Comprehensive Performance Metrics for Complex Fenestration Systems Using a Relative Approach

by

Shreya H. Dave

S.B. Mechanical Engineering
Massachusetts Institute of Technology, 2009

SUBMITTED TO THE DEPARTMENT OF ENGINEERING SYSTEMS DIVISION AND THE DEPARTMENT OF MECHANICAL ENGINEERING IN PARTIAL FULFULLMENT OF THE REQUIREMENTS FOR THE DEGREES OF

MASTER OF SCIENCE IN TECHNOLOGY AND POLICY AND
MASTER OF SCIENCE IN MECHANICAL ENGINEERING
AT THE
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

FEBRUARY 2012

Signature of Author: ____
Department of Engineering Systems Division
Department of Mechanical Engineering
January 13, 2012

Certified by: ____
Marilyne Andersen
Associate Professor of Sustainable Construction Technologies
Ecole Polytechnique Federale de Lausanne
Thesis Supervisor

Certified by: ____
Leon Glicksman
Professor of Building Technology & Mechanical Engineering
Thesis Supervisor

Accepted by: ____
Dava J. Newman
Professor of Aeronautics and Astronautics and Engineering Systems
Director, Technology and Policy Program

Accepted by: ____
David E. Hardt
Ralph E. and Eloise F. Cross Professor of Mechanical Engineering
Chairman, Committee on Graduate Students

Comprehensive Performance Metrics for Complex Fenestration Systems Using a Relative Approach

by

Shreya H. Dave

Submitted to the Departments of Engineering Systems Division and Mechanical Engineering on January 13, 2012 in Partial Fulfillment of the Requirements for the Degree of Master of Science in Technology and Policy and Mechanical Engineering

ABSTRACT

Buildings account for over 40% of the energy consumption in the United States, nearly 40% of which is attributed to lighting. The selection of a fenestration system for a building is a critical decision as it offsets electric lighting use as well as impacts energy performance through heating and cooling systems. Further, the fenestration system contributes to both occupant comfort and ambiance of the space. Complex Fenestration Systems (CFS) address these factors with a variety of innovative technologies but the language to describe, discuss, and compare them does not exist. Existing traditional metrics for fenestration systems are unable to reveal the benefits that characterize complex fenestration systems because they are rigid, do not reflect annual performance, and were developed for a different purpose. The framework presented in this research offers a solution to this problem by using an annual climate-based methodology to provide a comprehensive evaluation of a system by incorporating three of the most relevant performance aspects: energy efficiency, occupant visual comfort, and ability to view through. Three metrics, the Relative Energy Impact (REI), the Extent of Comfortable Daylight (ECD), and the View Through Potential (VTP), were derived from these three criteria to express, in relative terms, a façade's contribution to building energy use, comfortable daylight conditions, and the degree of transparency, respectively. Several practical matters were considered when developing a policy-relevant set of metrics, including both ease of calculation for manufacturers and usability for consumers. As such, the calculation methodology evolved from its initial proposal into a simplified approach, analytical where possible, and into a label-like concept for visual representation. These metrics are intended to exist as a mechanism by which manufacturers can evaluate and compare façade systems, provide high-level intuition of relative performance for designers and contractors, and enable the balance of performance objectives based on user preference. Ultimately, the creation of this comprehensive language is intended to stimulate innovation in fenestration systems and encourage their use in both new and retrofit building applications.

Thesis Supervisor: Marilyne Andersen
Title: Associate Professor of Sustainable Construction Technologies, EPFL
Thesis Supervisor: Leon Glicksman
Title: Professor of Building Technology & Mechanical Engineering, MIT

Acknowledgements

First, I would like to thank Marilyne Andersen, supervisor and mentor, for being the most encouraging and compassionate thesis advisor I could ask for. Thank you for teaching me about the world through amazing experiences and for ceaselessly and tirelessly helping me to improve my work. These words cannot explain how much I have learned from you and how much I appreciate your support.

A hearty thank you also to my co-advisor Leon Glicksman for incredibly insightful feedback and a great perspective on my work. I have had a wonderful experience in BT, and many thanks to you for facilitating that through your vision and dedication.

I would also like to acknowledge the contributions of Mike Rubin and Lisa Heschong in helping me understand what I was trying to achieve by patient conversations and invaluable pieces of advice.

Thank you to the whole BT family – especially to my fellow Illuminatis: Jaime Gagne, Siobhan Rockcastle, and Kevin Thuot – for company, advice, and friendly faces in the now daylit lab space.

I would be remiss if I did not thank my great friends who have accompanied me on this graduate school journey. And finally, thank you to my family and especially my parents and sister, because without you I would not be who I am today.

Table of Contents

Table of Figures

Chapter 1
Introduction

The sun's rays are the Earth's ultimate source of energy. They provide fuel for plants to convert to usable energy which becomes sustenance for animals and eventually humans. Sunlight enables decomposition of organic matter that in due course returns as a fuel source in the form of fertilizer, natural gas, oil, or coal. Photovoltaic panels convert solar rays directly into electricity for human use and wind energy requires pressure gradients caused by temperature differences that are a result of the sun's interactions with the physical environment. The position of the Earth with respect to the sun is responsible for changes in seasons, on which the cycle of life is based in many species. Humans have evolved circadian rhythms driven by a response to sunlight and calendars were established based on sun position. Using the sun is as innate as it is prevalent in every aspect of life and civilization.

1.1 Daylighting in Buildings

The term "daylighting" refers to the use of natural light from the sun inside buildings and has implications in various aspects of the building's performance. Many of these interactions have been investigated in both research and practice, and have often become an inherent part of architectural designs and building construction. The use of daylight in buildings is not a novel concept. However, the reasons for and the ways in which we use daylight have changed with technological advancement, resource availability, and social paradigm shifts. Initially, civilization lived by the solar day, relying on the sun's light and heat for survival and supplementing it with an earthly version– fire. Fifteenth century cathedrals incorporated aesthetic form with the necessity of functional light with the use of stained glass windows (Figure 1). Despite handheld torches, terra cotta lamps, and early candles, daylight remained the predominant source of light well into the 1700s. With the sperm whale rush of 1751 came a commodity energy source that enabled reliable interior lighting, but even as it gave way to kerosene lamps, daylight was viewed as a valuable resource (Tertzakian, 2006). It did not cost money, produce smoke, or risk fires.

Once Thomas Edison invented and popularized the electric lighting element, the requirement of daylight inside a building relaxed considerably. In fact, a 1930 article from the *New York Times* presented the exciting concept of a "windowless buildings" – a building so climate controlled and perfect that it did not need windows, daylight, or any connection to the untame outdoors! Electric lighting was so convenient that it was sure to be the way of the future (Tallman & Keally, 1930). While Tallman and Keally were certainly not wrong in their assessment of the huge potential of electric lighting, they did not anticipate a trend towards increased glazing areas and desire for natural light in buildings. Today, the discussion has turned to the efficiency of electric lighting fixtures; countries such the European Union and Switzerland have begun to phase out the inefficient incandescent bulbs in favor compact fluorescent lighting (called the "bulb-ban") and light emitting diodes (LEDs) are becoming tailored for indoor lighting applications (Kanter, 2009). Meanwhile, skyscraper office buildings today are frequently covered in glazing, providing occupants in an increasingly digital world with a connection to the outdoors and natural light. Today, a climate-controlled space with comfortable lighting conditions at any hour but a view to the outside offers the best of all worlds, albeit at a substantial energy cost.

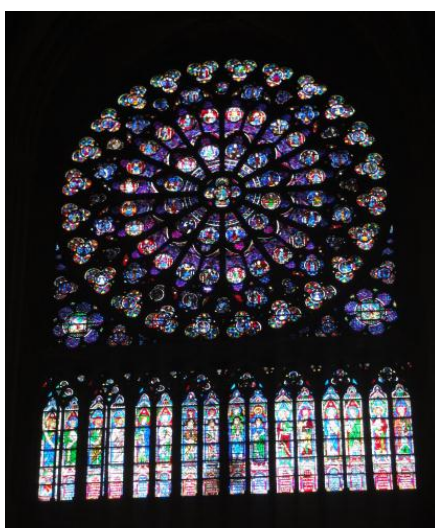


Figure 1: Stained glass admits daylight in 10th century cathedral Notre Dame de Paris.

Daylight affects energy performance of the building as well as occupant visual comfort, and subsequently to heath, well-being, and worker productivity. Daylight is a complex concept, dynamic in nature and subjective in interpretation. A number of innovative technologies have been developed to serve as fenestration systems (e.g. windows) to provide a modified, ideally more desirable, form of the raw daylight provided by the sun. The goal of this research is to develop and provide a language that can be used to evaluate and discuss these complex technologies in a framework that is intuitive and relevant to the building industry. The language is based on quantitative studies of daylight that provide insight into the complexity of its interactions with both the space and occupants. The following study acknowledges and appreciates both the quantitative impacts and qualitative aspects of daylight so that it can be enjoyed not only for its natural beauty but also for its ability to enhance the quality of an interior space.

1.2 Motivation for Using Daylight

1.2.1 Energy

Buildings in the United States account for about 42% of the nation's energy use (Energy Information Administration, 2010). Of this, an average of 38% can be attributed to lighting and 21% is due to the heating and cooling systems of a commercial building (EIA, 2010). Daylight affects these two aspects of a building's energy systems in specific and quantitative ways. First, using the sun's natural light can displace indoor electric lighting during the day. Artificial lighting provides a valuable service of lengthening the usable day and enhancing the ambiance of an interior space, but is dependent on electricity and affected by rising energy costs. Studies show that proper use of daylighting can reduce a building's total artificial lighting loads by 50 to 80% (Bodart & De Herde, 2002; Ihm et al., 2009), suggesting that a substantial portion of artificial lighting use can be eliminated. Even reducing the average artificial lighting load by just 10% for each building in the United States is equivalent to offsetting 1.8 billion gallons of gasoline over the course of a year (EIA, 2010).

Daylight also has potential benefits in heating applications. The sun's visible light corresponds to infrared heat that is also usable in its raw form. During heating seasons, contributions from the sun reduce the load for mechanical heating systems. Conversely, during cooling seasons, infrared solar heat adds to the load of mechanical cooling systems. Whether or not the overall heat gain is a net benefit to a space is highly dependent on system properties, climate, and seasonal operating conditions.

1.2.2 Comfort, Health and Productivity

In a talk she gave at MIT in 2011, Lisa Heschong commented that a study she conducted found that when considering daylight "more is better unless it is uncomfortable" (Heschong, 2011). This statement, although it might seem intuitive, summarizes the great implications of the role of daylight in the context of human factors. While occupant visual comfort is inherently a subjective concept, it is possible to value the benefits of comfort. Studies have shown that occupants prefer spaces with views (Keighley, 1973), perceive daylight as desirable (Kuller and Wetterberg, 1996), and that the presence of daylight contributes to overall well-being of the building's occupants (Farley and Veitch, 2001).

Attempts to measure well-being have been based in health benefits and worker productivity (Heschong et al., 2003; Edwards & Torcellini, 2002; Rashid & Zimring, 2008); studies are subsequently used to assess the cost-benefit tradeoffs of technologies and designs that improve daylighting conditions. Conversely, discomfort can be observed and measured using both user studies and predictive glare metrics (Wienold and Christoffersen, 2006). A serious challenge to working with daylight indoors is balancing its benefits with its risk of discomfort (Vos, 1999).

Humans have evolved to respond to the cues of natural light, using it to establish the internal biological clock (Rea et al., 2002). With Americans spending increasing fraction of their time indoors, an emerging concern is being exposed to sufficient daylight to regulate their circadian rhythm (Rea et al., 2002). The amount of daylight exposure is also correlated with serotonin turnover in the brain, a deficiency of which causes Seasonal Affective Disorder (SAD), or severe mood impacts as a result of insufficient daylight (Lambert et al., 2002). Rosen et al. found that about 10% of survey respondents in Nashua, NH experienced mood change associated with SAD (1990).

Furthermore, students have been shown to work about 20 to 26% faster, improve 19 to 20% faster, and achieve scores about 7 to 18% higher on tests when sitting near daylight or being exposed to natural light (Heschong et al., 1999). In offices, workers were found to perform 10 to 25% better on tests that require mental function and memory recall and process work 6 to 12% faster (Heschong et al., 2003). Workers in daylit spaces report fewer ailments such as headaches or eyestrains and studies have shown a correlation between daylight and reduced absenteeism (Edwards & Torcellini, 2002; Rashid & Zimring, 2008). These staggering statistics can be valuated over the building's life of about 20 to 50 years to provide benchmarks for potentially huge monetary benefit of investing in daylighting or window technologies.

1.3 Challenges of Using Daylight

There are a number of characteristics of daylight that make working with it difficult, presenting both challenges and opportunities for architects and the designers of fenestration systems. These fundamental principles are presented here and provide insight into the crucial considerations of its behaviors that need to be addressed when communicating about daylight.

Daylight is highly dynamic due to weather and other interruptions. From moving clouds to leaves rustling in the wind, the variables that interact with daylight between the sun and an interior space are entirely unpredictable and unique in almost every instance. The weather, the climate, and the obstructions between a window façade and the sun present a substantial variety of potential daylight conditions. Assumptions of clear skies and constant solar radiation simply overestimate the role of daylight in a built space. But statistical climate data can be used to address aspects of uncertainty related to weather.

The sun's position is not static. As the sun moves across the sky over the course of a day, the shadows inside a space shift correspondingly. And, as a result of the Earth's orbit, the sun's position at noon on one day will not be exactly the same as noon the next. While an assumption about a single sun position is an over-simplification, its position can be predicted mathematically based on a location's position relative to the sun, both with respect to longitude and latitude as well as orientation.

Daylight can cause glare. Glare is a complex concept, fundamentally defined as the discomfort associated with high contrast ratios, and illustrated by the challenge of viewing a computer screen under direct sunlight (Ruck et al., 2000). Daylight is more difficult to control in this aspect than artificial lighting and often spaces are not designed to mitigate glare situations. Glare assessment methods and metrics are discussed in the following chapter and the benefits of daylight must be considered in parallel with the potential for discomfort of occupants.

Without redirection, daylight is concentrated near façade openings. Whether next to a window or on the top floor of a building with skylights, daylight is limited to direct access to an opening. The bottom floor of a multi-story building will not benefit from a skylight and a desk far away from a window may not see any benefit at all from natural light. By contrast, light levels directly adjacent to the façade may cause discomfort, forcing the closing of blinds and blocking much of the incoming light, affecting other areas that may have been comfortable. The role of daylight distribution is as important as quantity of light admitted into a space.

Finally, the way in which daylight is treated today is very dependent on human behavior, which is imperfect. Blinds or shades are the most common method of dealing with uncomfortable daylight, and typically these are manually operated. Unfortunately, occupants tend to adjust blinds manually only when discomfort is perceived. Once corrected, the blinds will often stay closed throughout the rest of the day's potentially comfortable conditions (Reinhart and Voss, 2003). Automatic blinds are sometimes introduced in commercial buildings, but have not achieved unilateral success as a result of unreliable machinery and the perceived lack of control for the occupants (Ruck et al., 2000). Reducing the reliance on occupant behavior to access the benefits of daylight has significant potential in addressing one of the most uncontrollable aspects of daylight.

1.4 Research Goals

Daylight, governed by laws of thermodynamics, characterized by seasonal and climate conditions, and perceived by humans with subjective judgment, is not a simple concept to describe or prescribe for buildings. Traditional metrics have been developed to describe technical specifications of standard fenestration systems, daylight distribution of a particular space, and general information about visible transmittance. Meanwhile, complex fenestration systems have been developed to address the many challenges of using daylight inside a space, utilizing dynamic, spectral, and angular response approaches. These traditional metrics, described in Chapter 3, cannot be used to describe complex fenestration systems because they do not consist of enough input detail to reveal subtle aspects of performance, rely on a user's ability to extrapolate behavior, and most fundamentally, have been developed for a different purpose.

The ability to converse about daylight and complex fenestration systems in a standard way would enable a transformation in the building industry in the understanding of daylight and its interactions with the built environment. Such an understanding presents opportunities for further technological innovation, knowledge-based design, and increased successful implementation of daylight in the building system. Complex fenestration systems present potential for increased performance of built space, but cannot be discussed because the language does not exist. The decision to use performance metrics as a basis for this language is discussed in greater detail in Chapter 2. The goal of the research presented in this thesis is to develop policy-relevant metrics that provide insight and intuition about the performance of complex fenestration systems. More specifically, we will propose metrics that can:

1) Reveal the dynamics and benefits of complex fenestration systems, concisely;
2) Provide intuition to the user about system performance;
3) Address both energy and human factor performance aspects in the same framework;
4) Exist in a structure that can be presented visually as on a label.

Three relative performance metrics have been proposed to address three separate criteria identified as being relevant to the performance of fenestration systems. The three criteria are energy performance, occupant visual comfort, and ability to view through. The three performance metrics are as follows:

1) **Relative Energy Impact (REI)**: The total energy load attributed to the fenestration system, reported as relative to a reference case.
2) **Extent of Comfortable Daylight (ECD):** The percent of time and space which achieves comfortable daylight conditions, reported for a fenestration system relative to a reference case.
3) **View Through Potential (VTP):** The degree of transparency of a fenestration system as it relates to an occupants ability to see a faithful image of the view beyond the façade.

These three performance metrics provide the basis for evaluation, comparison, and discussion of complex fenestration systems. They exist in the same framework such that inherent tradeoffs can be identified and provide users with the power to select their own priorities. In a world concerned with rising energy costs, the metrics presented here allow for reduced energy consumption by making compromises on other aspects of system performance that are deemed acceptable by decision-makers in the industry.

1.5 Thesis Overview

Chapter 2 presents further context for the research that leads to the development of the three relative performance metrics. It includes an introduction to complex fenestration systems, a discussion of the mathematical dataset used to describe the behavior of these systems, and an explanation of terminology used in the policy framework for the rest of the thesis. And it is followed by an overview of existing traditional metrics used to describe energy efficiency, daylighting, and view through fenestration systems (Chapter 3). Each of these metrics informs the development of new performance metrics, but exhibit limitations that make them, in their current form, insufficient.

Chapter 4 then presents the approach and research framework developed for defining, evaluating, and assessing the metrics, including a justification for use of a relative approach and a description of input parameters. In doing so, the challenges of working with daylight are addressed and considered in the context of rating the performance of fenestration systems according to the three performance criteria indicated previously.

Chapters 5, 6, and 7 each focus on the development of one metric: the REI, ECD, and VTP respectively. Each chapter first introduces the goal of the metric and describes the initial calculation methodology that is used to arrive at quantitative values. This method is then revisited through sensitivity analyses that identify critical parameters and an approach to reduce the complexity of the calculation process and increase the usability of the final form of the metrics. For the REI and ECD metrics, which rely on some degree of annual simulation, analytic analysis provides some additional insight into potential areas of further research. Finally, each metric is validated with a study that has been developed to assess a critical component of the metric definition and presented in its final form via a label concept that could be used to describe complex fenestration systems in practice.

The new work of this research concludes in Chapter 8 with an analysis of the role of these metrics in the current policy context. In addition to a summary of current efforts, a proposed workflow for engaging the use of these metrics in the context of policy frameworks is discussed. Further, important considerations of using numbers in the polis are summarized and discussed. Chapter 9 reviews the achievements and results of this research and provides a description of potential areas for future work.

Appendix A provides some generally applicable additional information for this thesis. Appendices B, C, and D include results from the REI, ECD, and VTP metric development processes respectively.

Chapter 2
Research Context

In this work, three relative performance metrics are presented as a viable approach to describe complex fenestration systems. In order to define these metrics, it is important to understand the degree of variety that exists in the category of complex fenestration systems, the data available for assessment, and the role of metrics in a policy context. This chapter introduces categories of complex fenestration systems, presents the specific systems used for the evaluation in this research, and presents the current mathematical description of their behavior, known as the BTDF. These fundamentals are used in the definition and analysis of the relative performance metrics. Finally, this chapter introduces the terminology used when describing aspects of fenestration systems, façades, and buildings in policy and presents a case for the use of relative performance metrics for complex fenestration systems as opposed to the existing traditional metrics used for standard fenestration systems.

2.1 Complex Fenestration Systems

Complex fenestration systems (CFS) include a broad range of novel technologies that exert greater control of incoming daylight than a standard fenestration system can. The term “fenestration,” by definition, refers to windows, skylights, and doors (NFRC, 2010), but for the purposes of this document, complex fenestration systems will refer to window façade replacements, i.e. vertically oriented systems on walls. Five sample complex fenestration systems with varying properties were identified to represent a range of systems for evaluation.

CFS can be categorized by their physical installation requirements; some require modification of existing construction while others fit into the structure of standard fenestration systems. For example, light pipes bring light to lower floors of a multistory building by using optical reflections to guide sunlight through a cylindrical surface and exposing it below. By contrast, a diffusing panel is designed to produce more homogeneous illumination inside by redirecting light equally in many directions. This system can be considered physically as simply a “replacement window” with different properties (lower view, different light distribution etc.). A third category includes additional components to existing windows that modify the light and heat transfer across the fenestration system. For example, external blinds reject solar heat gains when the sun is above a certain angle, but allow skylight and direct sunlight from lower angles. Here, we look at complex fenestration systems that span the latter two categories described; comparing a structurally different system such as a light pipe to a standard window or skylight is not relevant because such a system is so involved in design decisions that are unrelated to the fenestration system.

CFS have been developed by manufacturers to achieve a variety of optimized performance objectives (International Energy Agency, 2000; Kischkoweit-Lopin, 2002). A relevant way to categorize complex fenestration systems is according to their performance objectives. An interactive database of complex fenestration systems, D-LITE, uses four criteria to describe these objectives: depth of daylight penetration, control of solar gains, privacy, and glare control or shading (Rosa and Urbano, 2008). Deeper daylight penetration is typically be accomplished by redirecting incoming light in a manner such that it can illuminate a greater proportion of the interior space. Control of solar gains requires less admittance of direct light into the space during cooling seasons, which can be accomplished by shading or by a very low transmittance of light. Privacy indicates that the fenestration system disrupts or distorts the incoming light such that a view through from the outside is not permitted. And finally, glare control suggests that shading is implemented so that direct light will reach the eyes of occupants or surfaces that are highly reflective and may cause glare.

Complex fenestration systems are designed to achieve one or more of these criteria and so each should be revealed by the proposed performance metrics. Thus, a set of complex fenestration systems were selected to create a balanced performance objective portfolio. As shown in Table 1, each criterion has two or more systems whose properties were developed to achieve it.

Table 1: Complex fenestration systems that aim to address a variety of performance objectives.

	Prismatic Panel	Mirrored Blinds	Holographic Optical Element	Opalescent Plexiglass	Fabric Blind
Depth of daylight penetration	✓	✓	✓		
Control of solar gains		✓	✓	✓	
Privacy				✓	✓
Glare control/Shading	✓	✓		✓	✓

More qualitatively, each system aims to achieve these objectives in unique ways.

(a) *Prismatic Panel*: A prismatic panel is intended to increase the depth of daylight penetration by redirecting incoming light toward the ceiling where it can then be reflected towards the work surface. Doing so also aims to reduce the direct light that may reach seated or standing occupants. The system is composed of horizontal prisms that appear as stripes and disrupt an occupant's view.

(b) *Mirrored Blinds*: Blinds are added to the exterior of an existing fenestration system to control solar gains as well as glare by reflecting incoming light above a certain angle away from the interior of the space. The blinds assessed are exterior blinds with a mirror surface and are user operated. The spacing of these blinds is about five centimeters and the unobscured portion of the façade provides a clear view to the outside.

(c) *Holographic Optical Element (HOE)*: A holographic optical element uses a film that refracts light to achieve distributional effects in a manner analogous to the three-dimensional images created by holograms. The system spreads the light inside the space, creates a rainbow effect on the façade surface, and offers no protection to solar heat gains or glare.

(d) *Opalescent Plexiglass*: This diffusive surface provides very even distribution of light inside, but transmits very small quantities of light as compared to the other systems by exhibiting a near-perfect lambertien effect in redirecting incoming light in all emerging directions equally. It provides no view to the outside but reduces glare source risk and solar gains associated with direct light considerably.

(e) *Fabric Blinds*: Fabric blinds are also used in addition to the existing standard fenestration system to reduce direct daylight that causes glare. They are interior, user operated, and do not control solar gains. These blinds are directionally diffusive, but a direct light source behind the blinds would be identifiable.

The visual perception of each fenestration system may be unique to each user, but certain traits can be characterized. Figure 2 shows three aspects of each fenestration system. The first row depicts a very simple schematic of the system's cross-section. The second row shows a photograph of each physical system, taken at normal incidence, and compared to the clear view obtained at the top of each frame. And the third row provides a light distribution rendering from the inside of a rectangular room for each fenestration system at 9:00am on December 21 in San Francisco, CA. The photographs and renderings both show the variety in physical and performance aspects of each complex fenestration system.

