times on September 21st. Images by the author.

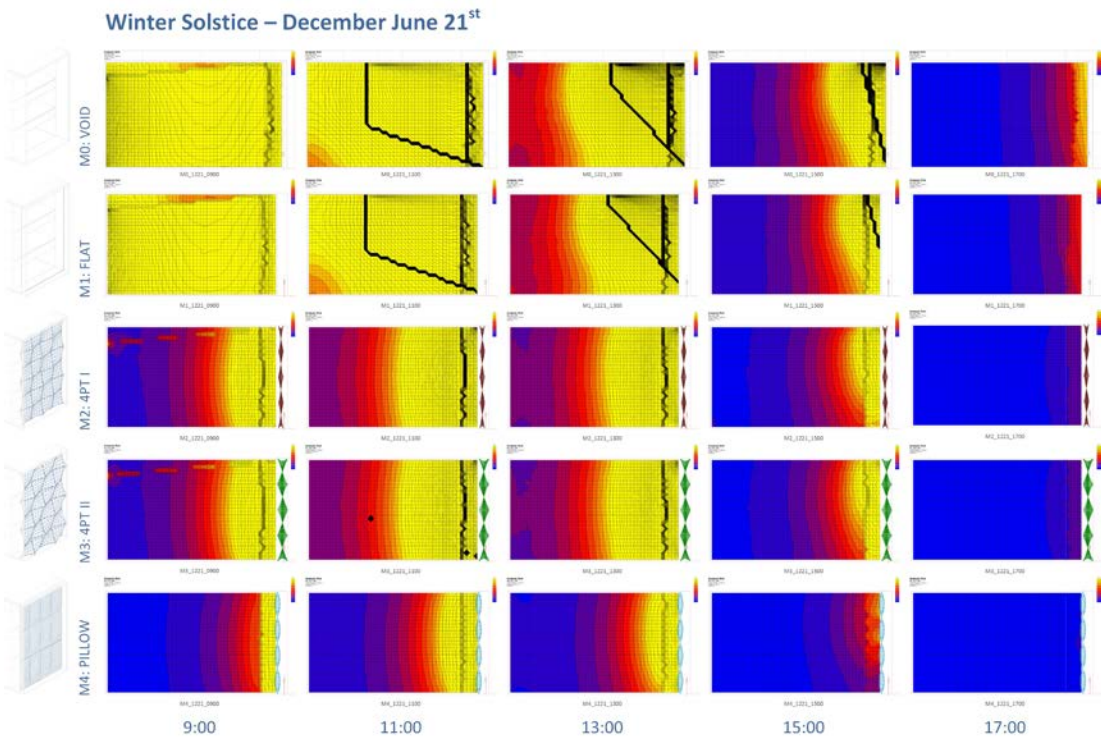


Figure 6-7: Illuminance levels distributions of all scenarios at different times on December 21st. Image by the author.

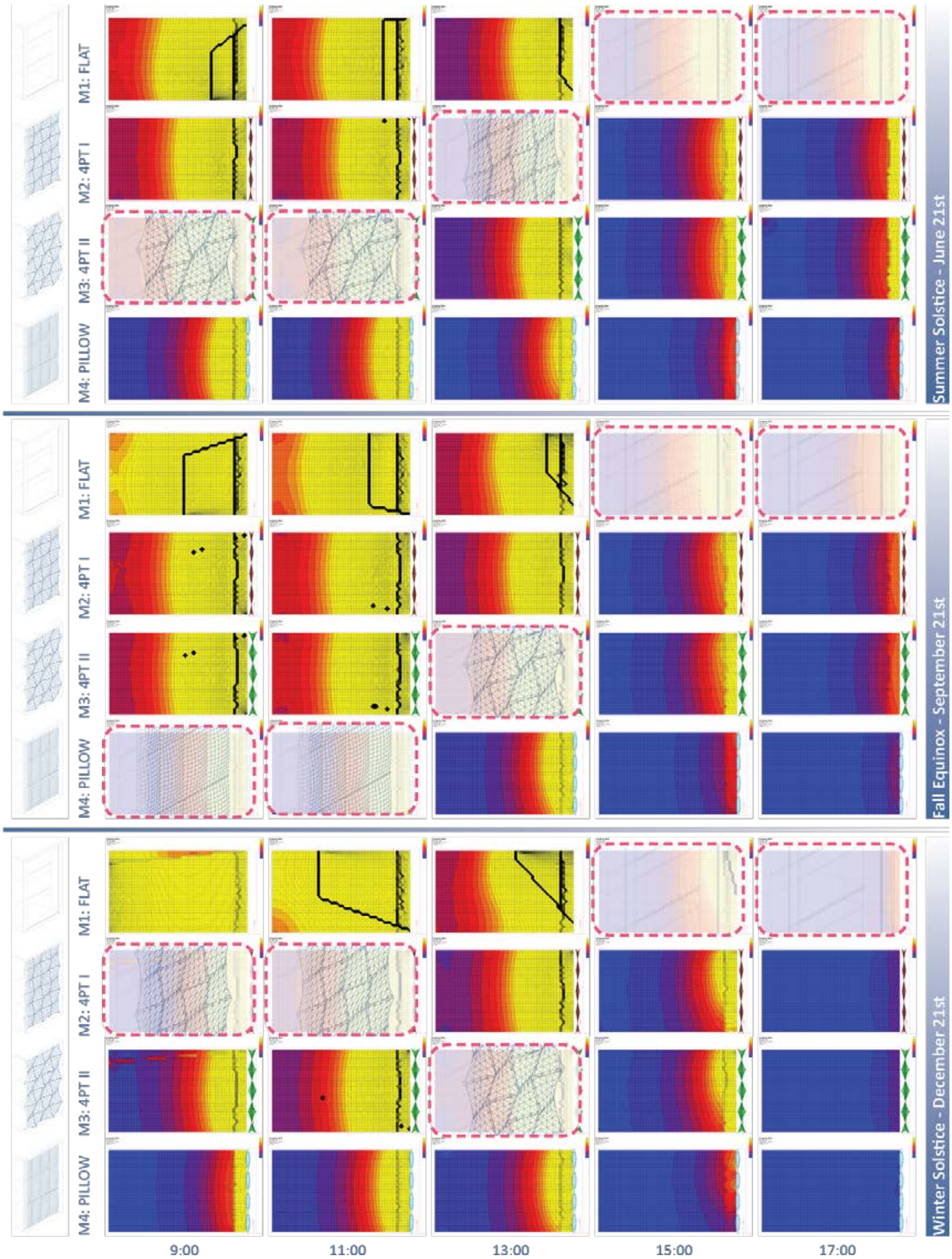


Figure 6-8: Illustration of the optimal façade variation for summer solstice, fall equinox and winter solstice. Image by the author.

It is evidence from Figure 6-8 that the optimal condition of different time is determined by varying configurations. For summer solstice, M3 provides the best illuminance distribution in the morning while the flat membrane, M1, is preferred in the afternoon to ensure the sufficient illuminance levels. During fall equinox, the membrane configuration of M4 is considered more suitable to accommodate the morning low sun angle since it provides adequate illuminance levels for work while minimizing the illuminance contrast throughout the space. On the other hand, M2 presents better performance during the winter morning. However, none of the scenario is able to provide the illuminance levels that meets the criteria during the winter afternoon. As a result, M1, the highest performing one during winter afternoon, is chosen.

This experiment demonstrates the use of geometric-adjustable membrane façade system is able to provide nearly consistent high performing illuminance levels despite the constant changing exterior environment. While this study only applies a specific performing criteria on a shoebox model as an example, more substantial opportunities can be foreseen that the adaptive membrane façade system is able to accommodate occupants' needs for different occupancy zones during different times, dates and orientations. In addition, the use of the adaptive membrane façade enables appearance variation with assorted possible configurations which can broaden designers' design space with fixable and inspirational yet high performing components. Imaging the adaptive membrane façade system can be applied on a geometrically-complex architectural skin, how much more opportunities emerges for designers that encourage them to expend their design spectrum with more aesthetic appealing and sexy elements while improving design performance simultaneously.

CHAPTER 7 CONCLUSION AND FUTURE WORK

In order to pursue and promote the use of tensile membrane façade system to enable responsive and higher performance buildings, this research started from literature review to obtain the initial support for the research hypothesis. Furthermore, the literature review was used as a means to isolate the fundamental problems that impede designers to adopt the tensile membrane façade system. It was confirmed that due to the complex optical and geometric properties introduced by the tensile membrane façade system, a suitable evaluation means to understand the benefits of tensile membrane façade system is absent in the current architectural design field. As a result, although the benefit of the tensile membrane structure is acknowledged, it has not been widely adopted. Consequently, its potential of improving building performance is still lacking of quantifiable evidence. To address the aforementioned issue, a goniometric lab test was first conducted to obtain the optical properties of the test sample followed by two case-based experiment to understand the impact of input optical properties, different shading strategies, and the impact of membrane's geometric variations.

Through the goniometric lab testing, the measured optical properties showed a slight difference from the theoretically derived results. This high-resolution measurement might have a significant impact on the lighting and energy simulation performance. However, due to the limitation of the current energy simulation tools, the full BSDF cannot be considered and therefore the actual impact cannot be obtained at this current research stage. As a result of the low-resolution intake of the energy simulation tool, only 7 angular optical values were taken into consideration during the energy simulation process.

For the first case based experiment, there were a total of 6 shading scenarios tested in three different climate zones. Based on current simulation results, although the performance variation can be observed, the impact of the Ts value might not be significant enough to affect the design decision making process. However, this research only tested flat fabric shading surfaces and excluded the potential of electrical lighting energy reduction, the actual impact of using optical properties cannot be accurately gauged based on the current results. Furthermore, the test sample demonstrates perfect Lambertain during the goniometric testing except for one small area. This indicates the potential of fabric shades to provide higher daylighting performance. As a result, the incorporation of the goniometric measured

Ts value or higher resolutions Ts value during the simulation process is still a research in question that is worth further exploration. When comparing different shading strategies, fabric shades are more effective than other tested scenarios in a warm climate condition in terms of solar heat gain and the total system energy reduction. The results also demonstrate that the control mechanism of the fabric shade has a significant impact on the performance. While the research only explored the fabric shading strategies as a flat system with one solar heat gain threshold control mechanism, the significance of the impact can already be observed. This implies higher potential with the incorporation of the dynamic system control along with the angular variation of the shading surface. This not only encourages designers to be more creative regarding the façade system but also promotes performance based design.