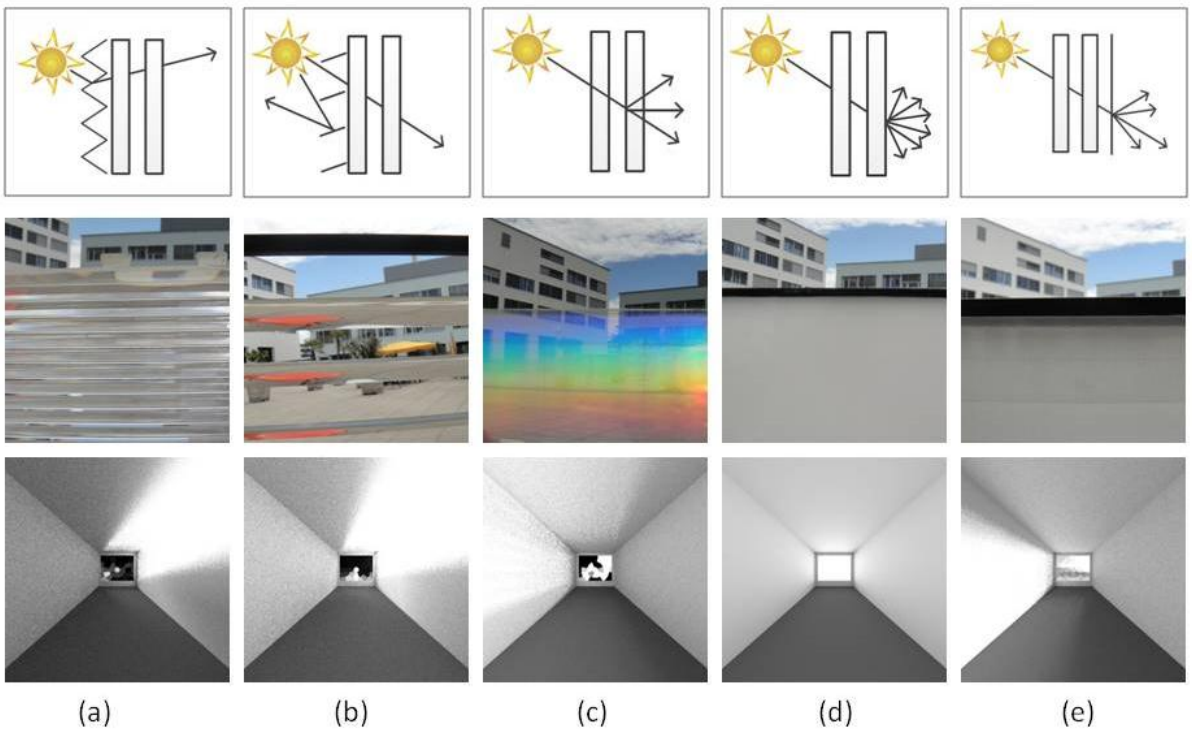


Figure 2: Five CFS used for analysis in this work: (a) Prismatic Panel, (b) Mirrored Blinds, (c) Holographic Optical Element, (d) Opalescent Plexiglass, and (e) Fabric Blinds.

Quantitatively, cross-section schematics and quantitative system specifications for each of the five systems are shown below in Table 2. These, along with each system's unique BTDF (introduced in the next section), are considered material properties for each complex fenestration system evaluated in this work.

Table 2: System specifications for five selected CFS, layers reported from outside to inside.

	Clear	(a) Prismatic Panel	(b) Mirrored Blinds	(c) Holographic Element	(d) Opalescent Plexi	(e) Fabric Blinds
Number of layers	2	3	3	3	3	2
Thickness (material) Layer 1	0.0032 mm (glass)	0.0032 mm (acrylic)	0.0016 mm (aluminum)	0.0032 mm (glass)	0.0032 mm (glass)	0.0032 mm (glass)
Thickness (material) Layer 2	0.0032 mm (glass)	0.0032 mm (glass)	0.0032 mm (glass)	0.0005 mm (acrylic)	0.0032 mm (acrylic)	0.0032 mm (glass)
Thickness (material) Layer 3	--	0.0032 mm (glass)	0.0032 mm (glass)	0.0032 mm (glass)	0.0032 mm (glass)	--
Thickness (gas) Gap 1	0.0128 mm (air)	0 mm	--	0 mm	0 mm	0.0128 mm (air)
Thickness (gas) Gap 2	--	0.0128 mm (air)	0.0128 mm (air)	0.0128 mm (air)	0.0128 mm (air)	--
NFRC reference U-factor	2.4 W/m^2K	2.3 W/m^2K	2.4 W/m^2K	2.4 W/m^2K	2.3 W/m^2K	2.4 W/m^2K

2.2 The Bidirectional Transmission (Reflection) Distribution Function (BT(R)DF)

Each metric proposed in this thesis is based most fundamentally on the mathematical description of the complex fenestration system behavior, known as the bidirectional transmission (reflection) distribution function (BT(R)DF). The transmission component of this dataset, the BTDF, relates incident and emerging angles of light transmission across a surface, angularly describing in discrete quantities where light is distributed on the emerging side. This enables a user to identify not only how *much* light is transmitted, but in what directions and is related to similar work in Fresnel lens development.

Originally proposed in 1970, BT(R)DF mathematically describes the behavior of light as it passes through or reflected from a façade by the ratio between the emerging surface radiance (W/m^{2}sr) and the incident surface irradiance (W/m^2) (Nicodemus, 1970; Nicodemus et al., 1977). This thesis uses only the BTDF component, as datasets for the BRDF are even less available than those of the BTDF.

The following equation shows the BTDF, defined as a photometric quantity by the Comission Internationale de l'Eclairage (CIE, 1977).

$$BTDF(\theta_1, \phi_1, \theta_2, \phi_2) = \frac{L_2(\theta_1, \phi_1, \theta_2, \phi_2)}{E_1(\theta_1)} = \frac{L_2(\theta_1, \phi_1, \theta_2, \phi_2)}{L_1(\theta_1, \phi_1) \cdot \cos\theta_1 \cdot d\omega_1} \qquad \mathbf{1}$$

where,

- (θ_1, ϕ_1) and (θ_2, ϕ_2) correspond to incoming and emerging elevation and azimuth angles respectively, expressed in radians;
- $L_1(\theta_1, \phi_1)$ and $L_2(\theta_1, \phi_1, \theta_2, \phi_2)$ correspond to the luminances of incoming and emerging light flux, expressed in Cd/m^2;
- $d\omega_1$ is the solid angle subtended by the incoming light flux, expressed in steradians (sr);
- And $E_1(\theta_1)$ refers to the illuminance on the sample plane due to incident light flux, in lux.

The BTDF angle convention used is defined for international use in the International Energy Agency's Task 21 (IEA, 2000). Care must be taken when switching between conventions from data sets to applications. The IEA Task 21 convention used here is shown in the schematic representation of the BTDF shown below in Figure 3 (Andersen, 2002).

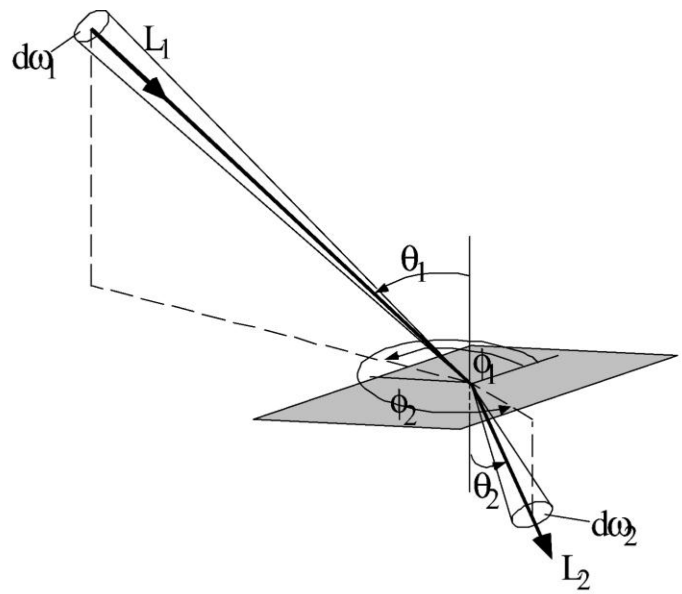
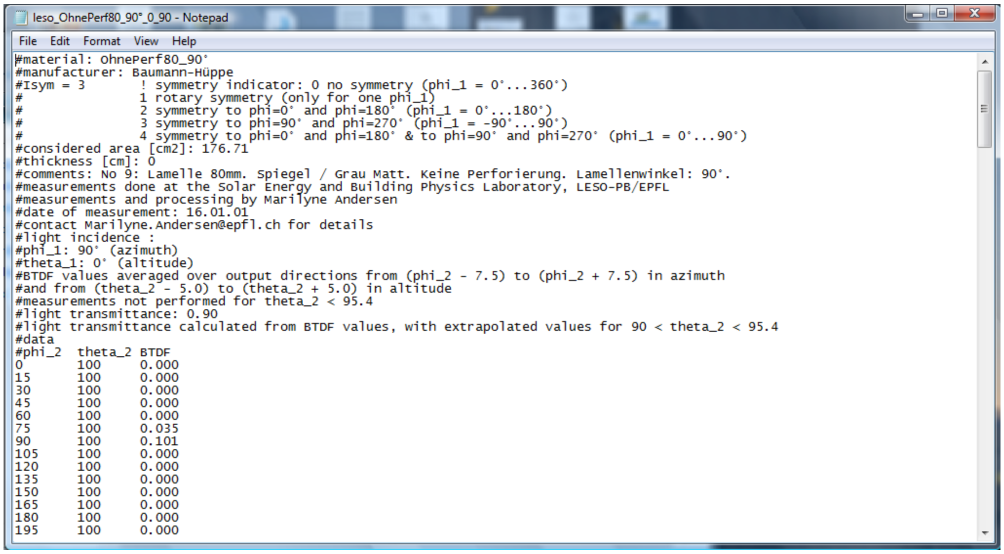


Figure 3: Schematic of photometric and geometric quantities in the definition of a BTDF (Andersen, 2002).

The BTDF exists in the form of quantitative datasets; a screenshot for a single incident condition is shown in Figure 4. These datasets can be generated either by measurement or by simulation. Measured data is a more accurate representation of a surface's behavior because simulations often rely on simplifying assumptions about ideal behavior (Window 6, 2010). For example, a simulated BTDF for a clear window achieves nearly 100% transmission with zero scattering (Window 6, 2010). Measured BTDFs are time consuming and often computationally expensive to generate, but provide insight about the actual properties of a material or façade construction.

A bidirectional video-goniophotometer that uses a Charge-Coupled Device (CCD) camera has enabled the development of a relatively extensive database of BTDFs for a range of advanced fenestration systems (Andersen, 2004). This innovation allows the data collection to be gathered in a complete, rather than discrete, manner, and reduces the gathering time by more than 80% (Andersen and de Boer, 2006). It was from this database that samples were selected for analysis in this research.



```
leso_OhnePerf80_90°_0_90 - Notepad
File  Edit  Format  View  Help
#material: OhnePerf80_90°
#manufacturer: Baumann-Hüppe
#Isym = 3        ! symmetry indicator: 0 no symmetry (phi_1 = 0°...360°)
#                1 rotary symmetry (only for one phi_1)
#                2 symmetry to phi=0° and phi=180° (phi_1 = 0°...180°)
#                3 symmetry to phi=90° and phi=270° (phi_1 = -90°...90°)
#                4 symmetry to phi=0° and phi=180° & to phi=90° and phi=270° (phi_1 = 0°...90°)
#considered area [cm2]: 176.71
#thickness [cm]: 0
#comments: No 9: Lamelle 80mm. Spiegel / Grau Matt. Keine Perforierung. Lamellenwinkel: 90°.
#measurements done at the Solar Energy and Building Physics Laboratory, LESO-PB/EPFL
#measurements and processing by Marilyne Andersen
#date of measurement: 16.01.01
#contact Marilyne.Andersen@epfl.ch for details
#light incidence :
#phi_1: 90° (azimuth)
#theta_1: 0° (altitude)
#BTDF values averaged over output directions from (phi_2 - 7.5) to (phi_2 + 7.5) in azimuth
#and from (theta_2 - 5.0) to (theta_2 + 5.0) in altitude
#measurements not performed for theta_2 < 95.4
#light transmittance: 0.90
#light transmittance calculated from BTDF values, with extrapolated values for 90 < theta_2 < 95.4
#data
#phi_2  theta_2 BTDF
0       100     0.000
15      100     0.000
30      100     0.000
45      100     0.000
60      100     0.000
75      100     0.035
90      100     0.101
105     100     0.000
120     100     0.000
135     100     0.000
150     100     0.000
165     100     0.000
180     100     0.000
195     100     0.000
```

Figure 4: Screenshot of measured BTDF (Andersen, 2004).

The improved accuracy of BTDF datasets is important to the future of metrics proposed in this work, but outside the scope of this study. The research presented here is a framework that will ultimately require accurate data inputs for veritable performance rankings but has been established based on current best available data. There is not yet a standard methodology for measurement and accuracy considerations of BTDFs that can be used across different manufacturers or research institutions. Moreover, a strong demand for BTDFs does not exist because they are large, unwieldy, and require significant analysis to provide useful information. Each of these creates barriers to development of widespread BTDF measurement and use. Efforts are currently underway to standardize the measurement and calibration of BTDF quantities (NFRC, 2011) and popularizing metrics that rely on measured BTDFs would encourage their creation and thus improve the quality of the databases and in turn, benefit the accuracy of the metrics.

2.3 Policy Terminology

To precede a discussion of metrics in policy, a number of terms are defined here in the context of buildings, the policy that governs them, and the work that follows in this thesis. This terminology, although potentially interchangeable, can be used to establish a baseline for understanding the contributions of this work.

Building *codes* are enforceable documents that are mandated by state and federal government regarding any critical component of a building. For example, structural codes ensure stability and fire codes govern aspects related to fire safety.

Building *standards* are created by independent organizations and provide guidelines for recommended performance. The American Society for Heating, Refrigeration and Air-Conditioning Engineering (ASHRAE) creates the building industry’s most widely recognized standards in the United States. Although written in enforceable (code) language, these documents are not enforceable unless a code specifically references adherence to a particular standard.

Technical *specifications* describe various components of building construction in quantitative terms. While some specifications are intuitively accessible to a layperson, others appear disconnected from the aspects that affect an occupant. Users typically do not consider the load bearing ability of a beam unless they are concerned specifically with the structural integrity of the building. Meanwhile, the recommended depth of a step on a staircase is something that users do interact with on a regular basis. Specifications are reported in their most fundamental technical terms.

The term *performance criteria* refers to aspects of building performance that can be described qualitatively or defined quantitatively. A relevant performance criterion of a mechanical heating system may be internal thermal comfort for occupants which can then be measured using a number of different models for thermal comfort whereas the technical specification would be the fan throughput. An even less glamorous performance criteria is a roof's ability to prevent water from entering the space. Whereas the size or load rating of the mechanical heating system and the roof's total porosity are specifications, what they describe is often a relevant performance criteria.

Indicators of performance may also be quantitative or qualitative and describe performance criteria indirectly. To continue the preceding examples, an indicator of thermal comfort may be users who do not complain or adjust the thermostat often. An indicator of roof's resistance to water penetration may be the absence of leaks. Indicators are indirect, and do not necessarily describe causal relationships, but may provide further insight into performance.

Finally, *metrics* are ways in which performance can be described in a quantitative manner. A metric for artificial lighting energy efficiency is the Watts per square meter of floor area that are required to light the space. This value is directly comparable across different buildings and types of space, and provides a user with a specific component of performance. In this example, the performance criteria is artificial lighting energy efficiency, a technical specification is the power consumption per lumen produced by the bulbs selected for use, and an indicator may be cooling loads associated with the space (more inefficient lights require additional cooling of waste heat).

2.4 A Need for Relative Performance Metrics for CFS

Metrics as a category of quantitative measures can be further divided into two categories. In this work, relative performance metrics aim to replace traditional metrics to provide more insight, greater flexibility, and improved accuracy of complex fenestration behavior perception.

Traditional metrics are often be used interchangeably with technical specifications. A material property that is easily categorized as a technical specification is its thermal conductivity (W/mK). This specification has been modified for surfaces to describe a material's resistance to heat flow across in the form of the U-factor; its reciprocal is also known as the R-value. The U-factor is a traditional metric that is used to describe wall constructions, insulation, fenestration systems, and basement foundations. Because traditional metrics are specific in their description, standards based on traditional metrics often prescribe a solution *a priori*. For example, energy standards that prescribe minimum U-factor and insist on achieving energy performance by reducing heat flow across the surface of materials.

By contrast, a *performance metric* describes the desired outcome, rather than the requirements for the process or approach to produce it (ASME, 2004). Where the performance criterion is energy efficiency, performance metrics that quantify and describe energy efficiency provide room for multiple methods of achieving it. Descriptive standards that are based on performance metrics allow for innovation and development in achieving the goal, whether it be structural integrity or energy efficiency. However, performance metrics in practice must also be wary of being too broad and not enforceable. Performance metrics that encompass too many components and potential choices for the user may provide little benefit to the policymaker.

In the case of complex fenestration systems, the traditional metrics that have been defined for standard fenestration systems rely on a certain amount of intuition and basic assumptions about behavior and thus, cannot be directly transferred to complex fenestration system. More specifically, traditional metrics that describe fenestration systems rely only on a single set of environmental and incident conditions (NFRC, 1999). This simplification necessarily assumes that users have the intuition to extrapolate behavior (or do not require it to make decisions), but these assumptions do not extend to more complex fenestration systems. For example, the window-to-wall ratio indicates the portion of a façade that is dedicated to windows. For a standard fenestration system, this value is correlated with increased daylight, solar heat gains, and resistive heat transfer out in a predictable way for a given climate zone. Whereas a maximum window-to-wall ratio provides a mechanism for reducing energy use due to standard fenestration systems, it precludes the use of complex fenestration systems that do not behave as assumed by the metric.

In an effort to include non-typical components of buildings, such as complex fenestration systems, in building standards, certain standards provide dual approaches for adherence. ASHRAE 189.1, the standard for high-performance green buildings, provides prescriptive requirements as well as the option for full building energy simulation to predict performance (ASHRAE 189.1, 2009). This approach is not ideal for two reasons: First, the designated simulation software, EnergyPlus, does not use BTDFs in heating and cooling analysis of buildings and although it does use BTDFs for lighting, the interface is not yet seamless. Second, because of the complexity and interactions of the energy simulation software, decisions made about the fenestration system may be difficult to deduce from results. Incorrectly attributing an aspect of performance to the fenestration is worse than not assessing it at all. For these reasons, and in response to demand from the building industry, the National Fenestration Rating Council (NFRC) has specifically identified developing metrics for complex fenestration systems as a priority for Phase II of the Daylighting Subcommittee/Daylight Potential Task Force (McGowan, 2011).

Performance metrics that describe complex fenestration systems can address each of the issues presented in this section. Because they are not technical specifications, performance metrics will aid users in understanding the behavior of complex fenestrations intuitively. They will also contribute to reducing the dependency of "all or nothing" approaches to energy standards in terms of simulation; the select processes selected for determining the performance metrics enable descriptive standards without the use of full building energy simulation which does not yet have the functionality required to evaluate complex fenestration systems. Moreover, performance metrics do not rely on users to extrapolate behavior because they rely on actual data, creating a more comprehensive feedback loop where intuition may not exist.

And finally, the performance metrics presented in this work provide a mechanism to allow assessment of multiple aspects of performance *on a comparative basis*. All three metrics presented are relative to a reference case, and are system-specific, rather than the current combination of system-specific energy metrics and space-specific daylighting metrics. Assuming full energy and daylighting analyses are both conducted, it is difficult to assess tradeoffs in each of these performance aspects; whereas energy metrics are system-specific, daylighting metrics are space-specific and without directly comparable metrics, intuition plays a significant role in evaluating tradeoffs. Furthermore, when these simulation analyses are used, they are often applied so late in the design process – because details about the building are required as inputs – that few significant changes can really be implemented. Creating the simulations and analyzing the results are also not necessarily feasible in all building design proposals as they require both time and expertise to conduct. Finally, relating the behavior of a complex fenestration system in a specific scenario (location or orientation) to the behavior of a simple fenestration system in the same scenario allows the user to perceive the system physically and understand it more intuitively.

The proposed metrics also enable users to dictate precedence in performance criteria. Although the Relative Energy Impact (REI) can reveal "better" energy performance with respect to another façade, the metrics make no attempt to suggest that energy performance is a higher priority than visual comfort, described by the Extent of Comfortable Daylight (ECD), or a view to the outside, described by the View Through Potential (VTP). Manufacturers should not be required nor encouraged to develop systems that achieve high metric rankings but do not satisfy user priorities, the "demand" of the industry, whether they are a function of building codes or individual preference.

The building industry is a unique combination of technical engineering expertise and artistic form through architecture. Often, these disciplines clash, the former being preoccupied with optimized performance and the latter focusing on creating spaces for human occupants. There is a general lack of communication between the two groups, resulting in a design process that is fragmented, inefficient, and resulting in less than desirable outcomes. Projects at MIT and ÉPFL, among other institutions, traverse this boundary by developing software such as CoolVent or Lightsolve which enable designers and architects to make intelligent technical decisions about buildings without requiring significant expertise in each area (Menchaca and Glicksman, 2008; Andersen et al., 2006). The role of performance metrics complements these efforts by providing another mechanism for information transfer between technical experts and decision-maker designers.

Chapter 3
State of the Art

Significant amounts of information can be obtained from the existing traditional metrics that are used to describe energy specifications of standard fenestration systems, daylight through simulation analysis and view through via visual observation of a building space and its fenestration system. However, each of these metrics has been developed for a specific purpose such that they cannot describe a complex fenestration system and its performance on an annual basis. Some energy metrics relate to the fenestration, while others reference the building system, and daylight metrics tend to be highly dependent on spatial geometry. These various frameworks, structures, and goals achieved by existing metrics do not allow a user to select a complex fenestration system based on his or her individual priorities in performance.

For example, a clear view to the outside might trump any other characteristic of the system (or, vice versa, privacy with good daylight performance might be a requirement). Meanwhile, in a highly-constrained environment, reducing cooling loads might be the single most critical design feature of not only the fenestration system, but the entire building. The information to make these comparisons is present in the literature, and although some metrics have been incorporated into industry practice, explicit rating systems for complex fenestration systems do not exist.

The ability to identify tradeoffs and select a fenestration system based on user-defined priorities are key components of the performance-based metrics presented in this research. The development of these metrics for complex fenestration systems builds on the substantial literature that describes validated energy and daylighting metrics. This relevant literature is summarized here.

3.1 NFRC Rating System

The National Fenestration Rating Council (NFRC) establishes guidelines and protocol for the calculation of the most widely used rating specifications for fenestration systems in the United States. The NFRC then regulates the fenestration industry by requiring manufacturers to calculate and display their products' specifications on a label that is designed for consumer understanding. An example label for a fictitious window is shown below in Figure 5 (NFRC, 2011).

Figure 5: NFRC sample label for windows (NFRC, 2011).

These specifications are used as traditional metrics in building standards such as the ones published by the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) (ASHRAE, 1999; ASHRAE, 2009). Local and state governments then use selected standards for building codes and are responsible for enforcement. As mentioned previously, the building codes are the only enforceable documents, although ASHRAE standards are written in code language. While ASHRAE depends on the NFRC for the calculation methodologies of its system-specific traditional metrics, other descriptive quantities are used in its standards, such as the window-to-wall ratio (ASHRAE, 2009). Examples of both widely used and more recently developed metrics are presented in the next section.

3.2 Energy Metrics

3.2.1 U-factor/U-value

The U-factor is a measure of the window's heat transfer resistance across the indoor/outdoor temperature difference. A full fenestration system contains a number of different components including the frame, edges and dividers, and the glass itself. The NFRC provides guidance for the calculation of each of these individual U-factors as well as the Total Fenestration Product U-factor which is a function of all associated U-factors and their relative surface areas (NFRC, 1997). For NFRC purposes, specific environmental conditions are used to calculate the U-factor, including indoor and outdoor temperature and exterior windspeed (NFRC, 1997). The U-factor is determined by measuring the total heat transfer by conduction, convection, and radiation, and relating it to the surface area as shown in Equation 2, where A is the surface area of the window and T_{in} and T_{out} refer to inside and outdoor temperatures, respectively.

$$U = \frac{Q}{A \cdot (T_{in} - T_{out})} \qquad \mathbf{2}$$

Manufacturers use a combination of measurements and simulations to produce the U-value, reported in the United States in BTU/hr-ft^2-F (SI units: W/m^2-K) on the label (NFRC, 1997). A higher U-factor indicates that more heat transfer is permitted across the façade which is undesirable in any climate when the inside temperature is being controlled mechanically.

Since the U-factor is dependent on heat transfer across the system, it is inherently related to the environmental conditions to which the system is exposed. Thus, if calculated with actual environmental conditions, it would vary throughout the year. The NFRC, and thus ASHRAE and other accreditations, require only that a single case be assessed, regardless of location of installation or otherwise.

3.2.2 Solar Heat Gain Factor (SHGF)

The Solar Heat Gain Factor (SHGF) and the Solar Heat Gain Coefficient (SHGC) both measure the solar gains permitted by a fenestration system. The SHGC is dimensionless, and is defined as the fraction of incident solar energy that is transmitted as heat across the façade at the normal incidence. The SHGF incorporates the incident solar irradiation and describes how much solar heat enters the space in W/m^2.

Because the SHGC can change for different sized systems, the NFRC prescribes a standard model size for measurement data and reference simulation software for extrapolation (NFRC, 2009; Window 6, 2011). The SHGC is often considered to be more desirable at lower values because high solar heat gains are associated with warm weather and thus, increased cooling loads for the building. Of course, this is a climate dependent consideration because in colder climates, higher solar heat gains contribute to the load of the mechanical heating systems (ASHRAE 90.9, 1999). The SHGF measures the quantity of heat that is permitted to enter the space through a clear window based on the SHGC and shown in Equation 3 $SHGF = I_{total} \cdot SHGC$ 3, where I_{total} is the total incident solar radiation.

$$SHGF = I_{total} \cdot SHGC \qquad \mathbf{3}$$

The calculation process for the SHGC is described in NFRC documentation (NFRC, 1997). The SHGC and SHGF are calculated only for solar incident radiation that is normal to the façade surface. Although this decision was initially made to simplify the metric and create a benchmark, it cannot identify systems that may have a desirable angle dependence for solar heat transmission. Furthermore, this condition never occurs in nature.