To further support the conclusion drawn from the previous experiment, the second case-based experiment focused on observing the potential introduced by transformable membrane façade system. A shoe-box model with four tensile membrane façade configurations was explored and compared regarding each configuration's daylighting illuminance levels. It is evidence that each configuration has varying performance throughout different time and day. However, none of the configuration can meet the designated criteria alone throughout the testing period. On the other hand, if transformable is allowed, the façade system is able to provide nearly consistent daylighting performance based on user-defined criteria regardless the time and date. This result begins to support and validate the research hypothesis that transformable membrane façade system is able to resulting higher performing design. Furthermore, it expends the design space and encourages more inspirational design for designers.

Currently, the research only explored a relatively simple system with the focus on limited performance aspect, i.e. energy, solar heat gain and daylighting performance. In addition, there are several unknowns and questions that need to be explored further. However, there is evidently potential can be expected to couple the transformable membrane façade system with kinetic and responsive control. With the advancement of the design and control technologies, this research believes that the use of transformable membrane façade system is the most promising and economical feasible means to overcome the increasing design complexity and to meet the growing performance demands synchronously.

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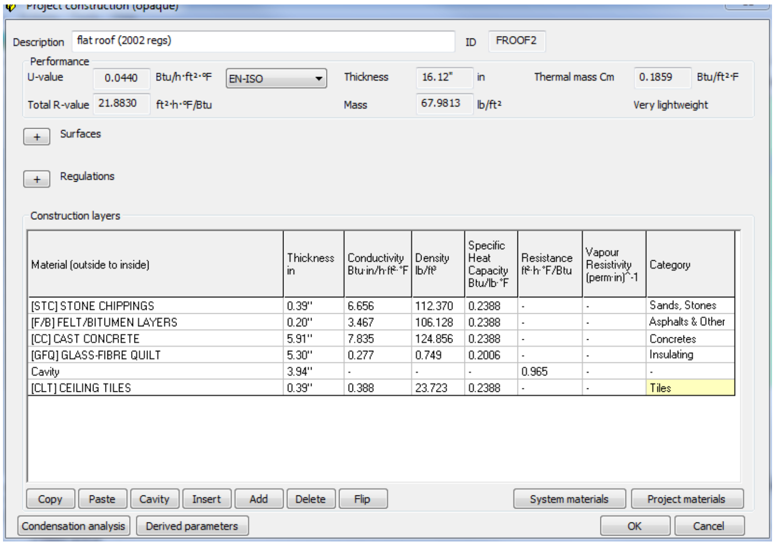
APPENDIX A IES <VE> ENERGY SIMULATION MODEL DETAILS

A.1 BUILDING CONSTRUCTION SETTINGS

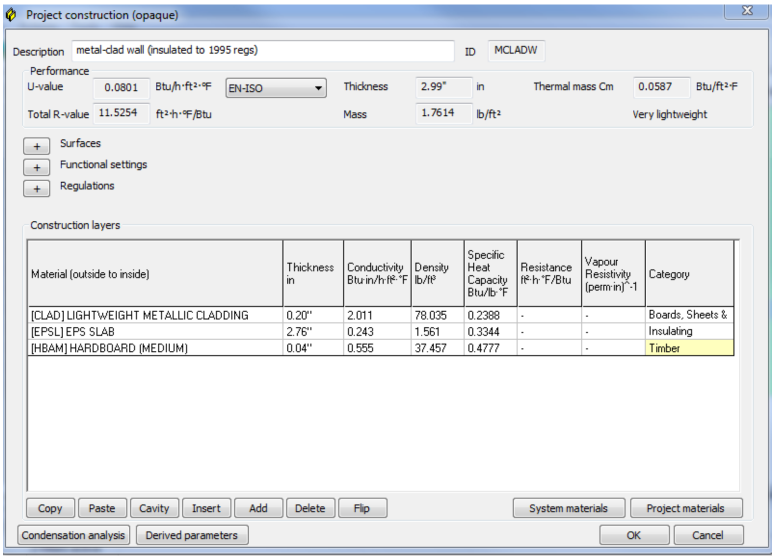
1. Roof:



Material (outside to inside)	Thickness in	Conductivity Btu·in/h·ft²·°F	Density lb/ft³	Specific Heat Capacity Btu/lb·°F	Resistance ft²·h·°F/Btu	Vapour Resistivity (perm·in)^-1	Category
[STC] STONE CHIPPINGS	0.39"	6.656	112.370	0.2388	-	-	Sands, Stones
[F/B] FELT/BITUMEN LAYERS	0.20"	3.467	106.128	0.2388	-	-	Asphalts & Other
[CC] CAST CONCRETE	5.91"	7.835	124.856	0.2388	-	-	Concretes
[GFQ] GLASS-FIBRE QUILT	5.30"	0.277	0.749	0.2006	-	-	Insulating
Cavity	3.94"	-	-	-	0.965	-	-
[CLT] CEILING TILES	0.39"	0.388	23.723	0.2388	-	-	Tiles

Figure A- 1: IES <VE> energy simulation model: roof input. Image from the screen shot of the research model.

2. Opaque Wall:
   a. Level 1: Metal clad wall – insulated
   b. Levels 2-6: Spandrel shadow box



Material (outside to inside)	Thickness in	Conductivity Btu·in/h·ft²·°F	Density lb/ft³	Specific Heat Capacity Btu/lb·°F	Resistance ft²·h·°F/Btu	Vapour Resistivity (perm·in)^-1	Category
[CLAD] LIGHTWEIGHT METALLIC CLADDING	0.20"	2.011	78.035	0.2388	-	-	Boards, Sheets &
[EPSL] EPS SLAB	2.76"	0.243	1.561	0.3344	-	-	Insulating
[HBAM] HARDBOARD (MEDIUM)	0.04"	0.555	37.457	0.4777	-	-	Timber

Figure A- 2: IES <VE> energy simulation model: Level 1 metal panel input. Image from the screen shot of the research model.

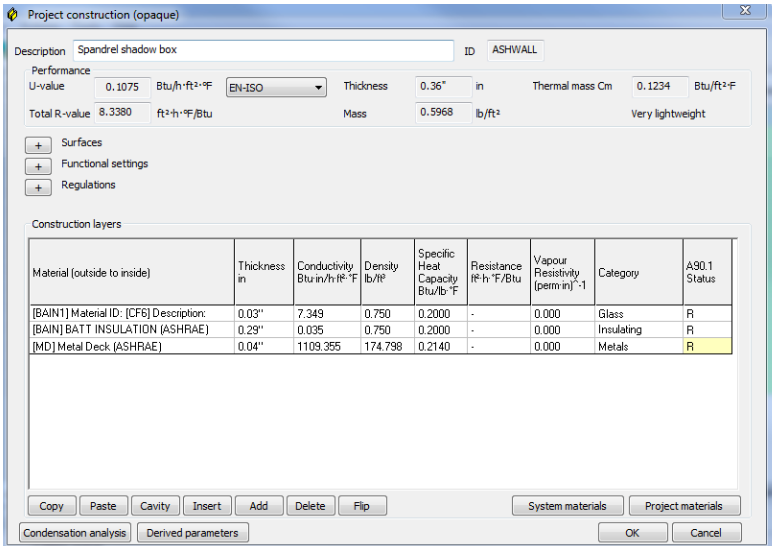


Figure A- 3: IES <VE> energy simulation model: Level 2-6 spandrel input. Image from the screen shot of the research model.

3. Glazing
    a. Level 1 Lobby: Viracon VE13-85 structural laminate
    b. Level 1: Viracon V3-2M
    c. Level 2: Viracon VE13-2M
    d. Level 3-6: double low-e glazing

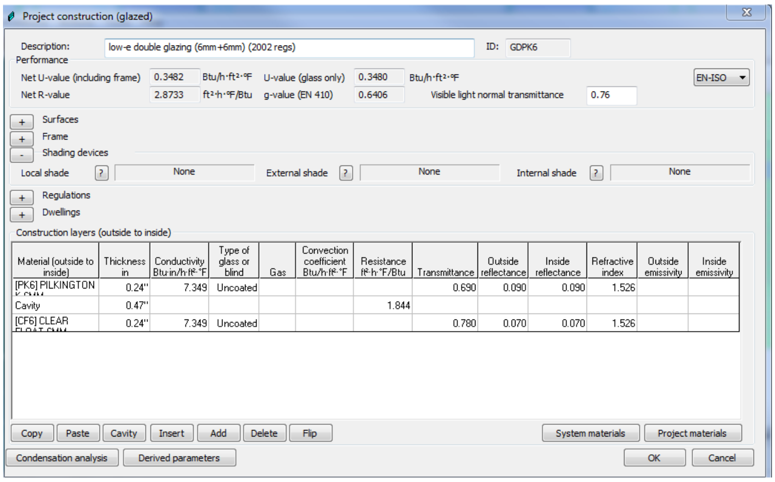


Figure A- 4: IES <VE> energy simulation model: Level 3-6 glazing input. Image from the screen shot of the research model.

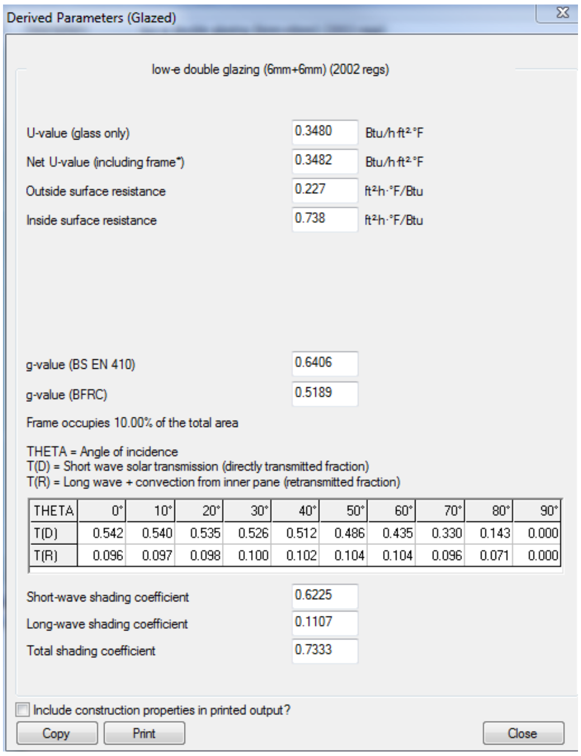


Figure A- 5: IES <VE> energy simulation model: derived parameters inputs for Level 3-6 glazing. Image from the screen shot of the research model.