The SHGF can also be assessed with respect to the direct and diffuse solar radiation, as shown in Equation 4, although the NFRC does not require this additional level of accuracy. Because there is a difference in transmission ($\tau_{direct/diffuse}$) of heat when considering direct and diffuse portions of solar radiation, they are considered separately, as shown in the equation below. Furthermore, some portion of the heat absorbed ($\alpha_{direct/diffuse}$) by the fenestration system is conducted across the surface and into the space. This value, N_i, or the inward flowing fraction of energy is a function of the interior and exterior heat transfer coefficients.

$$SHGF = I_{direct}(\tau_{direct} + N_i \cdot \alpha_{direct}) + I_{diffuse}(\tau_{diffuse} + N_i \cdot \alpha_{diffuse}) \quad \mathbf{4}$$

Visible and solar transmissivity differ in the portion of the spectrum that is considered in transmission across the façade.

3.2.3 Window-to-Wall Ratio (WWR)

The window-to-wall ratio (WWR) is the surface area of a fenestration system (window) divided by the surface area of the entire façade (wall). This is a metric used for both energy and daylighting assumptions as a mechanism to provide reference about how much of a façade is dedicated to glazing (Energy Plus, 2011; ASHRAE 189.1, 2009; Marceau and VanGeem, 2007). According to a 2010 report by the United States Department of Energy (DOE) the code-compliant WWR is 40%, but reducing it to 20% would contribute to reducing energy usage by half (Leach et al., 2010). ASHRAE 90.1 prescribes a maximum WWR of 30% (ASHRAE 90.1, 1999), while ASHRAE 189.1 provides more flexibility in the selection of a fenestration system by prescribing a 40% maximum WWR (ASHRAE 189.1, 2009). Meanwhile, the credit-based rating system known as Leadership in Energy and Environmental Design (LEED) provides a baseline of 31% WWR for achieving its relevant credit (Marceau and Van Geem, 2007). These prescriptions are based on the underlying heat transfer principles for commonly used standard glazing fenestration systems.

The window-to-wall ratio is an excellent metric to compare window surface area across different buildings. The façade area dedicated to fenestration systems is a crucial design decision that affects not only the visual perception of the building, but also structural considerations and layout plans. However, when used in the context of energy, it is based on fundamental assumptions that may or may not apply, thereby eliminating the possibility of innovative solutions to address the energy efficiency specifically, notably angle dependence for solar gains and daylighting. An angle dependent system – one that accepts heat gains in cold months and rejects them in warm months – will perform better in energy on an annual basis than a standard counterpart, regardless of its surface area, and simultaneously will contribute to reduction in artificial lighting electricity due to the allowance of daylight. Neither of these considerations is embedded in the window-to-wall ratio when used as a traditional energy metric.

3.2.4 Solar Heat Scarcity/Surplus (SHS)

Using the Balance Point Method (Utzinger and Wasley, 1997), Kleindienst defined the Solar Heat Scarcity or Surplus (SHS) as a metric to communicate to a designer the amount of solar gain associated with a particular design. A building is said to have excessive (surplus) solar heat gain when the outdoor temperature is above the building's heating balance point and insufficient (scarcity) solar heat gain when below the building's cooling balance point. The SHS ranges from -100% to 0% for Scarcity and 0% to 100% for Surplus as a function of the amount of solar heat gain that enters the space (Kleindienst and Andersen, 2010). The following equations show the calculation procedure for SHS.

If $T_{out} - T_{BP,S} \geq 0$, Solar Heat Surplus

If $T_{out} - T_{BP,S} < 0$, Solar Heat Scarcity

Equation 5shows the calculation of Solar Heat Surplus (cooling):

$$2 \times \frac{\Delta T_{SHG}}{\Delta T_{SHG} + \Delta T_{IHG}} \times \max\left[\frac{\Delta T_{load,S}}{\Delta T_{SHG}}, 1\right] = 2 \times \frac{T_{BP,NS} - T_{BP,S}}{T_{set} - T_{BP,NS}} \times \max\left[\frac{T_{out} - T_{BP,S}}{T_{BP,NS} - T_{BP,S}}, 1\right] \quad \textbf{5}$$

Equation 6 then shows the calculation of Solar Heat Scarcity (heating):

$$\frac{\Delta T_{load,S}}{\Delta T_{load,NS}} = \frac{-(T_{BP,S} - T_{out})}{T_{BP,NS} - T_{out}} \quad \textbf{6}$$

In these equations $T_{BP,S}$ is the balance point temperature due to both internal and solar heat gains, $T_{BP,NS}$ is the balance point temperature associated only on internal heat gain, T_{set} is the HVAC set point, and T_{out} is the outdoor temperature, all in degrees Celsius (Kleindienst, 2010).

This is then communicated to the designer by a temporal map, which plots annual building performance on a two axes; the horizontal axis represents the hours of the year where the space experiences gains while the vertical axis represents duration of the day (Kleindienst et al., 2008). The images below show surplus (red) and scarcity (blue) and comfortable amounts of solar gains (yellow) for an office building simulated in Phoenix, AZ (left) and Fairbanks, AK (right) (Kleindienst, 2010).

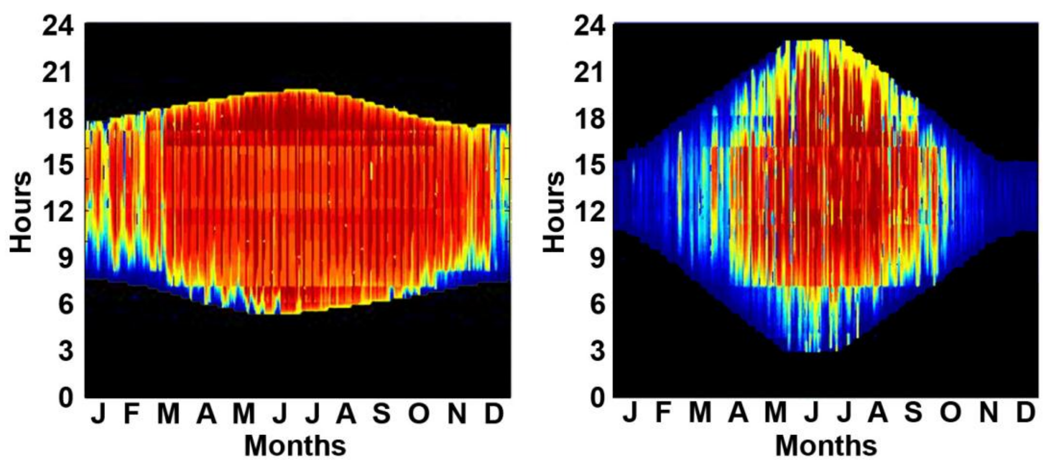


Figure 6: SHS for an office building in Phoenix, AZ (left) and Fairbanks, AK (right) (Kleindienst et al., 2010).

This metric and its temporal maps will become part of the Lightsolve simulation engine, a tool for designers to evaluate daylighting designs in an interactive manner (Kleindienst et al., 2008). This metric, like the others used in Lightsolve, provides information about a space, rather than the fenestration system.

3.2.5 Predictive Performance for Windows

A concept that has not yet been developed into a formal metric is Karlsson et al.'s simple model for predicting the performance of windows. Using existing metrics, namely the U-factor and SHGF, along with hourly meteorological data for a particular climate location to determine a balance point, an assessment of a particular window's energy performance can be determined in a quantity known as the heating energy balance (Karlsson et al., 2001).

The energy metric presented in this thesis takes a similar approach in using a simplified simulation method to assess annual performance of a fenestration system. However, Karlsson et al.'s model relies on more information about the building space to than is ideal for decisions related specifically to the fenestration system.

3.3 Daylight and Visual Comfort Metrics

Daylight is inherently connected to the interior space and daylighting design is typically an architectural consideration. Daylight analyses are currently conducted using simulation methods, model testing, or post-construction studies. Because comfort levels are highly dependent on the distribution of light within a space, very few metrics exist to describe the daylight quality (or quantity) achieved by a fenestration system.

There are two fundamental units of light measurement. Illuminance, measured in lux, denotes the quantity of light that reaches a sensor or surface. Luminance, measured in candela per square meter, indicates the luminous intensity per unit area. Luminance ratios are also known as contrast ratios. For example, the amount of light on a work area is measured in illuminance and the area of a light source is measure in luminance. High luminance values and/or ratios of adjacent surface luminance typically causes the discomfort to people known as glare (Vos, 1999).

In addition to physical measurements, illuminance and luminance values can be obtained using lighting simulation software such as Radiance, an open source, well-validated, and widely-used rendering and lighting calculation engine (Ward and Shakespeare, 1998). Studies have shown the accuracy with which Radiance can predict interior lighting conditions is very good (Mardaljevic, 2000; Mardaljevic, 2001).

3.3.1 Illuminance-Based Metrics

The Illumination Engineering Society of North America (IESNA) provides guidelines for acceptable illuminance levels for a variety of tasks or purposes, from detail tasks to office work to retail space. Generally, 300 lux is accepted as the minimum office space illuminance requirement (IESNA, 1982). The IES does not provide maximum illuminance recommendations (IESNA, 1982).

Lighting requirements prescribed by the IESNA are recommendations that are often adopted by building standards such as ASHRAE, and subsequently may be passed into law by building codes. They are created to ensure safety (low lighting conditions may affect machine operators in dangerous way), provide healthy working conditions (detailed task work with insufficient light creates eye strain), and maintain comfort (office spaces should have minimum lighting levels) for occupants. These recommendations are established by a stakeholder process in which lighting manufacturers, designers, engineers, and occupants weigh in on acceptable lighting levels.

As with any number in the policy realm, there can be no scientific consensus on the exact comfortable lighting condition (Stone, 2001). Illuminance levels of 299 lux are not prohibited while 300 lux are permitted. These numbers indicate preferences of the many stakeholder groups and represent a compromise reached by all parties, and although indicative of a cut off, are not truly considered as such in prescription or practice.

Daylight Factor (DF)

The daylight factor (DF) is a ratio that relates the amount of light that enters a space to the amount of light outside at the same moment in time, as can be modeled by a standard CIE overcast sky on the design day (CIE, 1989). Because the daylight factor is a ratio of interior illuminance to exterior illuminance, maps like the one shown in Figure 7 can be obtained for building spaces that show spatial distribution of daylight.

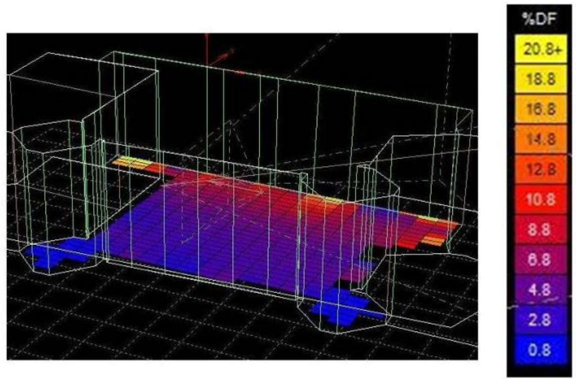


Figure 7: Daylight factor map for an existing building space.

A daylight factor at or below 2% is considered underlit and gloomy. A daylight factor between 2 and 5% suggests that the space is adequately lit, but may require artificial lighting. Finally, a daylight factor of about 5% is considered generally well lit (CISBE, 1999). In the image above, very high daylight factors are achieved along the south wall, but northern corners experience a daylight factor below 1%.

While the daylight factor is useful in providing information about the distribution of light in a space, it is a relative quantity where the denominator (horizontal illuminance of an overcast sky) is not representative of actual environmental conditions. It also provides information about relative interior conditions for only a given moment in time, so although the distribution is interesting information, it does not inform a user about changes in distribution with hour of day or time of year. In this way, it is similar to the U-factor and Solar Heat Gain Factor in that it is defined based on a single assumed set of exterior conditions, and thus can be considered a specification of the space, rather than a metric that reflects annual performance.

Daylight Autonomy (DA)

Daylight autonomy (DA) describes the percentage of occupied time that daylight alone is sufficient to light the space to desired illuminance levels (Reinhart and Walkenhorst, 2001). Unlike the daylight factor, it considers all sky types and orientations throughout the year, including time of day and sun position. Continuous daylight autonomy (DA_{con}) uses the same lower illuminance threshold, but gives partial credit for daylight illuminance below it. For example, if daylight can provide half of the required illuminance for a given moment, it would receive a credit of 0.50 for that moment (Rogers, 2006). Both of these metrics require a definition of a sensor or sensor plane as the workplane surface in the space that must achieve required illuminance levels, as predicted by time series simulation.

Although, DA is an annual metric that can be considered a performance metric, it describes the performance of a space, not a façade system. As a result, it is infeasible to presume that a user will relate DA values directly to the selection of a complex fenestration system. However, it is an excellent example of a metric that considers human factors to inform design decisions in quantitative ways.

Useful Daylight Illuminance (UDI)

The useful daylight illuminance (UDI) uses the concept of "useful daylight" as horizontal illuminance levels between 400 lux and 2000 lux, considering light levels outside this range uncomfortable based on user studies. However, neither threshold is binary; instead the UDI uses fuzzy boundaries around these values in an effort to recognize the subjective perception of human occupants. Like DA, it considers only occupied hours for the space (Nabil and Mardaljevic, 2006). Assessing the useful daylight illuminance results in three values: a percentage of occupied time that is below the minimum threshold, a percentage of occupied time that is within the desired illuminance range, and a percentage of occupied time that exceeds the desired illuminance. As for the DF and DA, UDI is a spatial metric and requires a three-dimensional model and building occupancy schedule for inputs to the simulation.

Despite being another spatial metric, two features of the UDI are interesting. First, the ability to define an upper boundary is novel and relevant for actual users in the space. Although more light is not directly uncomfortable to occupants it has been shown to cause glare, which suggests that there should be an upper boundary to comfortable conditions. Second, the fuzzy boundaries that define the UDI recognize that comfort or usability is not a binary situation and that users have some tolerance of light levels around designated thresholds. This metric appropriately assigns credit to this benefit of human behavior.

Acceptable Illuminance Extent (AIE)

The acceptable illuminance extent (AIE) was defined to provide a temporal metric that can inform the user of daylight performance over the course of a year (Kleindienst, 2010). Whereas DA can predict how many hours of the year a location receives sufficient light levels, it does not suggest which hours of the day or year are underperforming. As a result, a designer using DA as a daylighting metric does not have the information necessary to make design modifications that would then increase its value. The acceptable illuminance extent aims to combine this spatial and temporal information into a simple format (Andersen et al., 2008).

Using both lower and upper illuminance thresholds (as in the UDI), with partial credit buffers (as in the DA_{con}), the AIE identifies the percent of space that achieves desired illuminance. The AIE is then plotted on a temporal map such as the one in Figure 8, which shows the percent of space that is within the acceptable illuminance range. Similar maps can be created for percent of space below the illuminance threshold and percent of space above the illuminance threshold (Kleindienst, 2010).

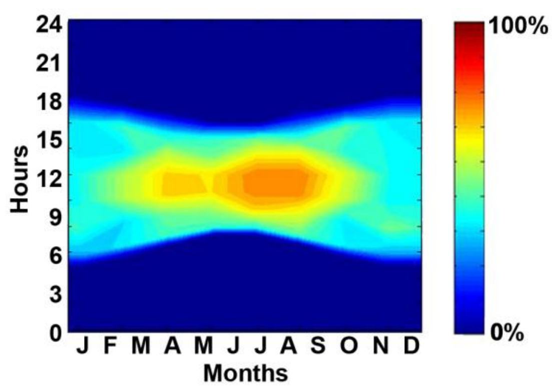


Figure 8: Acceptable Illuminance Extent represented on a temporal map (Kleindienst, 2010).

The AIE is the most comprehensive of the illuminance metrics presented here. It includes not only lower and upper thresholds, but it relates the performance of a space directly to the design by presenting it in a format that provides useful information to the user to inform design. However, it is presented in a qualitative way on a temporal map, which is useful and relevant to simulation assessment and the specific subsection of users that can and choose to use simulation methods.

3.3.2 Glare-Based Metrics

Glare is a second measure of lighting that is crucial for comfort conditions. Based on factors such as view point, luminance ratios, and vertical illuminance, glare can be described in several quantitative ways to ass performance of a space. Although much of the work on glare has been in the context of artificial lighting, some can be applied to the daylit context. The previously presented upper thresholds for illuminance levels are proxies for predicting discomfort associated with glare, but more specific glare metrics do exist, and are discussed here.

Disability, Discomfort, and Dazzling Glare

Two types of glare constitute the generally accepted definitions of glare associated with daylighting: disability and discomfort glare. Disability glare occurs when light is scattered over the retina, reducing the luminance contrast between an object and its surroundings and resulting in temporary inability to discern objects clearly (Vos, 2003). Discomfort glare is more difficult to quantify, but is function of luminance ratios, and view point (Eble-Hankins and Waters, 2004). These two thresholds are relevant to daylit spaces for occupant comfort because they describe levels of discomfort that occupants may experience. For office spaces, disability glare is a particular concern when viewing computer screens or white sheets of paper that reflect significant amounts of light.

Daylight Glare Probability (DGP)

Introduced by Weinold and Christoffersen, the daylight glare probability (DGP) metric provides a novel assessment of glare by predicting the likelihood of a person being disturbed by glare, rather than measuring the glare itself. Using experimental results of occupant behavior the equation below depicts the relationship between spatial variables and the DGP. In this equation E_v is the vertical eye illuminance (lux), L_s is the glare source luminance (cd/m^2), ω_s is the solid angle subtended by the source (sr), and P is the position index of the person with respect to the source (Weinold and Christoffersen, 2006).

$$DGP = 5.87\times10^{-5}\cdot E_v + 9.18\times10^{-2}\cdot\log\left(1+\left(\sum\frac{{L_s}^2\cdot\omega_s}{{E_v}^{1.87}\cdot P^2}\right)\right) \qquad \mathbf{7}$$

A simplified form of this equation, the DGPs was developed to streamline the metric and is based only on the vertical eye illuminance. It has been validated against the original DGP equation. Because the DGPs does not include the source luminance in the equation, it is not recommended for use when direct sunlight hits the eye. The equation for DGPs is shown in Equation 8 (Weinold, 2007).

$$DGPs = 6.22\times10^{-5}\cdot E_v + 0.184 \qquad \mathbf{8}$$

A DGP value of 0.33 indicates presence of uncomfortable glare, and 0.42 a presence of intolerable glare (Wienold and Chrisoffersen, 2006). This innovation in describing glare quantitatively provides the potential to be used in metrics as the upper threshold for comfortable or useful daylight conditions.

Although the DGPs does not hold for instances when direct sunlight is reaching the eye because it does not include the glare source luminance, that situation is considered an uncomfortable condition and further, results in values of vertical eye illuminance that exceed those required to predict intolerable glare. As a result, the DGPs provides an excellent potential for use as an upper threshold in definition of viewpoint specific comfortable daylight conditions.

Glare Avoidance Extent (GAE)

The glare avoidance extent uses a model-based DGP (DGPm) developed by Kleindienst and Andersen that uses three-dimensional model in the Lightsolve rendering engine to calculate a spatially relevant DGP value that was validated against the DGPs values for the same scenarios, known as the DGPm. The DGPm uses an approximation method that identifies glare sources and assigning illuminance values to all window patches in a light rendering program to calculate glare probability (Culter et al., 2008). DGPm can then be plotted on a temporal map as presented before, where yellow indicates that the glare sensor are within the glare range and red indicates presence of glare. An example temporal map for a classroom model in Sydney, Australia is shown below (Kleindienst, 2010).

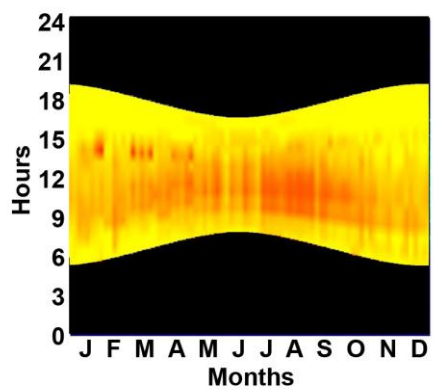


Figure 9: Glare temporal map for a classroom model in Sydney, Australia (Kleindienst, 2010).

The GAE provides a time-relevant indication of glare performance of a space, connecting design decisions to annual performance in a unique way. The GAE, as the AIE, requires working within a simulation program to evaluate a design and thus is directed at a subset of the building industry. Further, the simulation program which evaluates both AIE and GAE, Lightsolve, is not yet able to evaluate complex fenestration systems.

3.4 View-Through Metrics

The third and final category of metrics that relate to daylight and fenestration systems involve descriptions of the view through. Interestingly, there are really very few of them, and even fewer that have been assessed with a user study validation approach. Although the view through windows has been identified as improving the well-being, heath, productivity of occupants, in some cases privacy may be desired while still permitting light to enter (Farley and Veitch, 2001). Moreover, quantitative descriptions of this rely almost exclusively on the NFRC-defined visible transmittance. Other, more qualitative, mechanisms have been developed to address communication about view through, but none provides a means to rank complex fenestration systems according to their ability to provide (or not provide) a view.

3.2.1 Visible Transmittance (VT)

The visible transmittance (VT) is reported as the fraction of incident visible light on a fenestration system that is permitted to pass through at normal incidence (NFRC, 2009). This is the component of the light that provides daylight to the interior of the room, and so is inherently included in all daylight simulation calculations that produce the daylight metrics presented in the previous section. However, the visible transmittance also provides a potential window-buyer the information about how clear the view to the outside will be. A high VT suggests a clear view, while a VT of less than 0.50 indicates that the system diffuses incoming light and very little or no view is perceived. There is no comprehensive database to provide benchmarks for full, little, or no view perception of a full façade, primarily because the VT represents only the normal incidence case.

This single-incident condition problem is similar to those described previously: it does not describe a physical system in operation. A system that achieves a very high view at the normal incident may not allow an occupant offset by even ten or fifteen degrees to the normal to see through. Therefore, using the current approach will over- or under-state view for complex fenestration systems which transmit light angularly.

3.4.2 Sample Viewing

Because the visible transmittance does not speak to angular variance in view ability, it is not representative of the view through complex fenestration systems. Most fundamentally, this approach assumes that users can identify their view priorities from looking at an object, whether physically or virtually. Physically viewing a sample would require in-store purchase experiences, but virtual viewing using photographs provides a means to do so remotely.

In the absence of another metric, one component of D-LITE, an interactive database that provides a virtual means of characterizing and communicating aspects of complex fenestration systems, including view. This mechanism includes a photograph of a complex fenestration system from a number of angles so that a user can identify view characteristics on a subjective basis (Urbano and Andersen, 2008). This approach takes into consideration the impact of multiple viewing angles, a user's specific view priorities, and the aesthetic experience of the complex fenestration system.

3.4.3 Efforts to Quantify View

Finally, some efforts have been conducted to quantify view in a manner that is relevant to occupants and human perception of view. The European Commission sponsored work at TNO, known as the project REVIS to assess daylighting products with redirecting visual properties (van Dijk, 2000). In this work, researchers have identified methods to identify two specific factors of daylighting products: redirect/scatter and obstructions. Each of these is associated with a formula that relates the "disturbance factor" with the view through index. Some of the understanding of these parameters lead to the development of a new view performance metric in this work. But while very comprehensive in identifying reasons for view disruption, this work has not yet been validated to correlate view index with actual users' perceptions of view.

Chapter 4
Framework for Metric Development

A general framework for developing all three of the proposed performance metrics was established prior to any substantial data analysis in order to maintain consistency across the performance criteria as well as reduce biases in the procedures used for analysis. First, specific criteria were defined for performance metrics to address. These were selected based on a detailed study of daylight in buildings and the tradeoffs and decisions associated with selecting a fenestration system. Second, a relative approach is used to normalize assumptions that are required to place a complex fenestration system in its contextual environment. Finally, a clearly defined simplification methodology is used to reduce the resolution of input quantities such that a more streamlined method for the calculation of usable metrics.

Because fenestration systems do not perform in isolation with their environment, and further, are not designed to do so, it is also necessary to use assumptions that place the fenestration system in context. However, these assumptions must also be as widely applicable as possible; generic sets of assumptions that mask realistic annual performance work directly against the goals of creating comprehensive performance metrics. Although, as will be explained, some aspects of these assumptions may be simplified in cases where their effect is not significant, it was crucial to define them in their full resolution case first. This chapter presents both the framework for metric development as well as the selection of full resolution input conditions that enable the definition of each performance metric.

4.1 Research Approach

Three important components drives the creation of the research approach used in this thesis. The first defines the three critical performance criteria which the metrics address. The second presents an argument for using a relative approach to describe complex fenestration systems. And the third lays out a methodology for reducing the metrics' dependency on highly detailed input conditions. The goals and justification of each are described here.

4.1.1 Performance Criteria

In order for performance metrics to consider and reflect relevant features of the complex fenestration system, these important characteristics must first be defined. Fenestration systems are an integral component of a façade, performing for various reasons. These considerations may include:

- Interior and exterior aesthetics: for overall architectural form
- View to the outdoors: for a connection to nature as a standard window provides
- Privacy from the outdoors: as may be required in a crowded city
- Daylight admittance: for natural light and reduction in electric light requirements
- Direct daylight blocking: to protect delicate objects or prevent glare
- Protection from solar heat gains: to reduce cooling loads
- Exposure to solar heat gains: to reduce heating loads
- High heat transfer resistance: to maintain thermal integrity of façade

Conventional fenestration systems, windows, are evaluated through each of the considerations in this list, but doing so relies on basic knowledge about how it operates. Meanwhile, complex fenestration systems may achieve better performance in one aspect (say, daylight admittance and depth of daylight penetration) at the cost of another (say, view). In other words, complex fenestration systems improve upon a particular characteristic or characteristics of a standard fenestration system in novel ways; for example, standard fenestration systems alone cannot control solar gains seasonally. When considered holistically, each of the considerations can be grouped into one of three broad categories when considering the performance of a complex fenestration system as follows:

1. Energy
2. Daylight
3. Physical features

The metrics should not aim to encourage a user to assume any of the three criteria above as more important than the others, nor should they form an opinion about them when not warranted. However, it is also possible to assume that, *when considered independently*, reduced energy use is preferred to increased energy use, comfortable daylight conditions are preferred to uncomfortable daylight conditions, and better aesthetics are preferred to poor aesthetics. The first two criteria can be defined using methods that are well-accepted, but physical features are a subjective concept and difficult to quantify even without making a judgment.