4. Floor:
    a. Typical carpeted floor
    b. Ground contact floor

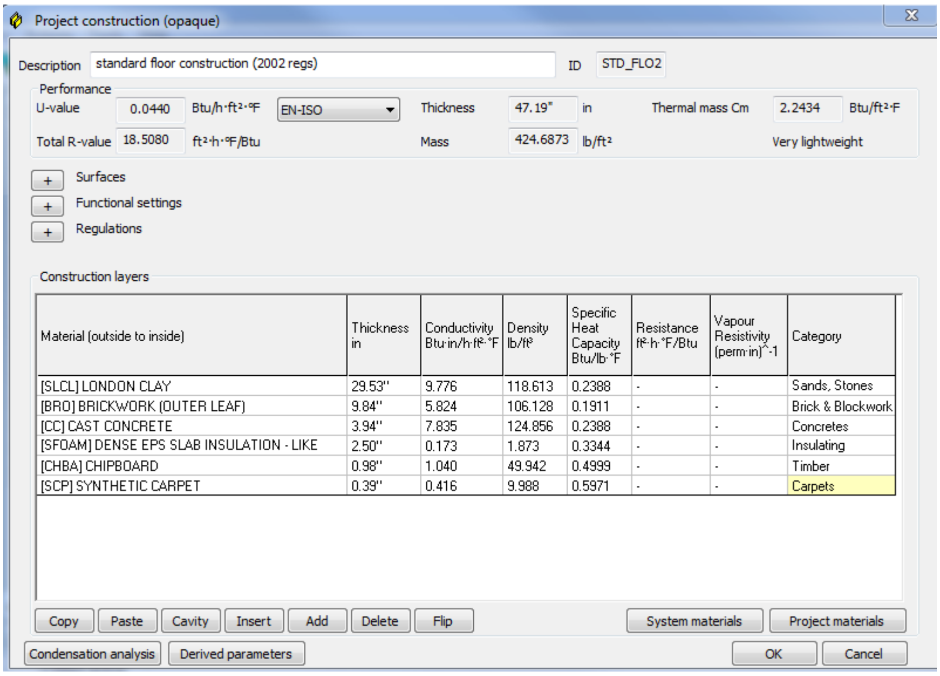


Figure A- 6: IES <VE> energy simulation model: ground floor input. Image from the screen shot of the research model.

A.2 BUILDING SYSTEM SETTINGS

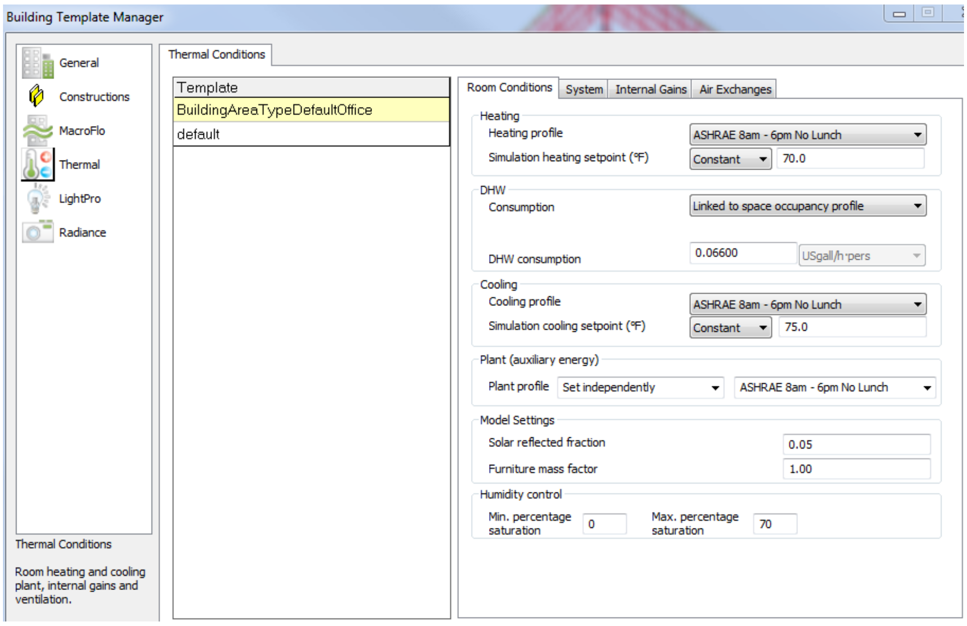


Figure A- 7: IES <VE> energy simulation model: room thermal condition settings. Image from the screen shot of the research model.

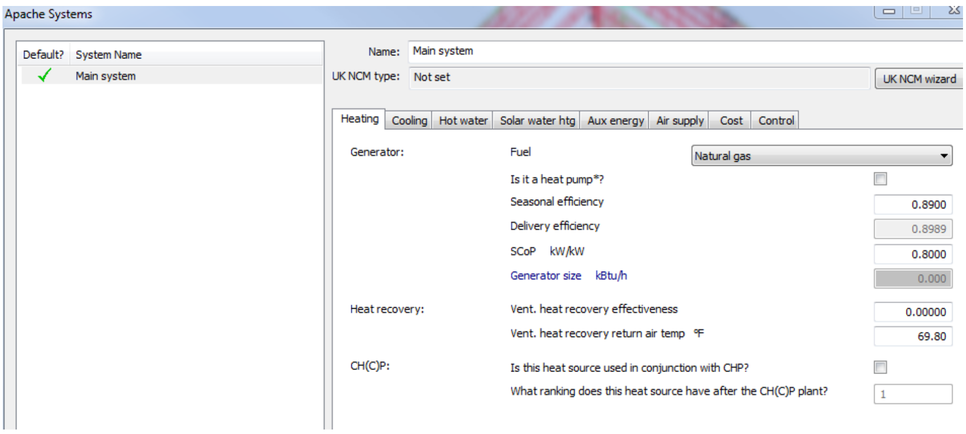


Figure A- 8: IES <VE> energy simulation model: heating system settings. Image from the screen shot of the research model.

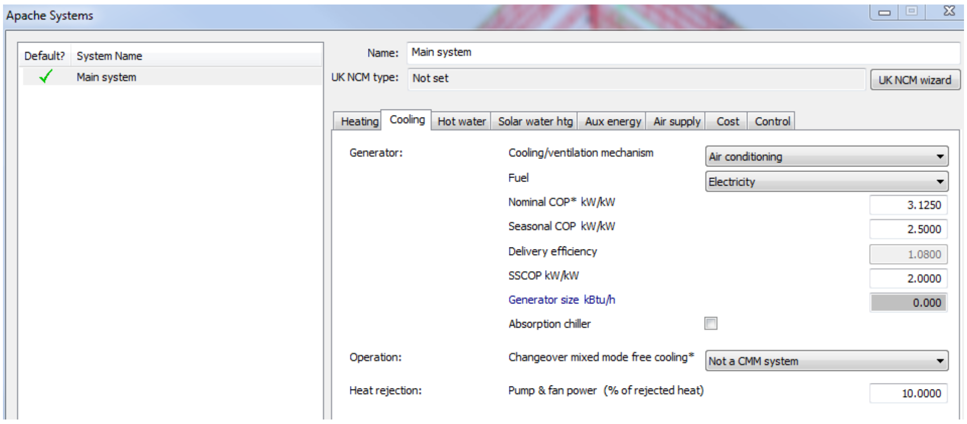


Figure A- 9: IES <VE> energy simulation model: cooling system settings. Image from the screen shot of the research model.

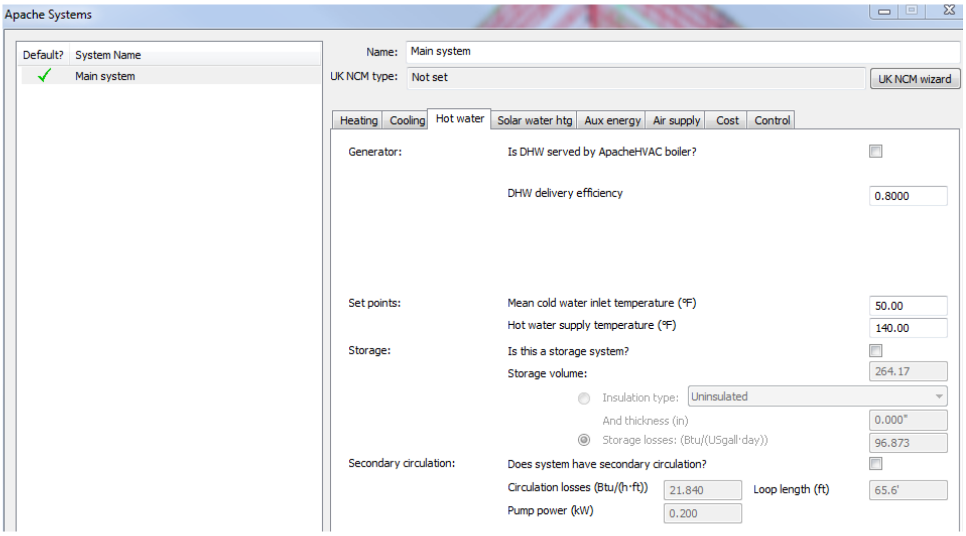


Figure A- 10:IES <VE> energy simulation model: hot water system settings. Image from the screen shot of the research model.

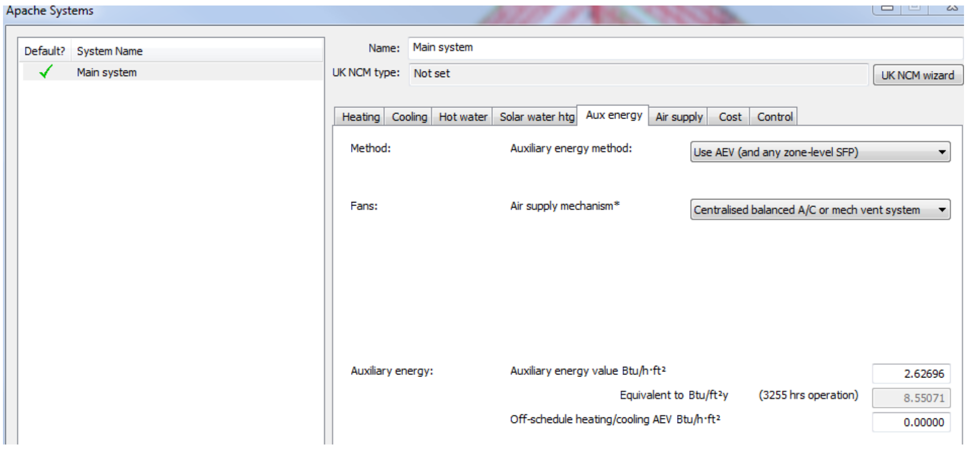


Figure A- 11:IES <VE> energy simulation model: auxiliary energy system settings. Image from the screen shot of the research model.