Although the way the system looks is crucial to design elements of a building, this aspect is impossible to describe using a quantitative metric. The view which the system provides to the outdoors, however, is theoretically quantifiable. And, because a clear view may be desirable in some cases while an obstructed view may be desirable in others, simply describing the degree of view without judgment provides a user with relevant information.

Thus, the three categories presented previously can be restated in terms of performance criteria that address all the considerations listed earlier, except for subjective perception of interior and exterior aesthetics:

1. Energy efficiency
2. Comfortable daylight conditions
3. View through

One metric will be proposed to address each of these performance criteria.

4.1.2 Relative Approach

A crucial element of the performance metrics that this work aims to define is their widespread applicability (i.e. being independent from as many conditions as possible) and their ability to provide intuition to users (i.e. capability to relate performance to something that is easily understood). Both of these elements inform the user of a relative approach that both normalizes external factors and provides context for the user.

A relative approach normalizes external factors by relating performance of a complex fenestration system in a space to the performance of a standard fenestration system in the same space. Thus performance is no longer an absolute quantity, but a relative value that describes the degree to which the complex fenestration performs better or worse than a standard fenestration system in the same situation. For example, the performance (whether it is measured in Watts of energy use or amount of the year which it achieves comfortable daylight conditions) is highly dependent on the size and configuration of the space when considered in absolute terms. However, when compared across systems for the *same* space and configuration, it is possible to identify better performing options in a particular criterion.

The second benefit of a relative approach involves usability of the metrics. Users require a benchmark for which performance can be considered better, worse, or different. Normalizing performance of complex fenestration systems with a reference standard fenestration system that is intuitively obvious makes the metrics relevant to users. In other words, using a well-understood benchmark for the relative approach contextualizes performance in ways that provide insight to users. Users can then determine that a complex fenestration system performs better or worse in a given performance category than a standard alternative which they can understand. Thus, the selection of the system which is used as a reference is extremely important.

Although using a reference case does not fully eliminate dependency on spatial considerations, it does provide a benchmark reference for general performance and enables the user to compare across complex fenestration systems. This concept will be discussed further in assessment of validation studies for the metrics. Of course, all systems must be normalized with the same standard fenestration configuration and this reference system is described in detail in Section 4.2.

4.1.3 Simplification Methodology

As noted previously, usability of the metrics is a critical feature. Similarly, practical calculation procedures are equally important because complex and very detailed approaches are likely to be misused or not adopted at all by the industry. There are a number of challenges that must be addressed in defining a calculation procedure that is conducted and interpreted in the polis. These precede the discussion of the approach used in this work.

First, complexity precludes inclusion by limiting the number of participants that can realistically access the calculation process. If the process is time consuming, requires specific skills or expertise, or results are complex to interpret, wide-spread adoption is not feasible to expect. As evidenced by the existing NFRC standard calculation procedures, descriptions must be clear, explicit, and where software is required, packaged such that learning the program does not require significant specific prior knowledge. Performance metrics that reveal more about annual performance than the traditional metrics will inevitably require more inputs, more calculations, and produce a wider range of results. But limiting these only to the necessary is important for usability by the manufacturer who is required to report performance metrics of its complex fenestration systems.

Second, where there is an opportunity to misunderstand results due to oversimplification, there will likely be misuse of the calculation procedure. There are situations where oversimplying the packaging of a software results in incompetent users – those without the basic prerequisite knowledge – and subsequently, misuse of the results. Oe clear example of this can be found in the role of Life Cycle Analysis (LCA) in the policy realm. Whereas an LCA may provide a very informative basis for comparison among product alternatives, converting embedded energy into offset carbon without considering additional factors, such as user behavior or consumer patterns, is clear misuse and overstatement of the results. When numbers may potentially be used in the polis, what they are counting or measuring must be transparent, approachable, and specifically designed for the purpose (Stone, 2001).

Third and lastly, exploitation of numbers in the polis, either intentionally or nonintentioanlly, is reality; factors that are measured respond to being measured (Stone, 2001). Some performance rating systems incentivize specific factors that can be achieved outside the spirit of the rating system. A well-respected but also highly-criticized rating system for sustainability of buildings, LEED, has experienced this phenomenon in practice. Although LEED has successfully popularized high-performance green buildings and has incentivized movement in a number of industry standards, there are examples where credit is received for misinformed reasons. In a local example, the Genzyme headquarters building received a LEED Platinum certification. One of the credits it received was for having plant life inside the space, bringing nature closer to the occupants and providing benefits in air quality. However, these plants were imported from more than 50 different countries (each of the countries in which Genzyme has operations) and further, insect life from each of the different ecosystems have to be imported on a regular basis to maintain the health of the plants (Capozzi, 2009). This cannot be considered sustainable, although the motive and spirit of the rating system is honorable. Similarly, relying on a single incident condition for rating complex fenestration systems presents an opportunity to optimize around creating better technical specifications for that single case. When the single case does not extrapolate into annual performance, the efforts are essentially fruitless.

With these concerns in consideration, a simplification methodology was proposed for the performance metrics described in this work. This approach was identified before any results or analysis was conducted.

1. Evaluate full resolution conditions: First, and to create a benchmark, sample complex fenestration systems are to be evaluated with the full resolution of inputs for each of the metric definitions. This will result in a unique value created for each climate location, orientation, and period of the year for each system. From these results, trends and similarities will be identified.

2. Conduct a sensitivity analysis: In order to begin to streamline the calculation methodology, trends and similarities identified in the previous step will be converted into a statistically relevant sensitivity analysis in order to reduce the number of unique values required to describe each complex fenestration system. This will enable a reduction of the resolution of inputs. Because the metrics are relative values (and not absolute) variation in accuracy is acceptable, as long as each of the five complex fenestration systems would be ranked in the same relative position as if the full input resolution were conducted. The fewer values required to describe a complex fenestration system the more accessible the metrics are to users. However, this should not be pursued at the expense of revealing important performance characteristics of these systems.

3. Create an analytical approach: As a further attempt to increase usability of the calculation procedure, eliminating the simulation workflow from evaluating each metric would be ideal. However, where this is not possible, analytical relationships between critical aspects of the calculation procedure can inform the creation of intermediate metrics that can be used as these performance metrics are being introduced on a wide scale.

This workflow, shown schematically in the figure below, was applied to each metric and ultimately determines the final definition for each metric. The parallel framework presents opportunities for comparison between metrics, but because each metric responds to input parameters differently, the reduction in input resolution must be conducted for each individually. The following chapters describe the decisions made for each of the three proposed performance metrics.

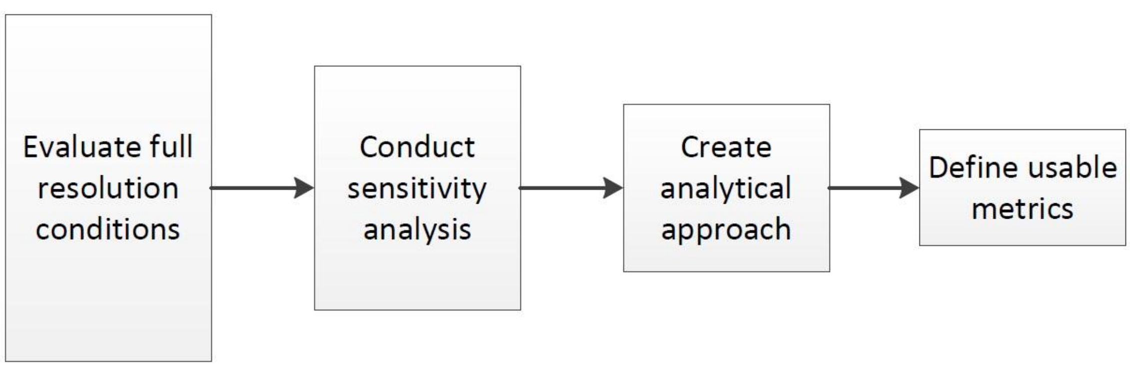


Figure 10: Schematic of simplification methodology workflow.

In the spirit of the development of these metrics, it is apparent that a validation study on each metric is required to provide insight into its wide-spread applicability and inform potential revisions. Because the metrics were not developed as a research exercise, rather as a very applicable approach to the integration of complex fenestration systems into the building industry, the dynamic development process requires additional considerations (e.g. ease of implementation, policy stakeholder assessment, etc.). These validation studies provide indication about the effectiveness of the metrics to describe a wide range of scenarios in the way that is desired. An individual validation study was conducted for each metric to assess a critical component of the metric definition.

The goal of each study was to identify whether the established calculation procedure was reflective of the results obtained by doing a space, site, and sample specific analysis. These validation studies are described and results reported in the following chapters as well.

4.2 Basic and Full Resolution Inputs

The critical inputs that are required for assessment of the three proposed performance criteria are a simple space that is used to determine interior conditions, orientation of the fenestration system, a reference fenestration for comparison, a standard BTDF form, and climate data to determine environmental conditions. Manipulation of the measured BTDF into a standard form that is useable both by simulation engines and by future calculation methodologies was conducted. This process was neither trivial nor perfect, but presents insight for future BTDF databases.

4.2.1 Generic Test Module

In order to evaluate daylight distribution and view angles to the window, a physical space was required for calculations. This space was selected to be as generic as possible, with the goal of being able to reveal benefits or disadvantages of complex fenestration systems. Furthermore, the space was selected in tandem with decisions made at the École Polytechnique Fédérale de Lausanne (ÉPFL) for physical testing and assessment of the effects of various façade systems. This consistency will be beneficial for further validations of the complex fenestration samples and metrics proposed in this work. The three important considerations when selecting a test space were the ability to assess depth of daylight penetration, ability to perceive changes in daylight distribution, and sufficient variation in view angles from inside the space to evaluate view. Thus the test space exhibits a deep plan with respect to its window head height, sufficient floor area, and a relatively large window width.

The depth of daylight penetration for a standard fenestration system is typically equal to about 1.5 times the window head height (in Figure 11, right, the use of a clear window of head height 3 meters results in a depth of daylight penetration of about 7 meters). This rule of thumb typically suggests that deeper daylight penetration requires taller windows, but complex fenestration systems often achieve this goal in unique ways. Therefore, the depth of the test space is 3 times the window head height, enabling complex fenestration systems that achieve depth of daylight penetration to be identified.

Furthermore, the width and depth of the space provide a floor area of 300 square meters. As is shown in the illuminance plot, a standard fenestration system results in direct sunlight landing on about 10% of the floor area. An additional 20% of the floor area is illuminated indirectly, and the remaining 60% of the space is nearly unaffected by the direct light. In the absence of creating more daylight (impossible due to the first law of thermodynamics), a complex fenestration system that more evenly distributes this light may be desirable to a user, thus the large floor area (60% unaffected with a standard fenestration system) was selected.

Third, a wide window results in a large range of view angles between potential occupant locations and the fenestration surface. With a width of three meters, occupants may view parts of the window at anywhere between 3 and 90 degree angles. This is important because a system that presents a clear view only when viewed perpendicularly (90 degrees) should not perform the same as a system that presents a clear view at all view angles.

Thus, the dimensions of the generic test module are 3 meters wide by 9 meters deep by 3 meters high. The fenestration system is located on the surface that is 3 by 3 meters, and is 3 by 1.5 meters in area. The reflectances of major surfaces are 0.87 (wall), 0.87 (ceiling) and 0.13 (floor), and are relevant for light bouncing analysis. The perceived colors of the walls and ceilings are gray such that benefits are not overly stated by highly reflective surfaces. The brown floor also provides this conservative assumption. A schematic is shown in Figure 11, left, below. The test space can then be rotated such that the window is in the direction of the orientation being evaluated.

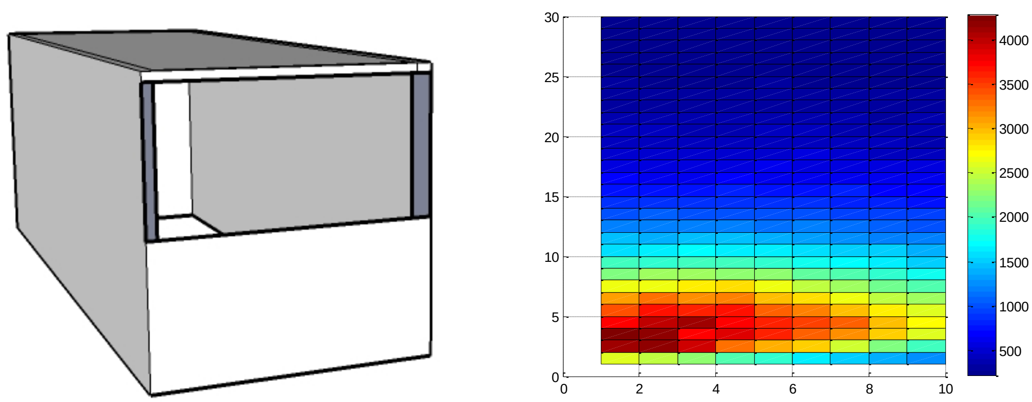


Figure 11: Generic test module and sample horizontal workplane illuminance plot, in lux, for a standard clear window.

In order to evaluate illuminance values, sensor grids were required for input into the calculations for the metrics. A grid of horizontal workplane sensors represents task illuminance and is set at a height of 0.76 meters, a standard office desk height in the United States. A grid of vertical eyelevel sensors represents a standing person's perception of the window and is set at a height of 1.15 meters, an average eye height for adults, facing the window. Each sensor represents the square area of 0.09 square meters, which provides the space with 300 data points that each represent about the width of one standing person.

Finally, an important characteristic for the generic test module is the direction in which the fenestration system faces. Although the module could be rotated in any number of directions, a practical and feasible number of directions was required. And because interpolation between orientations is feasible due to symmetry of sun patterns, as well as a general understanding of sun course in the building industry, assessment at each of the four cardinal directions was selected. So, to evaluate a complex fenestration system in the generic test module, four versions of the module are required. These, along with the space dimensions, provide the physical inputs required for lighting evaluation of the space.

4.2.2 Reference Fenestration System

As discussed previously, a reference standard fenestration system is required to exist as a base case for performance. Climate, location, orientation, along with spatial dimensions, affect energy performance, interior daylighting conditions, and view in different ways, an intuitive and standard alternative fenestration system is desired to provide context.

The reference fenestration system is intended to be a standard alternative fenestration system, to be an intuitive performer with respect to user understanding, and to provide a base case to which other systems may perform better or worse. Thus, the reference case was selected to be a clear, double-glazed window as described by the International Glazing Database (IGDB) from the Department of Energy, often considered the default window for construction (Optics 5, 2010).

Using values from the IGDB, the reference case was thus defined as two panes of clear glass, each 3.2 mm separated by a sealed air gap of 12.8 mm. The overall visible transmittance is 81% and the U-factor and Solar Heat Gain Factor as defined by the NFRC modeling process are 2.73 W/m^{2}K and 0.761, respectively (Window 6.1, 2011).

4.2.3 Klems Basis BTDF

A third static input for analysis of complex fenestration systems is a form of the BTDF that can be compared across systems. This information is used in calculation of the metrics as it represents the mathematical description of the fenestration system's behavior. As discussed previously, the BTDF datasets used in this work are derived from a database of measured complex fenestration systems. Resolution, number of discrete files, and symmetries differ for each system which makes side-by-side comparison difficult. Thus, a standard form that can be used by energy calculations, lighting simulations, and view studies is required.

In selection of the standard form, consistency was prioritized. Because the lighting simulation program Radiance is inflexible in the form of BTDF that can be used, and in order to maintain consistency and easy of data access across metrics, this form was selected for all three metrics. The form used by the commands that handle BTDF in Radiance, and thus by the metrics in this work, is known as the Klems basis BTDF and is characterized by a matrix that represents 145 incident conditions by 145 emerging conditions (Klems, 1994). Thus, a conversion process is required to manipulate measured data into Klems basis data. This process is presented here.

The BTDF dataset used from Andersen's PhD dissertation follows the IEA format for defining BTDF (Andersen, 2004). Each of the 145 incident and emerging angles are described by two angles each. The elevation angle (θ) refers to the projected angle with respect to the horizontal and the azimuth angle (φ) refers to the projected angle with respect to the vertical. Each pair describes the unique incident or emerging angle with which the BTDF value is associated.

Where input conditions were required but not available, the input condition closest in distance was substituted in the Radiance version, rotated such that the peak emerging direction matched the relative peak input condition. For example, if the (θ, φ) input condition (12, 0) results in a peak at (θ, φ) emerging condition (12,180), substituting (12, 0) at (12, 90) would result in a peak at (12, 270). This example is intuitive when considering a clear glazing (or a hole), but peaks and dips are less obvious for samples that redirect light. However, maintaining the observed relationship is critical for accurate extrapolation.

Emerging conditions needed to be condensed into the number of angle bins described by Klems. Each Klems angle bin contains multiple angle bins from the measured BTDF dataset as shown in Figure 12. The sum of the fluxes that pass through each of the angles within the Klems basis angle bin is equal to the flux associated with that bin. Thus, condensing the measured dataset requires allocating measured angles to Klems angles, summing the flux, and relating it back to the angle that represents that Klems bin. This logic is consistent with the first law of thermodynamics as it ensures that energy (in terms of flux) remains constant.

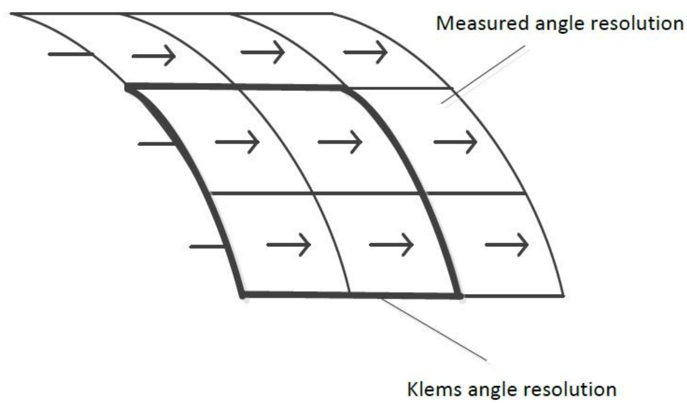


Figure 12: Schematic of condensing from measured to Klems basis BTDFs.

Analytically, the resolution of measured BTDF emerging angles were in multiples of $(d\theta,d\varphi) = (5,5)$ or $(d\theta,d\varphi) = (10,15)$. The Klems basis BTDF is reported in theta multiples of 12 and phi multiples that change as a function of theta. Equations 9 and 10 were used to condense the measured data into the Klems convention by converting and then reallocating the flux of light transmission. Equation 9 calculates the light flux that is transmitted across the patch of the uncondensed BTDF and Equation 10 relates it to the angles associated with the condensed BTDF.

The variables θ and φ refer to the elevation and azimuth angles respectively as described by their subscripts. Subscripts $_1$ indicate incident angles, $_2$ indicate emerging angles, and $_K$ refers to the Klems basis.

$$flux(\theta_1,\phi_1,\theta_2,\phi_2) = BTDF(\theta_1,\phi_1,\theta_2,\phi_2)\cdot \sin\theta_2 \cdot \cos\theta_2 \cdot d\theta_1 d\phi_1 \qquad \mathbf{9}$$

$$BTDF(\theta_{1K},\phi_{1K},\theta_{2K},\phi_{2K}) = \frac{flux(\theta_1,\phi_1,\theta_2,\phi_2)}{\sin\theta_{2K}\cdot\cos\theta_{2K}\cdot d\theta_{1K} d\phi_{1K}} \qquad \mathbf{10}$$

This process was conducted using a combination of manual input and assessment as well as Matlab codes. For example, relationships were first observed and symmetry was applied manually. Rotation was conducted using Matlab, but individually for each required output BTDF. Finally, the condensing was carried out with Matlab using Equations 7 and 8 and each BTDF was compiled manually to ensure that trends could still be observed.

Another limitation of the measured BTDF dataset is its specific measurement of visible transmission. In assessment of complex fenestration systems, there are two types of transmissions that are relevant: visible light and infrared light, two different portions of the solar spectrum. Ideally, BTDF data would be determined both for visible and infrared spectrums and used independently. However, the data available is only the visible BTDF (vBTDF). In reality, the vBTDF and the infrared BTDF (iBTDF) may not be correlated at all, but for the purposes of this study, the vBTDF is used in place of the iBTDF. At normal incidence, the iBTDF is typically 0.6-0.9 of the vBTDF (Window 6.1, 2006). But since this relationship may not – and probably does not - extrapolate to all angles, it does not add accuracy to include it as a correction factor (Rubin, 2010). This research is intended to present a methodology for determining metrics, given specific requirements for input data accuracy. Therefore, it is assumed that when these metrics are used commercially, both the vBTDF and iBTDF will be compiled in the resolution required for each fenestration system. For the purposes of this work, the vBTDF is used in all cases, and is herin referred to as the BTDF.

4.2.4 14 U.S. Climate Zones

Complex fenestration systems, unlike standard fenestration systems, are typically very angle dependent. As a result, the incident solar angle on the façade surface is a critical variable in assessing their performance. Moreover, when aiming to describe annual performance, using realistic climate conditions is required. A system will perform differently with the solar position and climate conditions of Southern Florida than with the same for Northern New England. Therefore, in an effort to describe annual performance accurately for a wide range in solar angles and climate characteristics, location is a critical factor.

Defining locations for assessment of complex fenestration systems has two implications. First, solar position depends on both latitude and longitude. It is, however, more dependent on latitude because time zones account for the variation in sunrise and sunset time associated with different longitude coordinates. Second, locations are associate with particular climate conditions. These conditions include incident solar radiation, outdoor temperatures, and wind velocities and directions. Both contribute to variability in performance of complex fenestration systems across different locations in the United States.

Location-dependent assessment has been accomplished before; the most widely accepted method is grouping locations into climate zones to reduce the number of unique locations that must be assessed. This approach will be used for the metrics proposed in this work as well. Definition of these climate zones, however is important to maintain integrity of the performance characteristics.

A common climate zone system for building technologies is the one described by International Energy Conservation Codes 2004 (IECC), adopted by both ASHRAE 90.1 and 90.2, energy standards for all buildings including low-rise residential buildings. 4755 weather sites operated by the National Oceanic and Atmospheric Association (NOAA) were statistically analyzed to determine eight temperature regions and three moisture regions. The permutations of this climate data result in fifteen unique zones in the United States. The eight zones temperature regions are shown in the figure below (EIA, 2004). For each climate zone, a city with validated TMY3 data (discussed more in the next section) is identified as statistically representative of the entire zones (EIA, 2004).

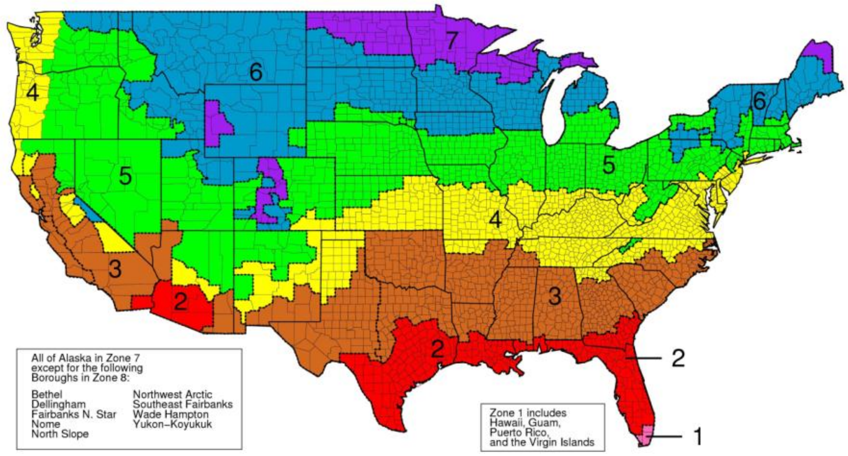


Figure 13: Eight climate zones in the United States as described by the IECC (EIA, 2004).

Another common climate zone definition is the one used by the US Department of Energy's Energy Star rating system. The 359 climate zones available from US data were reduced into the following four zones: mostly heating; heating with some cooling; cooling with some heating; and mostly cooling. The last zone, mostly cooling, may also be split into two zones of climate data, but respond to the same code requirements. For each of these zones, Energy Star defines maximum allowable U-factors and solar heat gain coefficients (SHGC). Figure 14 below shows these zones. The NFRC currently uses these zones for its Energy Star ratings (NFRC, 2004).

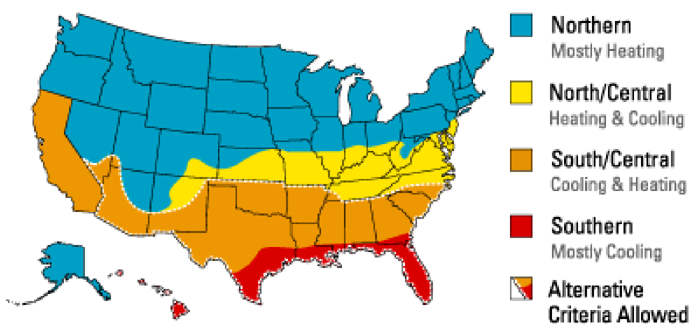


Figure 14: Energy Star climate zones (NFRC, 2004).

Because the NFRC and other Energy Star rating systems do *not* include daylighting assessment and are based solely on heating and cooling requirements, it is difficult to ascertain whether this simplified climate zone approach will be sufficiently descriptive for all of the performance metrics presented here. One can imagine that the solar positions associated with El Paso, Texas and San Francisco, California would result in sufficiently different performance than the Energy Star climate zone suggest. Therefore, the more commonly characterized IECC climate zone system was used as a base case, with one modification. The extremities of climate zone 15 (represented by Fairbanks, Alaska), both in daylight hours and temperatures, the remaining locations of the United States are distorted when included in the dataset. This is expected, as the latitude of Fairbanks is 30 degrees north from the next most northern location, which in itself is less than 30 degrees north from the southern-most location. Thus, the performance metrics analysis here will be limited to, and thus apply to, the continental United States.

4.2.5 56 Representative Periods

Substantial climate data is available for the 14 statistically representative cities used as a proxy for the 14 climate zones. This data is available from the United States Department of Energy and is known as the Typical Meteorological Year Data version 3 (TMY 3). Hourly data on a number of weather conditions including solar radiation, temperatures, wind speeds and directions, among others has been collected and combined into a single year's worth of *statistically relevant* data. This data therefore represents climate conditions for a statistical year, as opposed to hourly variations in weather for an absolute year. Components of this data are the critical climate inputs for many simulation programs including the benchmark energy simulation engine, EnergyPlus.

Hourly data provides 8760 values for each parameter over the course of the year. This information is extremely valuable, but daylighting analysis for each hour, or even each daylit hour, is computationally infeasible when dealing with multiple complex fenestration systems. An approach that reduces the number of simulations is required to even define the metric.

In a method analogous to using representative cities as a proxy for climate zones that describe the entire country, representative periods have been derived to represent the hourly climate conditions that describe the entire year. The approach used by the light rendering engine Lightsolve for daylighting analysis bins annual data into 56 daylit periods of the year (Kleindienst et al., 2008). Each of these periods can be represented by the average climate condition for the period as well as the solar position for the central hour of the binned period. This approach has been shown to provide a reasonable proxy for annual calculations (Kleindienst et al., 2008).

The following graph shows the direct horizontal irradiance for each of the 56 moments (black dots) and how they follow the trend of the year's hourly data (red xs) for Memphis , TN. The graph shows both how the representative moments cluster around one day, but are equally spaced throughout the year. Further, it shows how extremes in solar radiation that are indiscernible on an annual scale average into a predictable pattern of seasonal variation when condensed. This is very important because complex fenestration systems should be designed for holistic annual performance, rather than for hourly optimization, so the trends that can be using the binned periods are extremely relevant.

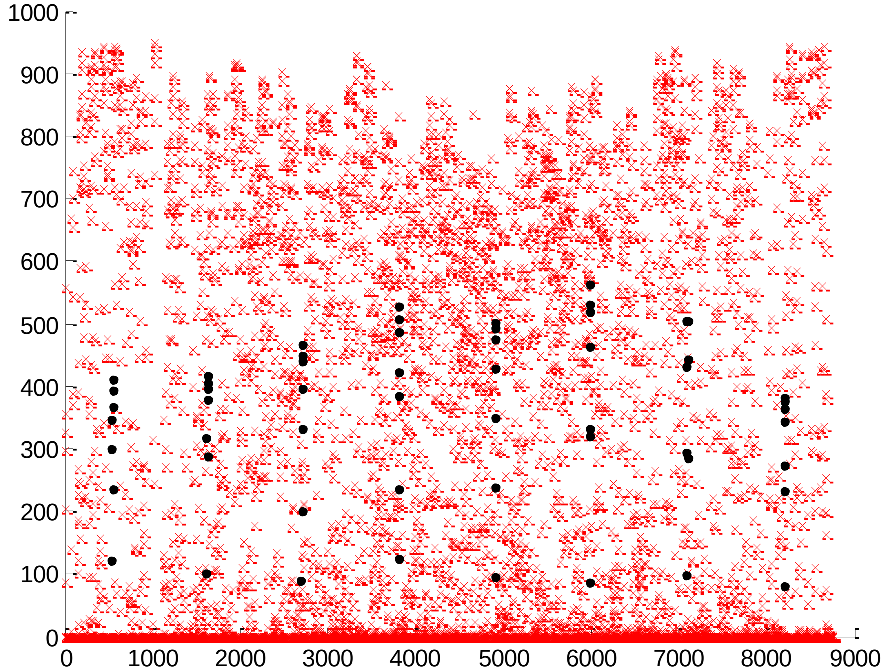


Figure 15: Full and condensed direct normal solar radiation climate data (lux vs. hour of the year).

The actual periods and center hours vary with location due to variations in the length of solar day. Therefore, for each climate location, a unique set of condensed climate data has been created.

Chapter 5
Relative Energy Impact (REI)

The Relative Energy Impact (REI) is a performance metric that describes the heating and cooling energy that can be attributed to the fenestration system as compared to the reference case. The goal of this metric is to communicate information about the balance of heat gains and heat losses due to the system on an annual basis.

5.1 Defining the REI

The REI is intended to allow users to make an informed decision about the characteristics of a complex fenestration system as they apply to the building's energy consumption. Fenestration systems contribute to energy use in three distinct ways, as shown in Figure 16, left. Each of these factors should be considered in the definition of the REI:

1. Heat loss across the surface of the façade.
2. Heat gains due to solar infrared.
3. Lighting electricity.

The innovation of the REI over other energy metrics is its ability to relate these technical characteristics to annual performance of the system. Each of these components can be calculated for each hour of the year, but simply identifying the net energy use without context is not useful. Thus, the REI will relate energy use associated with the fenestration system with environmental conditions in each of the 14 climate zones presented previously.

For each hour of the year, the net heat loss or gain as a result of heat loss across the surface of the façade and heat gains due to the sun can be calculated, as shown in the temporal map in Figure 16, right.

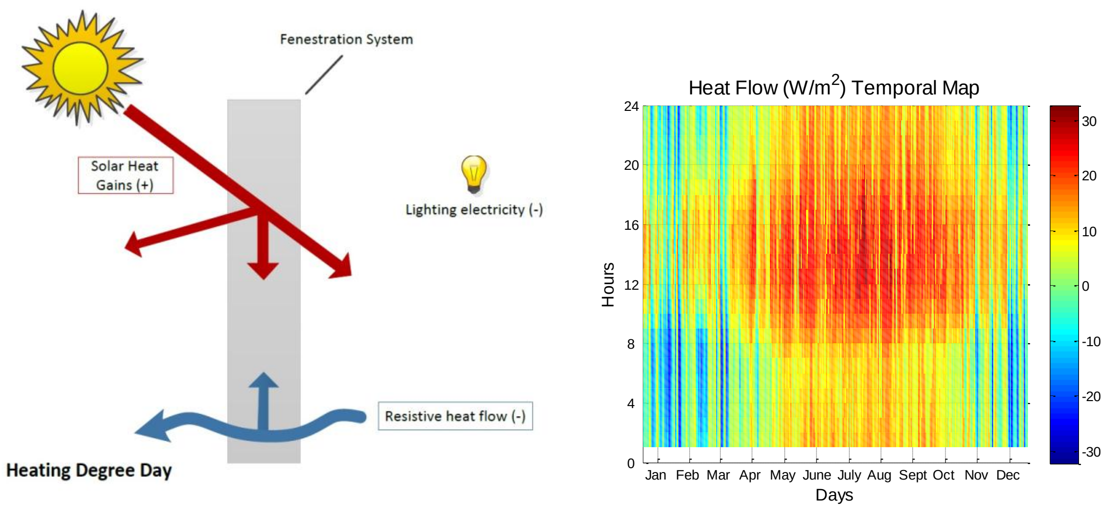


Figure 16: Schematic of net heat transfer (left), and a sample temporal map that shows the instantaneous net heat transfer for the entire year (right).

Then, each of these values can be related to the building energy system by identifying whether the building would be using a mechanical heating system or cooling system. If the net heat flow is into the building during the heating season, it is a benefit. If the net heat flow is out of the building during the heating season, it is a loss. Similarly, if the net heat flow is into the building during the cooling system, it is a loss because the cooling system must compensate. Each of these cases will be considered in order to arrive at a single value that represents annual performance.

In order to relate this definition of annual performance to that of the reference case system, a percent difference approach will be used. A simple ratio will not provide users with context about the base case scenario, but a percent difference will enable them to identify how systems are performing with respect to a standard alternative. If energy use reduction is a priority, the system with the highest REI value is the clear choice.

5.2 Initial Calculation Approach

The initial calculation approach describes how each of the three factors of energy performance is calculated as a function of the fenestration material properties and external climate conditions. It will also present how, mathematically, these parameters are related to annual performance.

In its full resolution approach, the REI is calculated for the 14 different climate locations in the United States and the four cardinal directions. This is to ensure that both climate and orientation dependency of a fenestration system's performance is revealed. Thus, each of the calculations described here are conducted for 56 different scenarios, for each fenestration system.

5.2.1 Resistive Heat Transfer

The first component of fenestration energy use is heat transfer across the façade. Just like any other surface, fenestration systems conduct heat across between interior conditions and exterior conditions. Unlike walls, ceilings, and floors, however, there is no additional insulation that resists heat transfer. Thus, windows are usually considered the thermal weak point in the surface of a façade. For the REI, a simple, independent heat transfer model was created and vetted through comparison with other validated models.

Heat transfer models have been developed to calculate the amount of heat that is transferred across a fenestration system as a result of this phenomenon. The current mechanism for calculation uses a single set of environmental conditions to determine the NFRC-specified U-factor, a measure of how much heat transfer resistance a surface exhibits (NFRC, 1997). This is done using a radiosity model developed by Lawrence Berkeley National Laboratory and packaged in the Window program. This method accounts for internal reflection and radiation interactions between layers of a fenestration system, but insofar as they are parallel and planar (Carlie, Inc., 2006).

Because, most complex fenestration systems are *not* parallel or planar in the ways that this model assumes, the additional benefits from considering these interactions do not apply to complex fenestration systems. From venetian blinds to prismatic panels, this assumption cannot inherently describe the physical characteristics of the systems. Furthermore, the model also assumes that interior reflections are predictable as they would be for a clear glazing. In the absence of detailed BRDF (bidirectional reflection distribution functions) for individual layers, it does not add accuracy to include this component. All of these concerns are masked by a simple user interface on the software which might lead a user to believe that any fenestration configuration will yield accurate results. In an effort to maintain transparency and remain faithful to the goal of this metric, a simple heat transfer coefficient model was developed to calculate the resistive heat transfer of a complex fenestration system to achieve the same level accuracy as the unfounded radiosity assumptions would.

Thus, interior condition assumptions provide values for the internal convective heat transfer coefficient due to natural convection and the internal radiative heat transfer coefficient as a function in indoor room temperature. Similarly, exterior condition assumptions allow calculation of the external convective heat transfer coefficient as a function of wind speed parallel to the façade surface and the external radiative heat transfer coefficient as a function of the exterior root-mean-squared temperature. Material properties – number of glazing layers, material of glazing layers, thickness of gaps, and gas in gaps – were used to develop the internal material conductive resistance to heat transfer.

These three components, the interior heat transfer coefficients, the exterior heat transfer coefficients, and the façade layer and gap heat transfer resistance can then be combined into the total instantaneous heat flow per unit area on an hourly basis, as shown in the flow diagram in Figure 17.

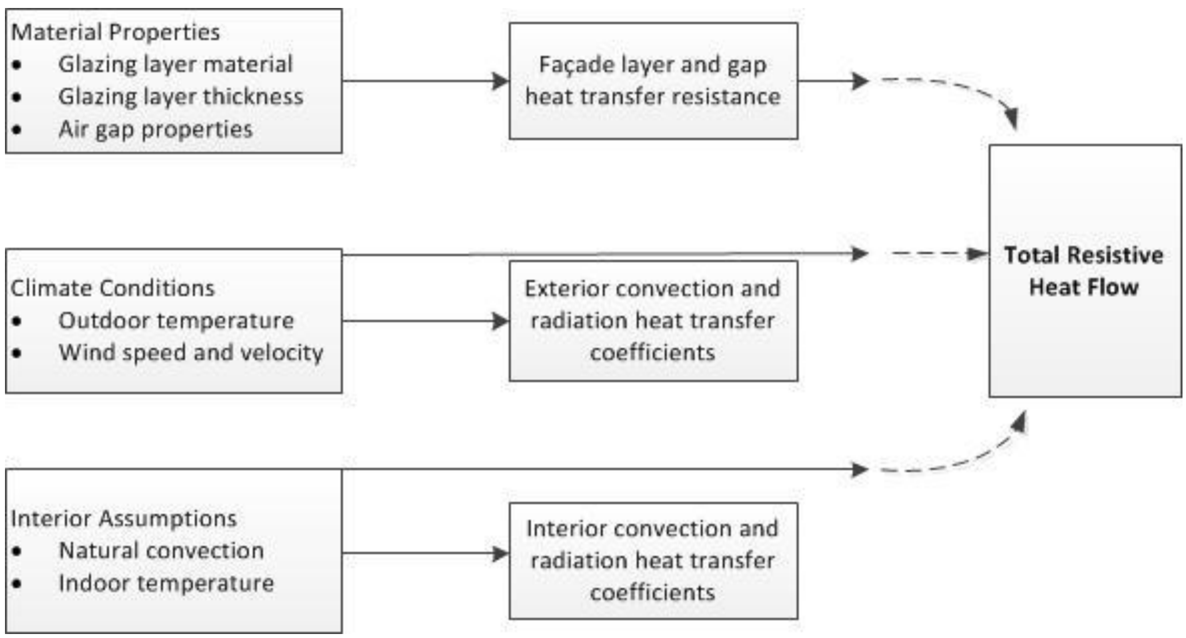


Figure 17: Flow diagram showing calculation of the resistive heat transfer across a fenestration system.

As mentioned previously, the traditional metric that considers these interactions is known as the U-factor and has calculation procedures specified by the NFRC. The U-factor is the ratio between total heat flow and the temperature difference associated with interior and exterior conditions. Both the calculation of the total heat flow and this temperature difference are directly dependent on environmental conditions, thus so is the U-factor. And although the U-factor is currently reported as a single value based on assumed environmental conditions, it actually varies over the course of the year, shown in the graph in Figure 18.

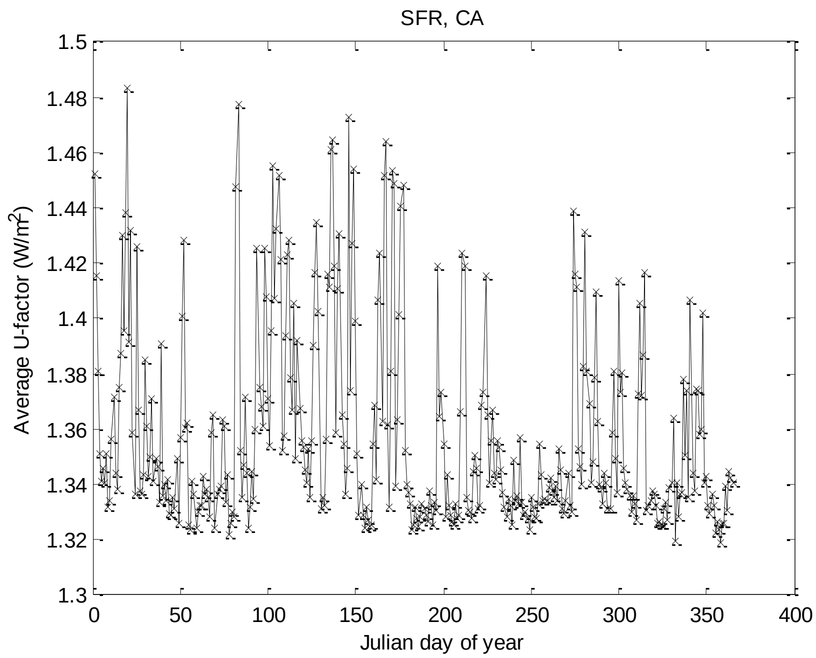


Figure 18: Daily average U-factor for a clear double-paned glazing in San Francisco, CA.

This graph shows the average U-factor for a clear glazing as a function of day for San Francisco, CA, which has only an 11% spread between maximum and minimum values, which may suggest that a single value to describe the year is an acceptable assumption. However, the average is 1.35 W/m^2 while the NFRC predicted U-factor for the same system is 2.73 W/m^2. The discrepancy is a result of the environmental assumptions selected. Because they do not match the average environmental conditions of San Francisco, their values will not match. The small spread around a value that does not match the NFRC quantity suggests that there may be a better way to define the U-factor.

5.2.2 Solar Heat Gains

The second component of the energy interactions of a fenestration system are the result of a physical phenomenon of solar infrared radiation. Fenestration systems, standard and complex, are transmit some fraction of the incident infrared solar radiation. Walls, floors and other opaque surfaces, however, absorb this short wave solar infrared and convert it to long infrared. Windows are not transparent to long infrared, and so once solar radiation enters a space through a window and is converted to heat, it is trapped. (This principle is known as the greenhouse effect, and occurs on an atmospheric scale as well.) The trapped heat is now part of the building's interior energy system, whether it is desirable or not.

This interaction is described in traditional energy metrics by the Solar Heat Gain Coefficient (SHGC), which is defined as the proportion of incident solar infrared radiation that is transmitted across a fenestration system, and thus trapped inside a space. The Solar Heat Gain Factor (SHGF) includes incident solar radiation to report the quantity of trapped heat in Watts per square meter. As with the U-factor, calculation as defined by the NFRC is dependent on a single set of environmental conditions that does not result in accurate extrapolation to annual performance because complex fenestration systems are angularly dependent in the quantity of solar infrared that they transmit (NFRC, 1997).

In order to relate the fenestration systems to its contextual environment, latitude and longitude coordinates can be used to calculate the exact position of the sun at each hour of the year. This identifies the direction from which the direct solar radiation is coming and falling on the fenestration system.

Because TMY 3 climate data provides direct normal solar radiation and horizontal diffuse solar radiation, some initial calculations must be conducted to determine the quantity of solar radiation reaching the surface. Using this data, the quantity of direct radiation that reaches a vertical window can be determined using Equation 11. Similarly, the quantity of diffuse and reflected radiation that reaches the vertical fenestration system can be determined using Equations 12 and 13, where the angle i is the incident angle of the sun on the (vertical) slope, α is the slope of the vertical surface (90 degrees), and α_s is the ground surface albedo. Equation 14 sums the diffuse light from the sun with the diffuse light from ground reflectance for a single value of diffuse light (Hay, 1993).

$$I_{direct,vertical} = I_{direct,normal} \cdot \cos i \qquad \textbf{11}$$

$$I_{diffuse,vertical} = 0.5 \cdot (1 + \cos\alpha) \cdot E_{diffuse,horizontal} \qquad \textbf{12}$$

$$I_{reflected,vertical} = 0.5 \cdot \alpha_s \cdot I_{global,horizontal} \cdot (1 - \cos\alpha) \qquad \textbf{13}$$

$$I_{diffuse,total} = I_{diffuse,vertical} + I_{reflected,vertical} \qquad \textbf{14}$$

Knowing both the quantity and direction of direct solar radiation, the BTDF is then used to determine the angularly-dependent direct transmissivity, $\tau_{direct,}$ and absorbtivity, α_{direct}, using Equations 15 and 16. Similarly, under the assumption that diffuse and reflected light reaches the façade surface from all exposed angles equally, both from the sky and from the ground, the angle-independent diffuse transmissivity, $\tau_{diffuse,}$ and absorbtivity, $\alpha_{diffuse}$, can be expressed as the average of all angle-dependent transmissivities and absorbtivities, as shown in Equations 17 and 18.

$$\Phi(\theta_1, \phi_{1,} \theta_2, \phi_2) = \begin{cases} 2\pi \cdot BTDF_{direct} \cdot (1 - \cos(\alpha)) \cdot \cos\theta_2,\ for\, \theta_2 = 0 \\ BTDF_{direct} \cdot \sin(\theta_2) \cdot \cos(\theta_2) \cdot d\theta \cdot d\phi, else \end{cases} \qquad \textbf{15}$$

$$\tau_{direct} = \sum_{\theta_2 = 0}^{\theta_2 \max} \sum_{\phi_2 = 0}^{360 - d\phi_2} \Phi(\theta_1, \phi_{1,} \theta_2, \phi_2) \qquad \textbf{16}$$

$$\tau_{diffuse} = \frac{\sum \tau_{direct}}{145} \qquad \textbf{17}$$

$$\alpha_{diffuse} = \frac{\sum \alpha_{direct}}{145} \qquad \textbf{18}$$

The last parameter required to calculate the vertical angle-dependent Solar Heat Gain Factor is the inward flowing fraction of energy. This value indicates what fraction of absorbed energy is released to the inside, as opposed to released to the outside, and can be determined as the following ratio of the indoor and outdoor heat transfer coefficients, h_i and h_o respectively. The outdoor heat transfer coefficient is a function of the horizontal normal wind speed with respect to the inclined surface, V_s, while the indoor heat transfer coefficient is assumed to be a constant based on natural convection calculations (Li et al., 2002).

$$N_i = \frac{h_i}{h_i + h_o} \qquad \mathbf{19}$$

$$h_0 = 16.21 \cdot V_s^{\ 0.452} \qquad \mathbf{20}$$

$$h_i = 8.29 \frac{W}{m^2} \qquad \mathbf{21}$$

Finally, the combination of quantity of solar radiation $I_{direct/diffuse}$, the direct and diffuse transmissivities and absorbtivities, and the inward flowing fraction of energy can be used to determine the vertical, angle-dependent Solar Heat Gain Factor (Li et al., 2002).

$$SHGF_{vertical} = I_{direct,vertical} \cdot (\tau_{direct} + N_i \cdot \alpha_{direct}) + (I_{diffuse,total}) \cdot (\tau_{diffuse} + N_i \cdot \alpha_{diffuse}) \qquad \mathbf{22}$$

The workflow for this calculation procedure is shown in Figure 19. The result is the instantaneous heat transfer due so solar gains across a fenestration system for each hour of the year.

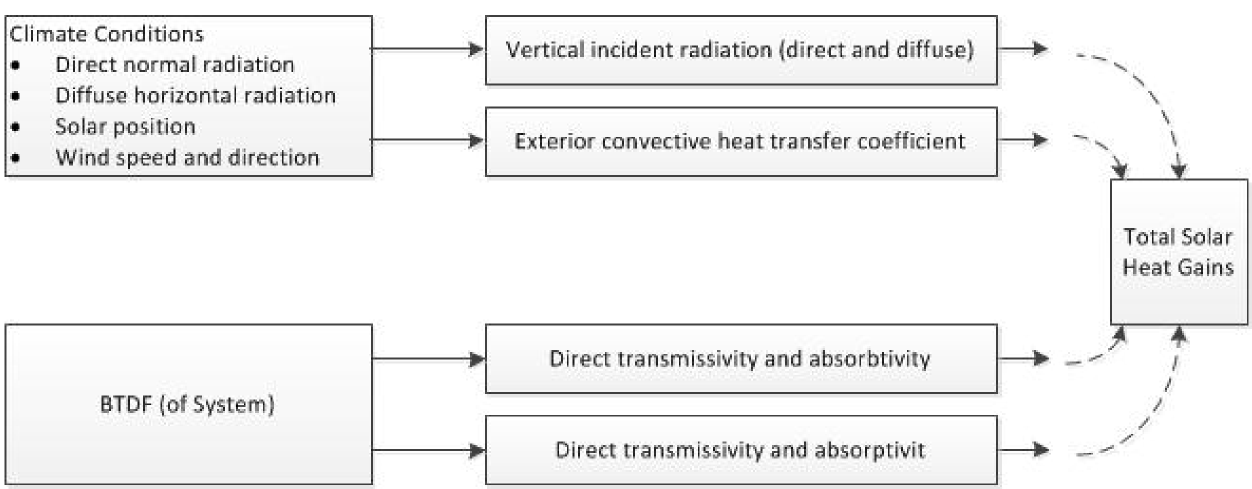


Figure 19: Workflow for calculating solar gain heat flow across a fenestration system.

As with the resistive heat flow, the angle-dependent solar heat gains are calculated for each hour of the year. This combined with the resistive heat flow (positive indicates flowing into the building) results in the hourly net heat flow associated with the fenestration system.

5.2.3 Heating and Cooling Load/Contribution

Once the net heat flow due to the fenestration system is calculated for each hour of the year, it must be identified as being a contribution to the mechanical HVAC system or a load to the mechanical HVAC system. This converts abstract annual energy values about the fenestration system into a performance metric that relates to the building's holistic energy system. Concepts from two established energy assessment methods were used to accomplish this task: the Balance Point Method and the Degree Day Method, both of which are endorsed by ASHRAE (ASHRAE, 2009).

The Balance Point Method identifies the outdoor temperature at which mechanical cooling is switched to mechanical heating, known as the balance point temperature. The balance point is affected by interior loads, façade construction, and the type of mechanical HVAC systems used, among other parameters, but none of these factors relate directly to the fenestration system. Meanwhile, the Degree Day Method provides information about how many hours of the year a building uses mechanical heating systems (Heating Degree Day, HDD) and cooling systems (Cooling Degree Day, CDD) (ASHRAE, 2009).

Using the combination of these two concepts, and assuming all other factors stay constant because they are not factors of the fenestration system decision, we define a balance point temperature that is widely accepted as being relevant to commercial office buildings. Thus, when the daily average exterior temperature exceeds this temperature, it is considered to be a cooling degree day (CDD) and when it is below this temperature, it is considered to be a heating degree day (HDD). The balance point temperature used was obtained by studies conducted by ASHRAE on commercial buildings, and is set at 18 degree Celsius (ASHRAE, 2009).