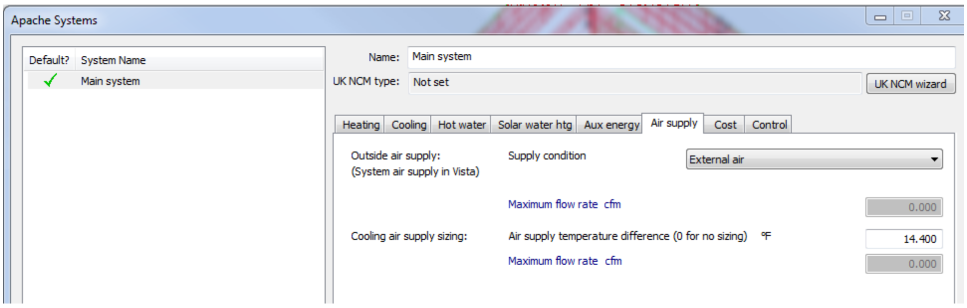


Figure A- 12:IES <VE> energy simulation model: air supply system settings. Image from the screen shot of the research model.

APPENDIX B LBNL REPORT OF THE PHOTO-GONIOMETRIC MEASUREMENT

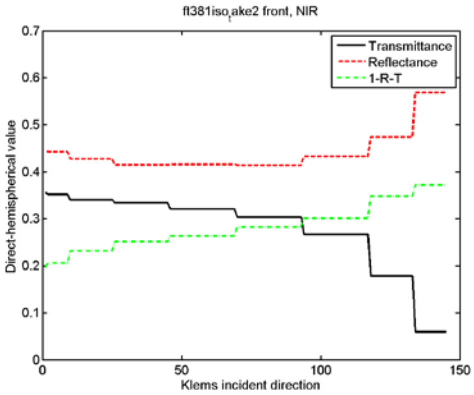
B.1 MATERIAL SUMMARY

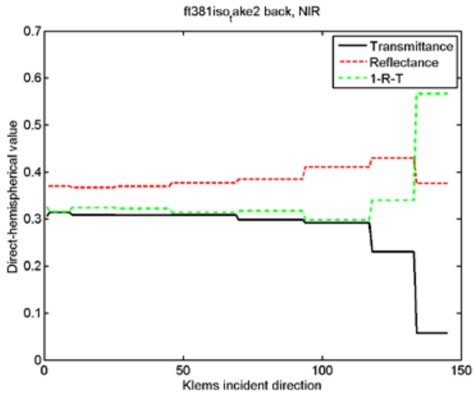
Property	Value
Name	Name
Manufacturer	Manufacturer
Thickness	0.001 Meter
IR transmittance	0
Emissivity, front	0.9
Emissivity, back	0.9
Conductivity	1

B.2 OPTICAL OVERVIEW

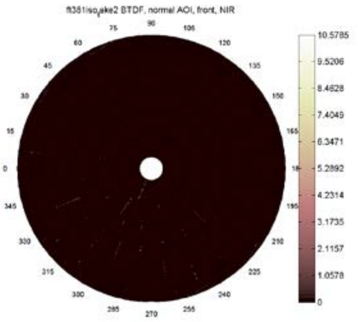
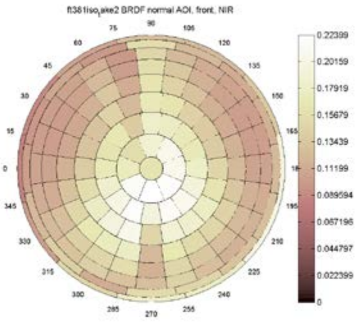
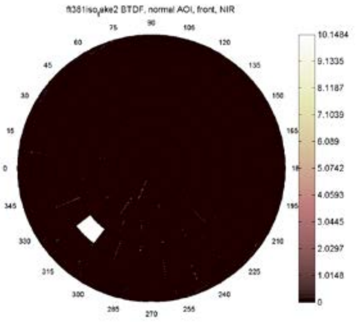
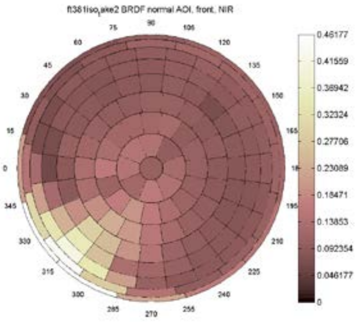
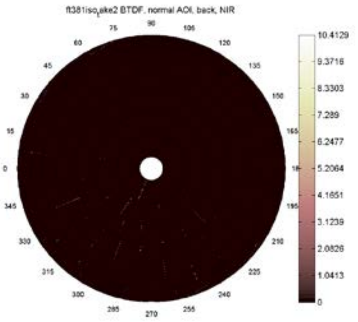
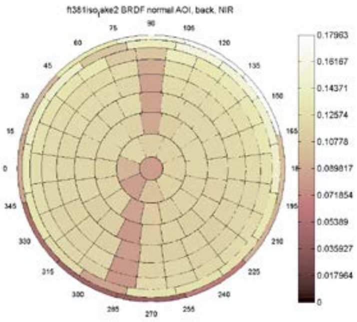
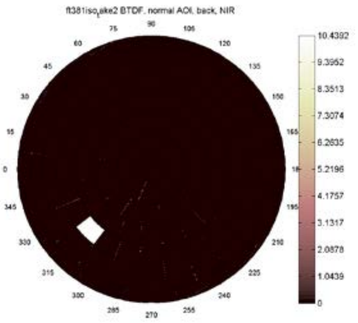
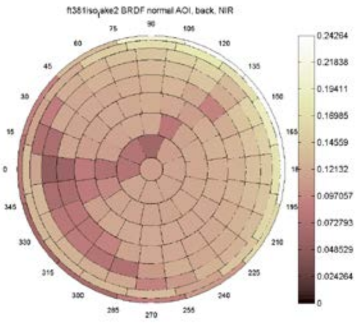
B.2.1 Wavelength: NIR