The rational for using the day's average temperature accounts for some existence of thermal mass and assumes that a mechanical HVAC system cannot switch between heating and cooling efficiently for an hourly timestep. It also assumes that the HVAC system serves the entire building and that independent zones are not being heated and cooled simultaneously.

Thus, when the day's average temperature is greater than 18 C, the cooling system is on and a positive inward flow of energy is a load to the system, as depicted in Equation 23. Similarly, when the day's average temperature less than 18 C, the heating system is on and a positive inward flow of energy is a contribution to the system, shown in Equation 24.

$$q_{load} = \sum_{Tout,average>18} q_i \qquad \textbf{23}$$

$$q_{contribution} = \sum_{Tout,average<18} q_i \qquad \textbf{24}$$

These two types of heat flow, q_{load} and $q_{contribution}$, are then combined into a single annual energy score for the fenestration system, where a more positive value indicates more energy saved in the form of contributions to the mechanical heating and cooling system. This value is expressed in terms of Watts per square meter of fenestration area, as shown in Equation 25.

$$q_{annual} = q_{contribution} - q_{load} \qquad \textbf{25}$$

Finally, this abstract value in W/m^2 must be compared to the reference fenestration system for the reasons described previously for using a relative approach. The REI value is determined by calculating the percent difference of the annual energy score as compared to the annual energy score of the reference case, as shown in Equation 26. It is not expressed as a simple ratio because the relevant information to the user is how much better or worse the selected system is performance as compared to a standard alternative.

$$REI = -\left(\frac{q_{system} - q_{reference}}{\left|q_{reference}\right|}\right) \qquad \textbf{26}$$

The workflow for this last step is depicted schematically in Figure 20.

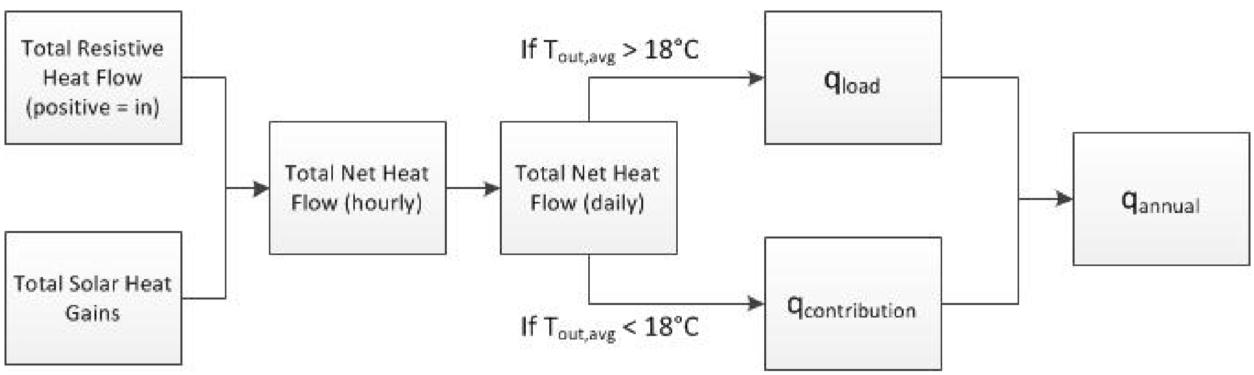


Figure 20: Workflow for determining REI from hourly heat transfer calculations.

5.2.4 Lighting Potential

The third important energy aspect of a fenestration system is its contribution to electric lighting requirements or reduction. It is obvious that permitting daylight allows the potential of reduced artificial lighting, but less obvious is exactly how much energy it is offsetting, as well as its secondary effect on the cooling system of the building. Electric lights consume different amount of energy per square meter of area, and similarly, give off different degrees of waste heat which, during the cooling season, need to be eliminated by the mechanical cooling system. Inefficient incandescent bulbs consume many times more electricity than their light emitting diode (LED) counterparts to achieve the same light levels. Incandescent bulbs also release more waste heat than do LEDs, but some people prefer the quality of light as well as the inexpensive up-front cost of incandescent bulbs. Thus, the decision is not trivial.

The REI as a performance metric is not intended to address issues of artificial lighting selection; its primary purpose is to inform the user about energy decisions made with regard to the fenestration system. As a result, the REI does not make an effort to endorse or disregard any type of artificial lighting strategy and thus cannot provide direct information about electricity and waste heat quantities. Instead, the lighting potential concept is introduced.

Lighting potential is a function of the quantity of lux that is required to supplement daylight by artificial lighting to provide acceptable lighting conditions. Analytically, it is shown in Equation 27, where $E_{acheived}$ refers to the achieved illuminance by daylighting and E_{target} is the target illuminance, in lux.

$$LightingPotential = 1 - \frac{E_{target} - E_{acheived}}{E_{target}} \qquad \textbf{27}$$

The data for this calculation are provided from the calculation methodology described for the ECD for 56 moments and using the lighting simulation program Radiance. For each square meter of floor area, the average horizontal workplane illuminance is determined. The artificial lighting requirement is the difference between the minimum allowable level of 300 lux and the average of the area. There is no credit given for achieving higher lighting levels. This approach therefore takes into account both quantity and distribution of daylight for a fenestration system. The higher the total value calculated, the lower the lighting potential is for the fenestration system, as shown by the three-dimensional graph in Figure 21. The horizontal plane is the surface of the generic test module and the vertical axis shows lux. A southern facing window is located on the left plane.

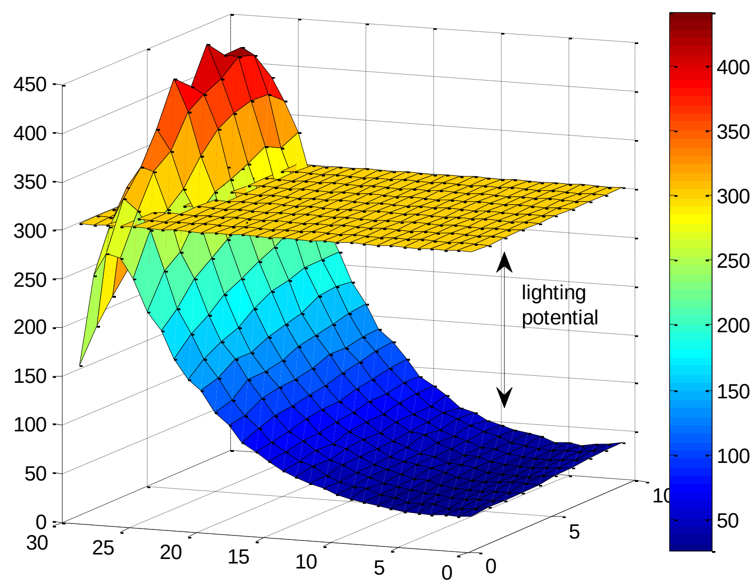


Figure 21: Graphical representation of the lighting potential of a north-facing fenestration system at a specific moment.

Again, because a discussion of artificial lighting efficiency is not directly relevant to the fenestration system's ability to provide natural light, this information is purposely *not* converted into units of electricity or cooling energy (both would be expressed in Watts per square meter of floor area). Today, artificial lighting is a popular discussion and the industry is witnessing considerable advances in LED technology. Addressing lighting potential based on current assumptions about a transitioning industry would make the metric obsolete in the foreseeable future and further go against the goal of performance metrics as a means to describe rather than to prescribe. Furthermore, it is impossible to predict user behavior, which will affect the artificial lighting load considerably.

Because the lighting potential is not expressed in units of energy, it cannot be combined with the previous component of the REI. Therefore, it will be expressed as a separate value and portrayed visually on the label concept presented at the end of this chapter.

5.3 Reduction Approach

The calculations from the previous section result in an REI value for each climate zone and cardinal orientation, for each complex fenestration system. It is easy to understand that these 56 values cannot be reported in a manner that can be easily understood by a user, and thus a reduction of input resolution is required to condense this data to some degree. The goal of this section is to identify the critical parameters of the REI calculation through a sensitivity analysis and use only the important and unique parameters to calculate a reduced quantity of REI values. A graph of full resolution REI values for the five complex fenestration systems and the reference system is shown in Figure 22. Similar graphs for each other orientation are available in Appendix B.

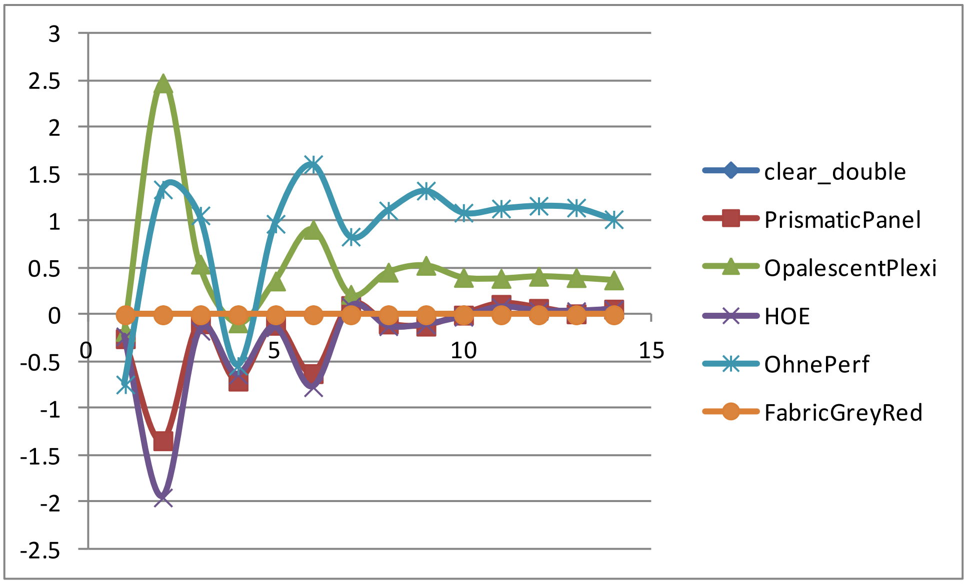


Figure 22: REI values for 14 climate zones (south façade).

First, the results from the initial calculation approach were analyzed to identify trends across the four cardinal orientations. Because the east and west orientations experience symmetric solar incident angles, the energy calculation differs only due to amount of incident solar radiation (a function of cloud cover and intensity) and wind direction and speeds. These two factors are not as critical to the REI value as the solar position is, and as a result, east and west REI values are essentially equal. Thus, we eliminate one cardinal orientation from the calculation procedure.

Second, we evaluate the impact of climate location on the final REI value. By conducting sensitivity analysis on the climate conditions used to calculate the REI, we found significant dependency on latitude as well as annual outdoor temperature variation. Because the critical aspect of the REI metric is being able to identify the relative performance of complex fenestration systems, i.e. their ranking, climate zones were identified based on consistent ranking for each orientation. Because some orientations saw more climate dependency than others (what would have been one climate zone for north might include two climate zones for south), the zones were split into their most precise for all orientations to maintain consistency. The use of only five complex fenestration systems may have an impact on this methodology, but for this framework, three climate zones were identified. Future work will have to validate three climate zones for a greater number of systems to ensure coincidences were not misconstrued as climate zones.

Using a reduced three climate zones identified with this sensitivity analysis, the REI calculation process can predict accurate REI rankings for the five sample complex fenestration systems. These three zones are shown in Figure 23.

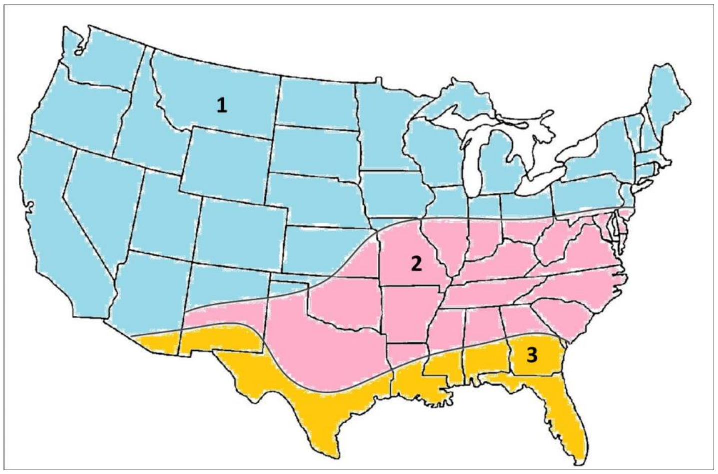


Figure 23: Map of United States split into 3 climate zones for REI evaluation.

As with the IECC climate zones from which these three were derived, a single climate location can be used to represent the statistical climate conditions for the zone. The representative climate location was determined by identifying the climate location that produced REI values with the least variance for all other locations represented by the zone. Thus, this representative climate location is specific to the calculation methodology of the REI and cannot be used for other purposes.

Using the least-squared method for the REI value, depicted in Equation 28, a single representative climate location was determined for each of the three zones. Zone 1 in Figure 23 is represented by Helena, Montana; zone 2 is represented by Memphis, Tennessee; and zone 3 is represented by Phoenix, Arizona.

$$location = \min\left(\sum_{location} (REI_{location,system} - REI_{mean,location}\right)^2 \qquad \textbf{28}$$

Third, the potential for using a single U-factor value to predict annual performance was evaluated. But since the goal of this process is to *reduce* the complexity of the calculation procedure, this approach was not pursued. As shown previously, the environmental conditions suggested by the NFRC do not do an accurate job of predicting the climate-dependent U-factor. When the annual average U-factor was used, however, it could predict the REI to within 10%. Determining the annual average U-factor for each climate for each system still requires calculation of the hourly U-factor. Thus, this approach requires an additional step to produce reduced accuracy; neither of which contributes to improving the REI calculation methodology.

5.4 Analytical Assessment

The results from the previous sections provide insight into a revision of an existing traditional metric that may be interesting to the NFRC and an intermediate approach to communicating about complex fenestration system. As mentioned before, the current singular environmental and incident conditions that are used to describe the U-factor and SHGC are not representative of climate-based annual performance. One approach to improve the accuracy of these traditional metrics is to evaluate them annually and include climate dependence. While this does not provide the connection to a building's energy system as does the REI, it does provide more information to the user than the current metrics.

Specifically, an annually-weighted U-factor could be determined for each climate zone. Similarly, an angle-dependent and annually-weighted SHGC would be a much more accurate representation of a complex fenestration system.

Using the angle-dependent solar heat gains calculated on an hourly basis previously, Equation 29 shows how a corresponding hourly and angle-dependent SHGC can be determined.

$$SHGC_{weighted,angle} = \frac{I_{direct}(\tau_{direct} + N_i \cdot \alpha_{direct}) + I_{diffuse}(\tau_{diffuse} + N_i \cdot \alpha_{diffuse})}{I_{direct} + I_{diffuse}} \qquad \textbf{29}$$

This hourly value is then averaged for the year, thus weighing each hour of the year equally in contributions to the SHGC. The following table compares the normal incident SHGC and angle-dependent SHGC for a standard fenestration system.

Table 3: Normal incident SHGC vs. an annually-weighted angular SHGC for a standard fenestration system.

		North			East/West			South		
Normal Incidence Transmission	NFRC SHGC	Zone 1	Zone 2	Zone 3	Zone 1	Zone 2	Zone 3	Zone 1	Zone 2	Zone 3
0.82	0.76	0.15	0.16	0.16	0.30	0.31	0.31	0.35	0.29	0.28

As shown in Table 3, the annually-weighted and angular SHGC is considerably lower even for a standard fenestration system. This is due to the overstatement of transmission when it is a function only of the normal incident angle. Furthermore, this approach reduces the impact of diffuse light because it is transmitted from all directions. The table also suggests that climate dependency for this fenestration system is limited to a South facing façade.

This example shows that the angle-dependent SHGC is considerably different from the SHGC defined by the NFRC. Because the angle-dependent SHGC considers all hours of the year equally, while the NFRC relies on a single (infeasible) moment of the year, the former is arguably more representative of actual performance. Fenestration systems, whether standard or complex, should not be required to compete on a metric that is misrepresentative of actual conditions and thus, consideration should be afforded to revise the current traditional metric definition.

5.5 Validation Study

There are two widely used simulation software packages that are relevant to the calculations made for the REI. The first is Window 6, a package from Lawrence Berkeley National Laboratory that calculates the NFRC-required specifications for a façade with properties from the International Glazing Database (IGDB). Window 6 has recently incorporated angular calculation components and can, in beta versions, create a BTDF for a façade (Window 6.1, 2006). Its heat transfer calculations are based on a radiosity method that includes inter-layer reflections and transmission quantities (Carli, Inc., 2006). It however, assumes parallel and planar surfaces in all cases (Carli, Inc., 2006; Rubin, 2010.) Individual U-factor calculations were compared to the results from this package in order to establish the accuracy of the heat transfer model developed for the REI.

The second simulation package was created by collaborations through the United States Department of Energy and is known as EnergyPlus. Although the simulation engine was developed in the public domain and is free for download, a number of private companies have developed user interfaces that make the program more accessible, relevant, and encourage use in the industry. The engine simulates the complex interactions among the building's energy systems and conducts annual energy analysis for a space. These interactions include mechanical heating and cooling, water systems, electricity, internal heat transfer, daylight and windows, among others (EnergyPlus, 2010). It is widely considered the industry standard in building energy simulations, and complete building analysis requires specialized expertise. Full building energy calculations from EnergyPlus were conducted to validate the fenestration system's effect on full-building energy analysis.

In comparing the U-factor determined using NFRC environmental conditions in both Window 6 and with the heat transfer model developed for this thesis for the clear double glazed system, the error was 11%. This standard fenestration system is the only system evaluated in this work that can accurately be considered using the Window 6 program. And, as described previously, Window 6 includes radiosity in its calculations (Carli, Inc., 2006; Rubin, 2010). Assuming that the prediction from Window 6 is accurate and well validated (Carli, Inc., 2006), this suggests that for parallel and planar surfaces, the simplified heat transfer model developed for this work can predict results with reasonable accuracy.

The Solar Heat Gain Factor calculation method was presented by Li et al. and has been shown to be an accurate predictor of measured solar heat gains in a number of different climates (2002). Further, the solar gains determined using this method were compared to those reported by ASHRAE for a standard clear double glazed system (ASHRAE, 2009). These ASHRAE values are typically used as a reference for additional building energy analysis calculations. The SHGF model proposed by Li et al. predicts the ASHRAE reported solar gains within 5%, indicating that this portion of the calculation process is accurate as well.

Finally, EnergyPlus was used to validate the fundamental assumption that the REI speaks to the fenestration's contribution to energy consumption in the context of multiple, interacting building systems. In other words, the results from the EnergyPlus simulations will ideally predict relative building performance in the same way as the REI does, but the REI does so without requiring a full building energy analysis. Although EnergyPlus has incorporated the use of BTDFs in its engine, the inputs are only relevant to the daylighting simulation module, not the heating and cooling load component

(EnergyPlus, 2010). As a result, only fenestration systems that have been individually incorporated into the system could be analyzed and compared to REI results.

Four fenestration systems were selected and EnergyPlus was run for the reference small office building as described by the DOE, located in a city *not* represented by one of the fourteen reference city: Boulder, Colorado. This building represents a space that is not the generic test module. Because EnergyPlus does not accommodate BTDFs in the heat transfer portion of the energy simulation, it was not possible to model the exact fenestration systems that were analyzed in the development of the REI. While this precludes direct comparison to the REI values, the overall performance characteristics can be observed using both calculation procedures. Three broadly defined fenestration systems were modeled: clear, diffusing, and shading. From these, a general understanding of the trends was desired. The following questions were posed and answered:

- Does shading decrease cooling energy use more than it affects heating energy use (leading to a total reduction in energy use)?
- What is the relative effect of a diffusing fenestration in each orientation?
- How do east and west total energy use compare?
- In this climate zone, is there a net energy benefit of a static shading device or diffusing glazing?

These questions allow general conclusions to be drawn from the three broadly defined fenestration systems. The results from the EnergyPlus simulations are summarized in Table 4. Greater detail is available in Appendix B.

Table 4: Results from EnergyPlus fenestration study.

Input Parameters		End use breakdown		
Direction	System	Heating (GJ)	Cooling (GJ)	Fans (GJ)
North	clear	35.65	9.5	33.31
North	diffusing	36.34	9.17	32.26
North	shade	38.78	8.3	32.26
South	clear	32.39	10.47	31.8
South	diffusing	33.58	9.83	31.69
South	shade	39	8.06	31.34
East	clear	31.68	11.68	40.14
East	diffusing	33.16	10.68	37.65
East	shade	37.47	8.44	32.68
West	clear	31.96	11.19	40.33
West	diffusing	33.16	10.36	38.22
West	shade	37.88	8.33	31.98

From the results reported above, the following answers can be derived:

- The shading device reduces cooling energy but increases heating energy by more due to lack of solar gains in cold months for north and south orientations, but reduces cooling energy by more than heating energy increase in east and west orientations.
- Diffusing glazings reduce cooling energy and the energy associated with fans more than it increases heating energy.
- East and west orientations are essentially equivalent.
- In this climate zone, there is no net energy benefit for the static shading device in north and south orientations, but there is a benefit in east and west orientations. There is a net energy benefit to the diffusing glazing in all orientations.

Each of the questions posed are either inherent in the calculation of the REI or is a piece of information that is provided by the REI. However, these answers required full building energy simulation and then further parsing and analysis of the results. Each question is deduced in the same way from the REI metric in a much more straightforward manner.

Lighting energy was not considered because the lighting potential is a metric that uses results directly from Radiance.

5.6 Summary of Results

This chapter has outlined the calculation methodology, reduction approach, analytical assessment, and validation of a new performance metric called the relative energy impact, or REI. The REI provides a user with information about the annual energy performance *of the fenestration system* and accounts for angular dependencies, climate variation, and orientation of the system.

Table 5 summarizes the final REI values for each of the five complex fenestration systems analyzed.

Table 5: REI values for five complex fenestrations in 3 climate zones.

	North			East/West			South		
	Zone 1	Zone 2	Zone 3	Zone 1	Zone 2	Zone 3	Zone 1	Zone 2	Zone 3
Clear	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Prismatic Panel	0.07	-0.09	-0.12	0.14	-0.08	-0.11	0.06	-0.63	-0.71
Opalescent Plexi	-0.28	0.09	0.14	0.36	-0.17	-0.25	0.37	0.91	-0.09
Holographic Element	0.29	-0.16	-0.23	0.25	-0.10	-0.13	0.06	-0.77	-0.64
Mirrored Blinds	0.29	-0.22	-0.31	1.36	-0.48	-0.63	1.02	1.61	-0.54
Fabric Blinds	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

As is shown, the standard clear double glazed system (the reference system) achieves a score of zero. Positive values indicate better annual performance while negative values suggest worse annual performance. A user can identify which façade orientation is relevant and which climate zone he or she is considering in order to compare results across systems. For example, given these five options, a clear glazing in Zone 2 (eastern mid-Atlantic) for an eastern façade would perform best with regard to energy use. An interior fabric blind may provide additional comfort benefits that are not directly related to energy.

In addition to being able to identify which is the best system, a user can also perceive to what degree better or worse a specific system is expected to perform. For example, considering again Zone 2 eastern façade, a user may be choosing between a shading device such as the mirrored blinds or a diffusing glazing such as the opalescent plexiglass. From this information and comparing these two specific systems, it is clear that the opalescent plexiglass will perform better in the selected configuration. A significant amount of information is contained in the table above.

Finally, an initial concept for communicating this information, along with the lighting potential information discussed previously, in a visual and relevant manner has been developed. An image such as the one shown in Figure 24 can be used on a label to concisely inform the user about the performance of the chosen system. In this figure, the REI as it applies to heating and cooling is reported on the horizontal scale, indicating better performance (to the right) or worse performance (to the left), where the reference fenestration system sits at the origin. The vertical axis shows the lighting potential value, again compared to the reference fenestration system which is also shown. Again, a more positive value suggests better lighting potential, and thus reduced energy use. The label concept was created as a way to communicate more information (e.g. the lighting potential for the REI) about the metric but also to exist as a qualitative and visual way to impart information on users. The example below shows the REI for a southern façade in Zone 2. The full label would require each orientation be shown for each of the three climate zones.

The description of final calculation methods, presentation of results for five sample systems, and introduction of a label concept for the REI metric provides the preliminary framework for a new performance metric for complex fenestration systems. This unique approach has aimed to make the metrics both usable for users and practical to calculate for manufacturers, while providing important information about the energy performance of a fenestration system.

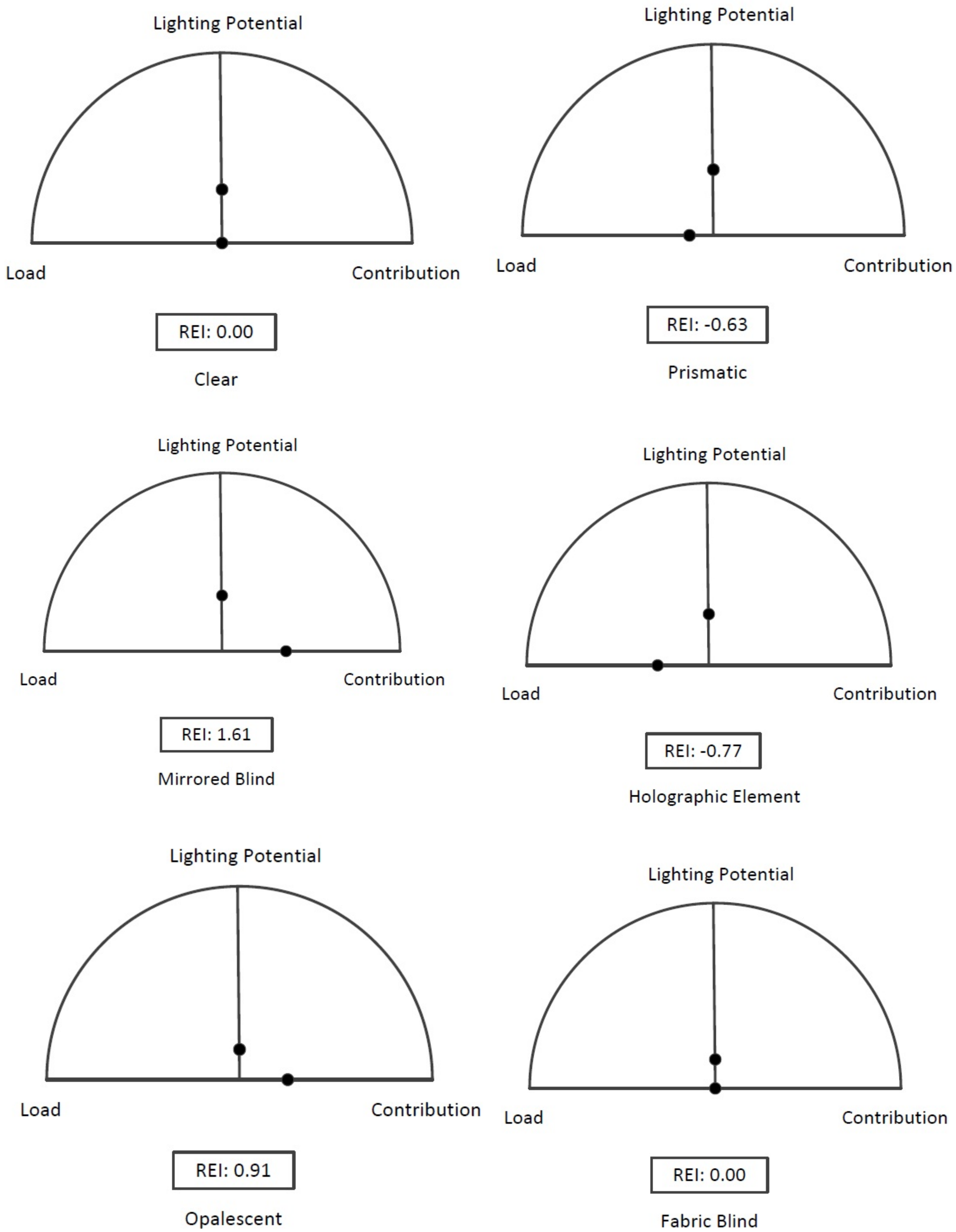


Figure 24: REI label concept for five complex fenestration systems.

Chapter 6
Extent of Comfortable Daylight (ECD)

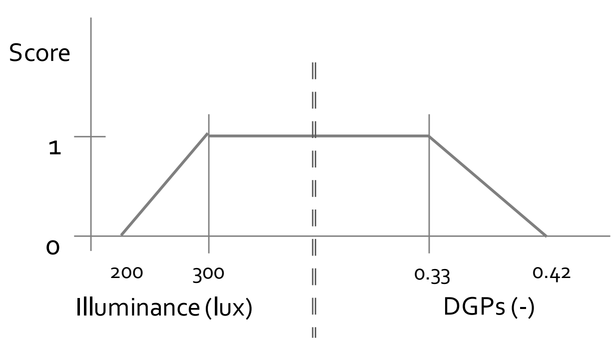
The Extent of Comfortable Daylight (ECD) is intended to provide a user with the information about the amount of time and space which can achieve comfortable daylight conditions as a result of the fenestration system. By comparing ECD values, a user can identify the complex fenestration system that provides the greatest fraction of comfortably daylit conditions for the orientation desired.

6.1 Defining the ECD

Daylight, as was discussed previously, has many health and well-being benefits for indoor occupants, but also presents the challenge of glare, or a sufficiently high luminance contrast ratio that occupants cannot comfortably view their task or computer screen. A substantial body of research exists in defining comfort parameters and metrics for daylight. These traditional metrics enable prediction of comfort in a daylit space.

The Extent of Comfortable Daylight (ECD) is intended to relate these spatial concepts to the performance of the complex fenestration system which achieves them. Visual comfort inside a space has not been related to the fenestration system before, rather the existing NFRC-specified visible transmittance (VT) metric is used to make assumptions about interior conditions based on location. For example, if a southern exposure space may receive too much light, a reduced VT for a standard fenestration system would be considered. Complex fenestration systems do not perform linearly and cannot be defined properly with a single VT value. As a result, an explicit performance metric that describes the fenestration system is defined here.

First, a method to measure comfort was required. Drawing on the literature, two thresholds were established to define a comfort range. The lower threshold suggests that without artificial lighting, the space will not be sufficiently lit. This is quantified in a horizontal workplane illuminance threshold of 500 lux, as recommended by the IESNA (1982). The upper thresholds indicates that there is a substantial chance of glare, and is quantified by the Daylight Glare Probability (simplified) index. According to Weinold and Christoffersen, a space that achieves greater than 0.33 DGPs suggests discomfort glare is present for the occupants (Weinold, 2007). However, because comfort is not a binary system – a space that achieves 499 lux is not absolutely required to add artificial lighting for comfort – a linear gradated approach was used. This concept is shown graphically in Figure 25, left, and has precedent in the UDI (Nabil and Mardaljevic, 2006). In the graph, a "score" of 1 indicates full comfort and a "score" of 0 suggests discomfort. This metric is also the first to define comfort using two separate, but mutually exclusive, scales for thresholds.



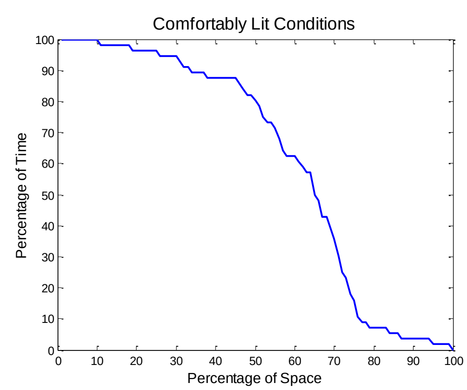


Figure 25: Gradated scoring system for determining the ECD metric (left), and a sample visual representation of the relationship between space and time that is comfortable (right).

Both the illuminance and glare thresholds can be ascertained for any given position and view direction in the space. In an effort to relate these quantities to the fenestration system, rather than the space, the interior space generic test module was split into sensor position that each represent a square area of 0.09 m^2. The year is evaluated by using 56 moments that each represent a period of the daylit year for a given climate location. Thus, using Radiance lighting simulations, it is possible to determine the percent of the space that achieves this definition of comfortable conditions for each period of the year. Shown graphically in an example in Figure 25, the relationship between percent of space that is comfortable and the percent of time which exhibits those comfortable conditions is an inverse relationship. Using this graph, users could identify a criterion that indicates how much of the year they expect a certain percentage of the space to achieve comfortable conditions. For example, if the requirement that 50% of the space if comfortable, this graph shows that this occurs for about 70% of the year. If the requirement is 80%, it is apparent that this only occurs for 10% of the daylit hours of the year.

Using the following calculation procedure, the information shown in Figure 25, right, is then condensed into a single quantity that defines comfort performance in the space.

6.2 Initial Calculation Approach

As before, the information that is used to determine the ECD must also be computed annually for each of four orientations at each of fourteen climate locations. Lighting simulation software Radiance was used to evaluate each complex fenestration system. Radiance must use the BTDF information to conduct the calculations necessary for evaluation. Radiance has been well-validated in this area of ray-tracing for complex geometries as well as annual simulation, but the ability to use BTDFs in Radiance in a time efficient manner for annual simulations was only recently developed (Ward, 2009; Saxena et al., 2010). This process, known as Dynamic Radiance, uses the BTDF to convert the fenestration system into a directional light source that can then be related to interior lighting conditions.

6.1.1 Dynamic Radiance

More specifically, Dynamic radiance utilizes three discrete phases to determine interior lighting conditions. These are described as follows (Ward, 2009):

- Phase I: Generate a daylight coefficient matrix that relates sky patches (containing climate conditions) to incident conditions on the façade (*genskyvec* samples the fenestration system from sky patches, *rtcontrib* calculates the daylight coefficient matrix).
- Phase II: Generate a coefficient matrix that relates emerging directions from the façade to sensor locations within the space (*genklemsamp* converts the emerging directions of the fenestration system into the equivalent of a light source, *rtcontrib* calculates the coefficient matrix).
- Phase II: Conduct time step calculation between sky matrix, incident conditions, BTDF, and emerging conditions (*dctimestep* relates each of these matrices to the BTDF and sensor positions).

The inputs required for this computation include climate conditions (direct and diffuse solar radiation, sky type, and sky clearness) to define the sky, physical definitions (for generic test module, sensor positions, material properties, and exterior ground) to define the space, and the BTDF for the complex fenestration system. Radiance accepts the Klems basis BTDF created previously in a .xml format.

The parameters used for each phase are described in Tables 6 and 7.

Table 6: Parameters for Phase I in Dynamic Radiance procedure *(rtcontrib)*.

Name	Description	Value
-c	number of rays to accumulate for each record	1000
-e	expr	MF:4
-f	source	reinhart.cal
-b	binv	rbin
-bn	nbins	Nrbins
-m	file to call for sky definition	sky_glow
-faf	file to call for model matrix	model_dmx.oct

Table 7: Parameters used for Phase II in Dynamic Radiance procedure (*rtcontrib)*.

Name	Description	Value
-c	number of rays to accumulate for each record	1000
-e	expr	MF:4
-f	source	Klems_int.cal
-b	binv	rbin
-bn	nbins	Nrbins
-m	file to call for window material	windowlight
-ab	number of diffuse bounces	3
-ad	number of hemisphere divisions for sampling	2000
-ds		0.15
-lw	minimum contribution of a ray to the final ray for it to be traced	0.0001
--	file to call for model matrix	model_vmx.oct

The following diagram depicts the Radiance workflow that conducts the calculation.

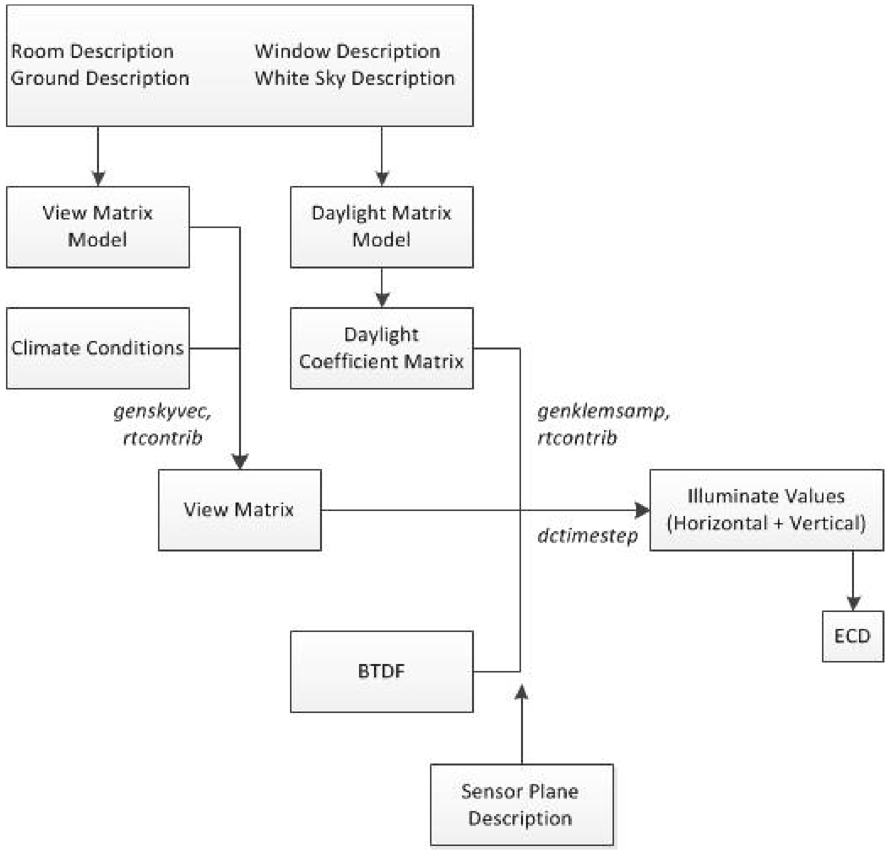


Figure 26: Workflow for Radiance simulation that uses BTDF.

In order to determine both horizontal workplace illuminance and the vertical eyelevel illuminance (used to calculate the DGPs value) for each sensor position, we use this workflow to conduct calculations for each of the 56 representative periods of the year. The process is relatively time intensive as compared to the REI calculation process; it takes about an hour to compute annual information for the 300 sensor points in the generic test module. Thus, for each fenestration system, conducting Dynamic Radiance for full resolution inputs requires over 50 hours of computer computation time.

6.1.2 Calculating the ECD

The Dynamic Radiance process generates horizontal workplane illuminance and vertical eyelevel illuminance. Although the horizontal illuminance values correspond directly with the lower threshold of comfortable conditions, the upper threshold is measured in term of glare probability. Calculating the DGPs from vertical eyelevel illuminance E_v is done as follows.

$$DGPs = 6.22 \times 10^{-5} \cdot E_v + 0.184 \quad (30)$$

Then, using these results, each sensor position is given a score between 0 and 1, where 0 represents discomfort and 1 represents full comfort, as presented previously. Thus for each of the 56 periods that represent the statistical year, a total space score can be determined using the following equation, where *i* is the sensor position and *j* is the period of the year.

$$Score_j = \frac{\sum_{i-sensor}^{300} Score_i}{300} \quad \textbf{31}$$

The annual score is computed using the scores of all the periods.

$$Score_{annual} = \frac{\sum_{j=period}^{56} Score_j}{56} \quad \textbf{32}$$

And finally, the score of a complex fenestration system is compared to that of the reference case standard fenestration system for each orientation and climate location.

$$ECD = \frac{Score_{annual,system}}{Score_{annual,reference}} \quad \textbf{33}$$

Because the ECD is a relative value is calculated for each climate and orientation, it describes the complex fenestration system rather than any of the other input variables.

6.3 Reduction Approach

A serious consideration in the practical application of this performance metric is the time required to calculate 56 ECD values for each complex fenestration system. (A secondary issue is the usability of a metric that requires 56 values to describe a system.) As for the REI before, the ECD was first evaluated in its full resolution case to identify trends and determine the sensitivity of the input parameters.

First, climate dependency was evaluated. Again as before, the goal of the reduction procedure is to maintain accuracy in terms of relative ranking of performance while reducing the complexity of the calculation. When graphed on a single graph for a given orientation, all five of the sample complex fenestration systems achieve the same relative performance ranking (in terms of the ECD value) in each of the fourteen climate zones. The following graph shows this ranking for a south facing façade; all other orientations exhibit a similar pattern and are included in Appendix C.

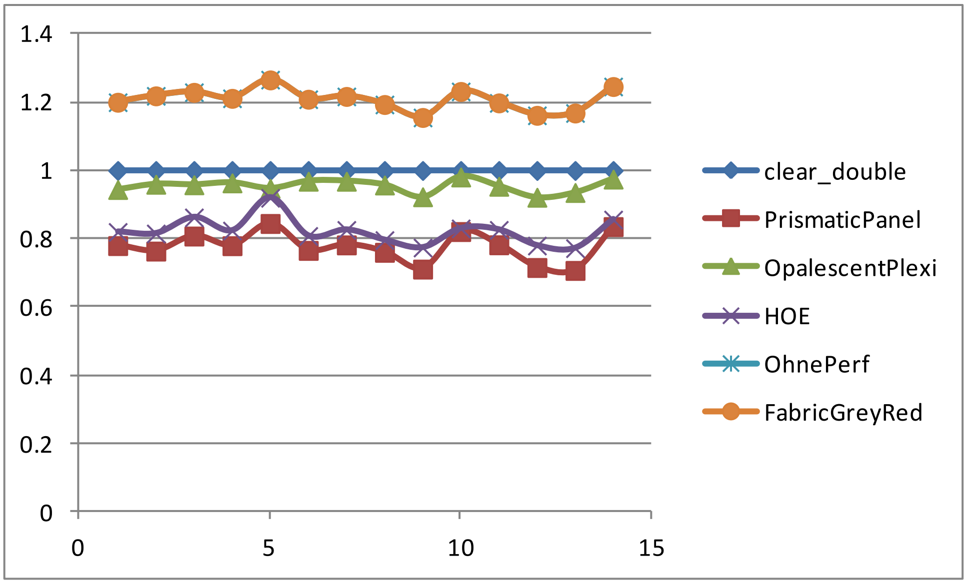


Figure 27: Ranking of ECD for complex fenestration systems for 14 climate zones (south).

As is apparent, the absolute value of the ECD varies with climate location (except for the reference fenestration system which will always stay fixed at a value of 1). However, even when values are close between systems, they never fully overlap, maintaining a fixed ranking in performance through all zones. Although the ranking itself – i.e. which system performs best etc. – is different for the other orientations, all four orientations exhibit fixed ranking, suggesting that there may be a climate location whose conditions can be used as a proxy for the entire country.

Using the same least-squared variation approach as introduced for the REI, each climate zone was evaluated as contributing to variance from the mean ECD value for the country. This approach was used in contrast to simply evaluating the average climate conditions among all climates because the latter process does not consider the effect on the ECD calculation, which is the critical component. Table 8 shows the mean-squared variance for each climate location as it relates to the ECD performance metric.

Table 8: Mean squared errors for ECD values based on climate location.

mean squared var.	
alb	0.0132782
bal	0.0023321
boi	0.0116298
bur	0.0068959
chi	0.0059454
dul	0.0041695
elp	0.0112215
hel	0.0102206
hou	0.0048297
mem	0.0006678
mia	0.0144735
pho	0.0011453
sal	0.0089213
sfr	0.0012663

The minimum variation is achieved by Memphis, Tennessee at 0.07%, indicating the potential of using a single climate location to achieve the average ECD value. Doing so results in a maximum percent error of just 0.79% in actual ECD value and maintains the relative ranking of the systems. Thus, the stated hypothesis is proved. Reducing the number of climate locations at which Dynamic Radiance must be conducted reduces the observed calculation required from more than fifty hours to less than four. Further, this reduces the number of values that must be reported to the user from 56 to 4 while maintaining accuracy to within 1%.

East and west facing façades still receive the same solar angles of incidence over the course of the year. Although cloud cover and solar intensity are climate dependent and may differ from morning to evening, the ranking of systems is identical for east and west; the same system achieves best ECD performance and so on for both. The values of ECD do differ, but using only results from only one results in an average percent error in calculation of the ECD of less than 9%. East was selected as a proxy for both, further reducing the simulation time required by an additional 25%.

Finally, input parameters for the Radiance lighting simulation were addressed as potential further reductions. Because of the structure of the simulation (shown previously in Figure 26), simplifying these parameters does not reduce the simulation time required, but simplifies the process by reducing inputs that must be determined. Defining all sky types as intermediate, rather that calculating the sky type based on climate data was shown to reduce accuracy by only less than 1%. But, reducing the resolution by using means for any other parameter input was shown to skew the rankings of the ECD metric and thus determined unusable.

In summary, the ECD metric for a fenestration system is evaluated at a single climate location (Memphis, TN) for three orientations (North, South, East/West) and uses binned climate data for 56 periods for solar position, direct horizontal irradiation, diffuse horizontal irradiation, and sky clearness without significant error and not affecting the relative ranking of systems evaluated.

6.4 Analytical Assessment

The goal of this assessment is to eliminate the simulation workflow process required to calculate the ECD by determining an analytical relationship between input parameters and the ECD value. Doing so would not only further reduce the calculation time, but would provide a methodology that is more easily packaged into a simple user interface for use by manufacturers. In order accomplish this, the relationships between input parameters and ECD value were evaluated through linear regression analysis.

Regression was identified as an approach to identify direct causal relationships between the ECD quantity and the value of specific input parameters. The intention was to assess linear, cubic, and quadratic relationships and combine the parameters into a single analytical expression for calculating the ECD, bypassing the Dynamic Radiance process requirements.

Unfortunately, although causal relationships *can* be identified on a case by case basis, as will be discussed further in this section, these relationships cannot lead to a single analytical expression that suffices for all five sample complex fenestration system and/or for all three orientations being assessed. The degree of accuracy to which the ECD value can be predicted using regression analysis is promising for further investigation. An account of the attempts and insight is included here to serve as a basis for future study.

6.4.1 Primary Causal Relationships

Regression analysis was first conducted between the ECD value and a number of parameters that were initially identified as having direct impact on the visual comfort performance of the complex fenestration system. If the relationship between each moment and its score can be identified, the ECD can be subsequently be predicted. Thus, using climate conditions for the each of the 56 periods in Memphis, TN, as was justified previously, the time-dependent score $Score_j$ was assessed as a function of the input parameters. The input parameters can be characterized in three categories, or combinations thereof: spatial geometry, climate conditions, and BTDF quantities.

In an effort to relate spatial geometry to the convention associated with BTDF quantities, the view of the interior space perceived by the fenestration system was converted from rectangular coordinates into polar coordinates. Five zones were identified, as shown in Figure 28, to represent each of the three walls in the view, the floor, and the ceiling.

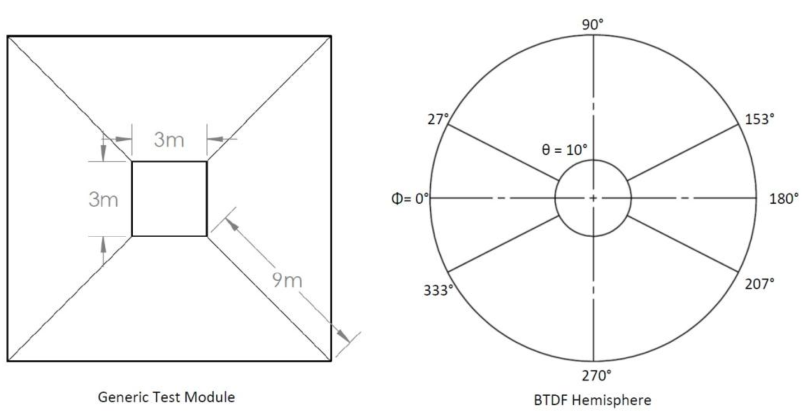


Figure 28: Hemispherical representation of rectangular generic test module.

This definition is a crucial innovation on spatial descriptions that suggests where light will fall in a rectangular space when characterized by the (θ_2,φ_2) emerging angles of the BTDF, whether or not it can predict the ECD value or other factors.

In a separate effort to relate climate conditions to the BTDF, the total emerging window luminance was calculated for each period. This approach was developed to be an analytical version of the Radiance methodology. First, the sky hemisphere was subdivided into 145 patches, as established by Tregenza and shown in Figure 29 (CIE, 1989). The luminance of each patch can be calculated using Perez sky models as a function of zenith luminance (Perez, 1993).

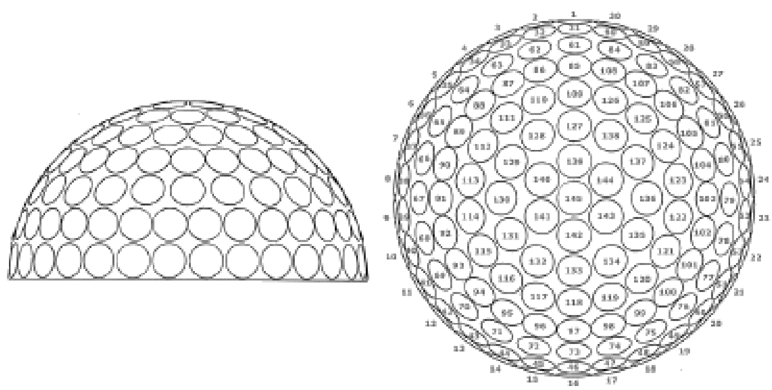


Figure 29: The sky hemisphere is divided into 145 patches (CIE, 1989).

Each of these sky patch luminances is associated with an angle of incidence for which to the BTDF of the complex fenestration system can be applied. As shown schematically in Figure 30, the emerging window luminance can be related to the incident luminance as a function of the BTDF and geometric parameters (CIE, 1977).

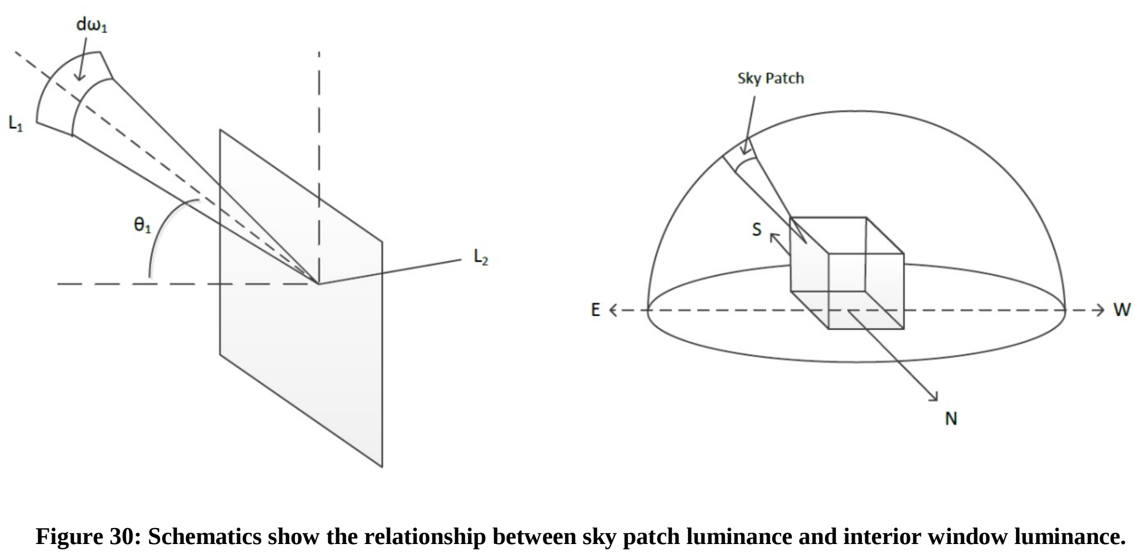


Figure 30: Schematics show the relationship between sky patch luminance and interior window luminance.