Direct-hemispherical values vs angle of incidence



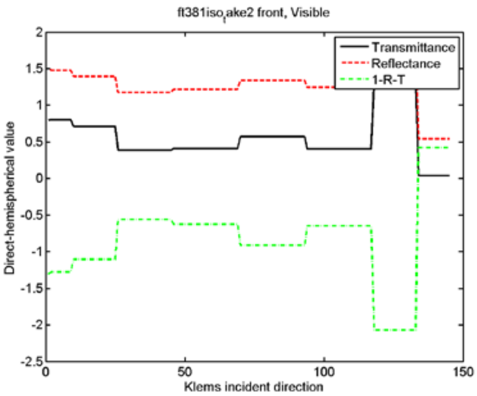


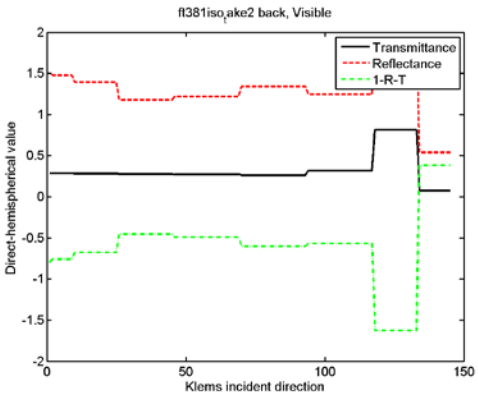
Projection on virtual hemisphere

Angle of Incidence	Transmittance	Reflectance
Normal AoI, Front		
50 deg AoI, Front		
Normal AoI, Back		
50 deg AoI, Back		

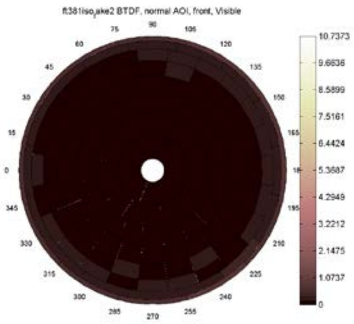
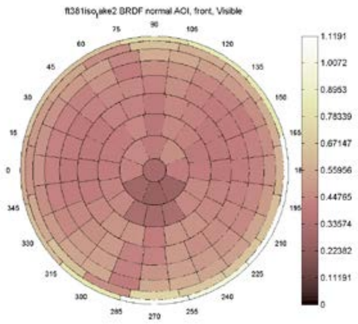
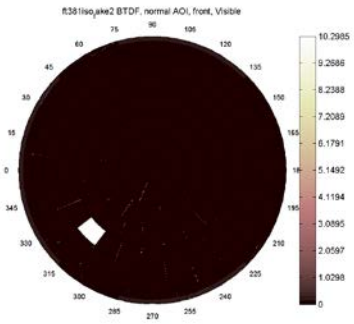
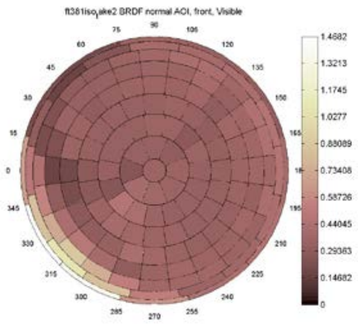
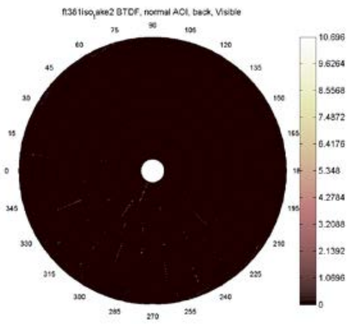
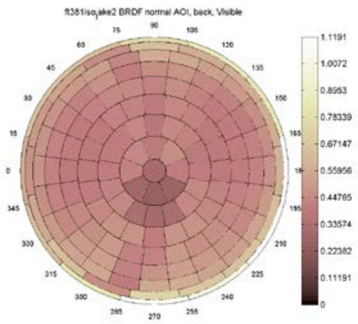
B.2.2 Wavelength: Visible

Direct-hemispherical values vs angle of incidence





Projection on virtual hemisphere

Angle of Incidence	Transmittance	Reflectance
Normal AoI, Front		
50 deg AoI, Front		
Normal AoI, Back		

50 deg AoI, Back