Analytically, the following equations are used to determine the emerging window luminance, where L_1 and L_2 are the incident and emerging luminances, respectively, θ_1 is the elevation incident angle, and $d\theta$ and $d\varphi$ are the elevation and azimuth lengths of the sky patch (CIE, 1977).

$$L_2 = BTDF \cdot L_1 \cdot \cos\theta_1 \cdot d\omega_1 \qquad \textbf{34}$$

$$d\omega_1 = \sin\theta_1 \cdot d\theta_1 \cdot d\phi_1 \qquad \textbf{35}$$

Emerging luminance for the window, as a function of climate conditions and BTDF could then be assessed as an input parameter.

Of all the parameters evaluated, most achieved a regression correlation with the ECD value of less than 0.3, which indicates that no stable relationship can be found. These attempts are listed below:

- Total hemispherical transmission
- Total direct, diffuse transmission
- Partial hemispherical transmission in any single zone, or any combination of zones
- Direct, diffuse transmission to any zone, any combination of zones
- Zone of peak transmission
- Zone of maximum total transmission

However, the following two input parameters achieved a regression correlation with the ECD value of more than 0.60, suggesting that there may be an analytical expression that relates them.

- Total vertical radiation
- Emerging window luminance

These were then selected for further study and is explained in the next section.

6.4.2 Characterization of Regression

Upon identifying correlation between these two input parameters, characterizing the actual relationship was required. For each complex fenestration system, a regression relationship was calculated that related the parameter to the ECD value for each moment of the year. When averaged, the final ECD can then be predicted, as shown in the examples in Figure 31 and Figure 32. These graphs show ECD predictions based on total solar radiation and emerging window luminance respectively for specific fenestration systems, plotted for 56 periods and compared to the actual ECD values for each period. Although the regression cannot predict the ECD exactly for each moment, the amount of over and underestimation cancels out such that the annual average for both input parameters is exactly the value predicted by the ECD calculation.

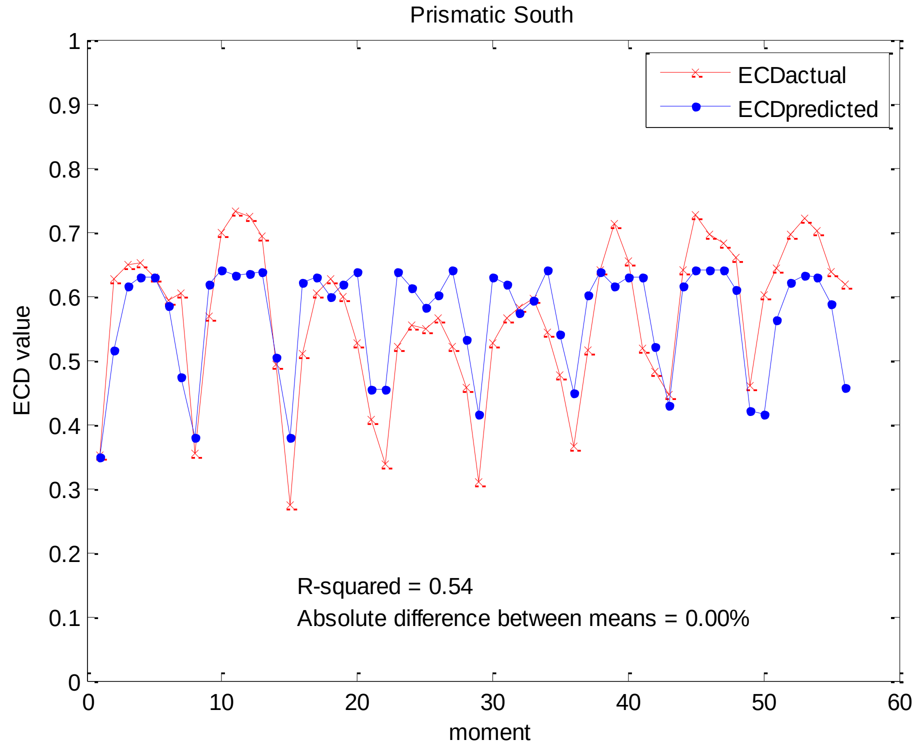


Figure 31: Example of regressive predictions of ECD based on total vertical solar radiation.

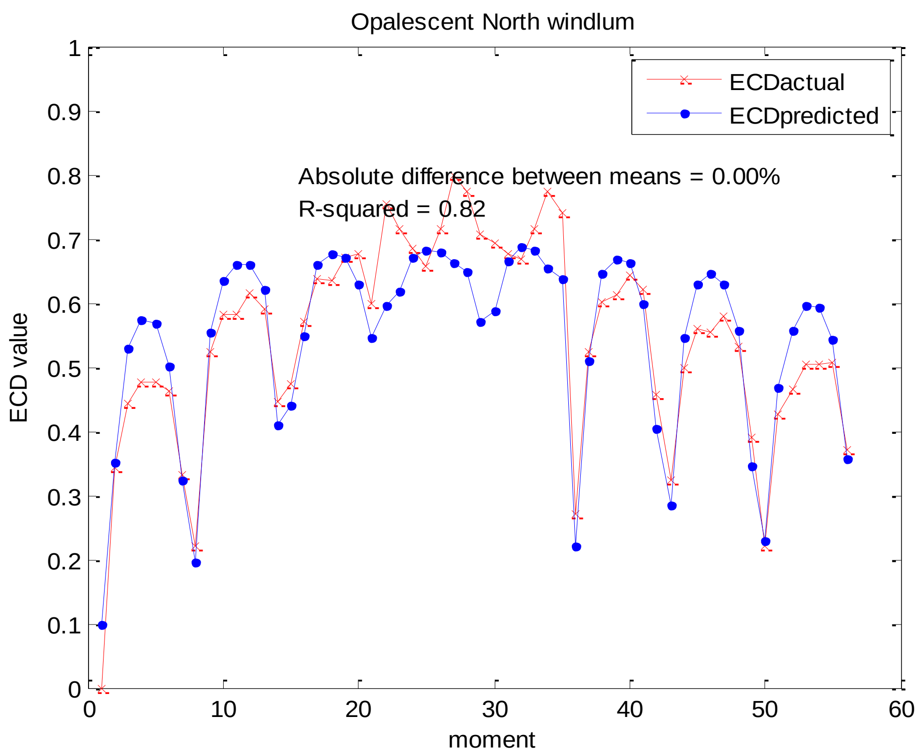


Figure 32: Example of regressive predictions of ECD based on emerging window luminance.

However, the constants that produce this very promising prediction are seemingly random: they do not have any correlations with other input parameters, nor do they hold constant or vary predictably for a specific complex fenestration system or orientation. For example, when attempting to use the average coefficients produced for the each complex fenestration system, the error in prediction of the ECD skyrocketed for both input parameters, including negative predictions for the ECD which are impossible. One example in which we use total vertical radiation and emerging window luminance is shown in Figure 33, and very similar patterns were observed across all five sample complex fenestration systems. It appears that it is impossible to use a statistically relevant combination of parameters to predict the ECD analytically.

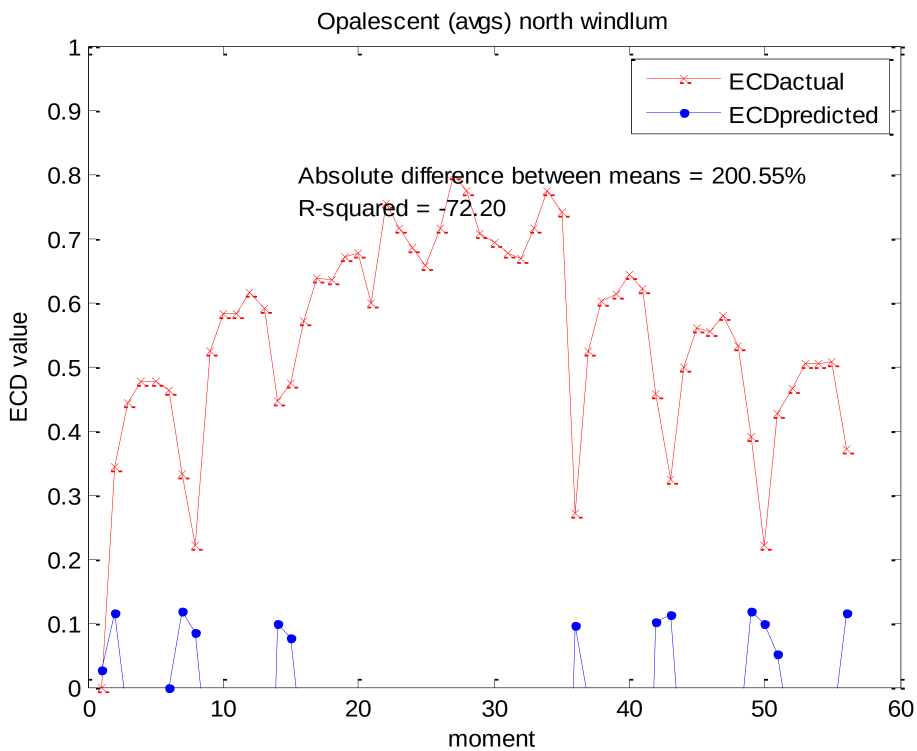


Figure 33: Example of regressive predictions of ECD based on average coefficients and total solar irradiation.

This analysis does not preclude the existence of some analytical relationship, but it does suggest that regression is not an adequate approach or that additional input parameters must be identified and evaluated for correlation. Indeed, the behavior of light is unique and unpredictable enough that ray-tracing has only recently become sophisticated enough to be able to incorporate the functionality of a BTDF. Nonetheless, the existence of some correlation between measurable input quantities and the ECD value indicate that there may be another approach for prediction. Further study should build on the lessons learned here if complete elimination of the simulation workflow for the ECD metric is considered a priority in the future.

6.5 Validation Study

Because the goal of the ECD metric is to describe the complex fenestration system, and not the space, the metric would ideally be entirely space independent. For daylighting, completely disconnecting visual comfort performance from the space may appear conceptually impossible, but the ECD metric aims to provide a relative ranking that predicts overall performance in a manner that reduces the impact of geometric features in assessment. It does so by using a deep generic test module and by normalizing the score with the performance of a reference fenestration system.

A validation study to evaluate the ECD metric as being able to describe a complex fenestration system accurately with little impact of the spatial layout would prove that the ranking predicted holds for any space. This study thus computes the ECD for each of the five complex fenestration systems in a building space that is very different from the generic test module. The space used for the validation is from the DOE Reference Small Office building used previously to analyze the REI metric with specifications from the Commercial Buildings Database. A simple drawing of the full building is shown below in Figure 34. For daylighting assessment, the walls that separate zones were considered walls that also block light to the interior zone. Thus, each zone exhibited a space that is significantly longer than it is wide, non-orthogonal walls, and multiple windows. Each of these characteristics has significant impact on daylighting predictions and is certainly not present in the generic test module.

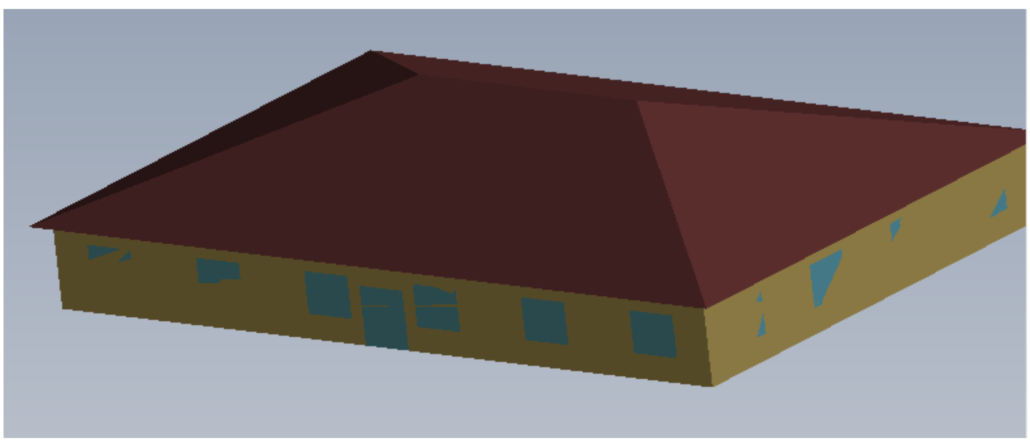


Figure 34: Three-dimensional model of Reference Office building.

The calculation procedure for the validation study mimics the ECD calculation method exactly in the use of Dynamic Radiance. The only variable was the space; the geometric definition of the analysis was thus changed in the workflow described previously in Figure 26.

The results, as shown in Table 9, indicate that while the use of the generic test module does succeed in predicting the ranking for four of the five test façades in all orientations, the prismatic panel exhibits some unusual behavior. The ECD value does not hold for only the prismatic panel when there is significant direct sunlight; it remains consistent when evaluated on the northern façade. In other words, the use of the simply generic test module seems to be able to predict the ranking of complex fenestration systems in a more complicated space for all but one of the systems evaluated.

Table 9: ECD full resolution results compared to validation results.

	South			North			East/West		
	ECD	Valid	% Diff	ECD	Valid	% Diff	ECD	Valid	% Diff
Clear	1.00	1.00	0%	1.00	1.00	0%	1.00	1.00	0%
Prismatic Panel	0.77	0.98	21%	1.12	1.51	39%	1.35	1.16	18%
Opalescent Plexiglass	0.97	0.96	1%	1.21	1.78	57%	1.42	1.14	28%
Holographic Element	0.81	0.93	13%	0.58	0.38	20%	1.03	1.01	3%
Mirrored Blind	0.00	0.00	0%	0.00	0.00	0%	0.00	0.00	0%
Fabric Blind	0.02	0.04	2%	0.00	0.00	0%	0.00	0.00	0%

The fact that consistent rankings can be observed with four of the complex façades suggests that there is validity in the use of the generic test module as described and that the error may be attributed to the definition of the prismatic panel in terms of its BTDF. When considering the results above, even when there is a large percentage difference in other systems (e.g. opalescent plexiglass and holographic element), the absolute difference is not very large, and further, does not disrupt the relative ranking. The ranking is only disrupted by the prismatic panel, and again, only when the façade experiences significant direct sun exposure.

Thus, preliminary analysis suggests that a strong contributing factor to the failure of the generic test model reflecting the performance of a prismatic panel in a real space may be due to the lack of BTDF resolution available for this system and that the BTDF used transmits light in a pattern that is infeasible for a physical object. Re-evaluation of the specific BTDF for the prismatic panel will be required before drawing any weighty conclusions from this study. Further, additional façades must be evaluated to ensure that the use of the generic test module provides consistent results.

6.6 Summary of Results

In summary, the ECD metric evaluates a complex fenestration system for its ability to provide comfortable visual conditions inside a space. It currently uses the generic test module to do so, an input that may require re-evaluation upon additional validation work in the future. The definition of comfortable daylight conditions is derived from substantial literature that suggests that fuzzy boundaries for a lower illuminance and an upper glare threshold are useful criteria for initial evaluation. The ECD value reported for a complex fenestration system is a relative value; it defines the comfort conditions as compared to the reference case standard fenestration system in order to reduce dependency on spatial inputs as well as provide a basis for understanding for a user considering his or her options. Finally, the ECD metric needs only to be evaluated for a single climate location and three unique orientations to represent performance for the entire continental United States. This climate location, Memphis, TN, was determined through a sensitivity analysis and variance study.

The calculation process for the ECD metric requires the use of Radiance simulations and then processing of the results through Matlab. However, the calculation time required to do so is just about 6% that of the initial full resolution calculation proposal due to reduction of climate and orientation dependency. In under 3 hours of observed simulation time, for which the simulation files are already developed, the ECD metric can be determined for any complex fenestration system. The ECD values for each fenestration system are shown in Table 10.

Table 10: ECD values for five complex fenestration systems.

	North	East/West	South
Clear	1	1	1
Prismatic Panel	1.12	1.35	0.77
Opalescent Plexi	1.19	1.42	0.97
Holographic Element	0.55	1.03	0.81
Mirrored Blinds	0	0	0
Fabric Blinds	0.02	0	0

For the ECD metric, the quantitative value represents the percent of time and space which achieves comfortable conditions. Since the ECD is not calculated directly and analytically from the BTDF, the simulation procedure can also reveal whether the space is uncomfortable due to too much or too little light, valuable information that informs users about the reason for discomfort. For example, if the space is designed to be a meeting space in an office, too much light may be less critical criteria. However, if computer screens or rare documents are decisive in the space's design, too much light may be absolutely unacceptable. Therefore, the label concept, shown in Figure 35 provides a dual axis scale on which a fenestration sample is plotted with respect to percent of time and space that is too low or too high in daylight conditions. The visual example shown is for a south facing façade, a full label would have three indications on the scale with three quantitative values to indicate each of the three potential orientation configurations.

Thus, the ECD metric is described both quantitatively and qualitatively in an effort to consistently serve multiple disciplines of users that may interact with the complex fenestration product and requiring no additional work on the part of the manufacturer. The ability to provide users with a visual comfort performance metric that is complementary to an energy performance metric recognizes the importance of creating a space that is both frugal and comfortable, and does not pass judgment on which is higher priority for any given situation.

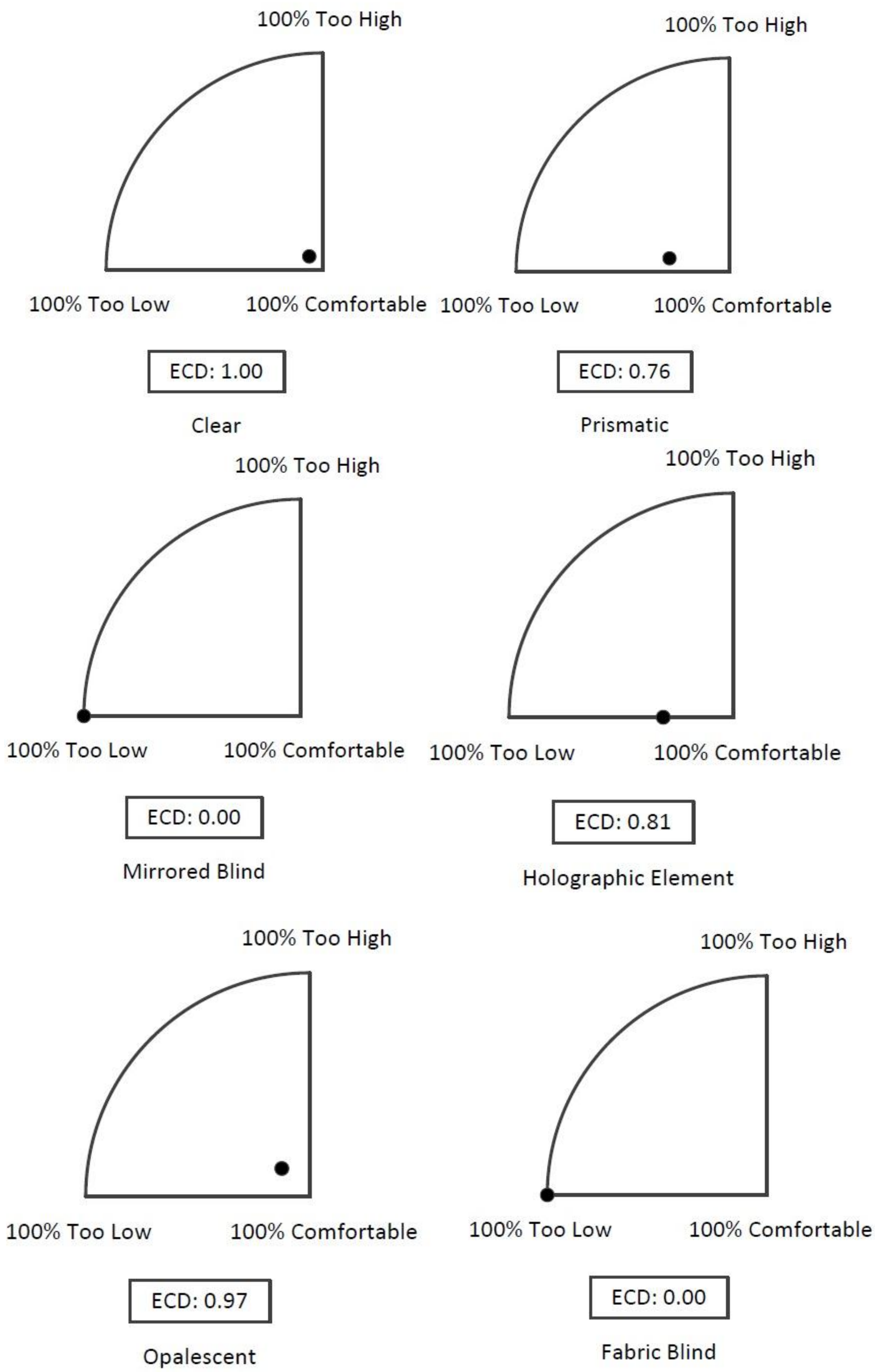


Figure 35: ECD label concept for five complex fenestration system and the reference fenestration system.

Chapter 7
View Through Potential (VTP)

The third and final metric, the View Through Potential (VTP), provides a quantitative value for the degree of visible transparency afforded by the complex fenestration system. This metric is intended to allow a user to select a fenestration system that achieves the view characteristics that he or she desires, whether it be privacy or a clear view to the outdoors.

7.1 Defining the VTP

A clear view is explained by light bouncing off an object and reaching a human's eyes without being distorted. Walls are opaque to visible light while windows transmit the reflection of light from objects outside. This happens in many directions as a person looks out a window, and the combination of light received by the eye is processed by the brain into an image. The image may be disturbed – for example, an insect screen on a window might render the image slightly fuzzy – or the image may be disrupted – a venetian blind blocks some parts of the image outdoors. The complex interactions that occur between the light and the brain struggle to quantify the exact definition of view.

For this research however, view is perceived by humans who compare any fenestration system to a clear window with no distortion. Defining the view through a façade, therefore, requires assessment of many different view angles along the window surface from many different view points in the space; a clear window provides a view to the outdoors at all view angles from all points in a room. Thus, for a different complex fenestration system to achieve a clear view, it must also do the same. One specific view angle from a specific view point is depicted in the figure below. The lighter light distribution represents a clear view, while the darker light distribution depicts the transmission of a complex fenestration system. At this particular angle and view point, considerably less light is reaching the occupant's eye.

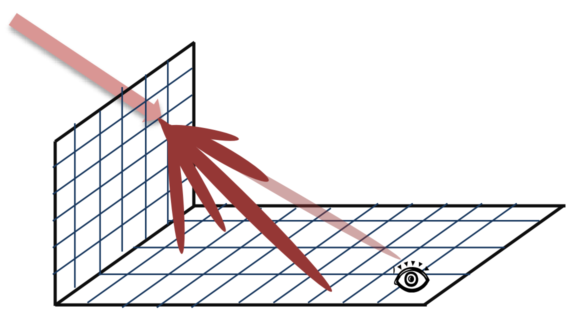


Figure 36: Schematic of VTP calculation procedure.

In order to quantify the characteristics of a clear view such that any complex fenestration system can be assessed, we used the BTDF of a hole. A hole represents no material or other distortion to the light and can be considered to achieve a perfectly clear view at any angle, from any view point. Then, a number of quantities derived from the BTDF for a complex fenestration system were related to the equivalent quantity for the hole in order to identify a mathematical proxy for view through. These were then related to a user study on view perception to validate the derivation.

7.2 Initial Calculation Approach

There is no previous calculation methodology that relates BTDF quantities to an occupant's perception of view. Therefore, one had to be identified. As stated previously, view in a particular direction is characterized by the view angle to the window as well the view point from the room. So first, a means to describe the test space mathematically was required.

In order to generate coordinates that relate position in the room with all angles required to perceive the whole window, both the room and the window are defined by a grid of points, as shown not to scale in Figure 37. The grid of points that describes the room is the same resolution as the grid defined for the lighting calculations described previously. The 4.5 m^2 area of the window surface is divided into 100 points, each representing a square of 0.45 m^2. The combination of these grids results in angles equal or more accurate than the resolution of the BTDF used to evaluate them. 300 space points and 100 window points result in 30,000 angular relationships between location and window surface, although not all will be unique.

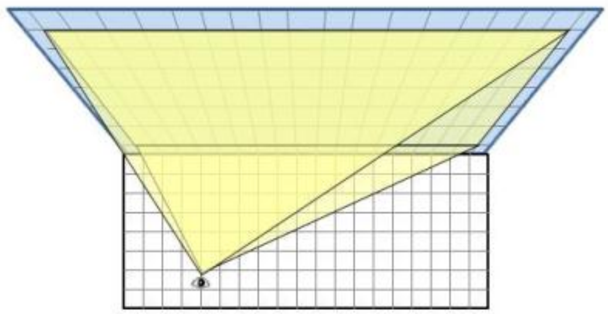


Figure 37: Schematic of space view points as they relate to surface grid points.

These 30,000 view directions are determined using the trigonometric relationships in Equations 36 and 37, where subscript $_A$ refers to the window grid and subscript $_B$ refers to the eyelevel grid and *x*, *y*, and *z* refer to the x-, y-, and z- coordinates of the grid point. *D* is the distance between *A* and *B*.

$$D = (x_B{}^2 + \delta^2)^{1/2} \qquad \mathbf{36}$$

$$\delta = (z_A{}^2 + (y_A - y_B)^2)^{1/2} \qquad \mathbf{37}$$

This mathematical definition of the potential view points associated with the space can then be used to analyze the BTDF.

7.2.1 Defining View Through

Because there is no validated literature to relate a previously measured BTDF to view perception, an exploration was undertaken. A considerable number of parameters that can be derived from the BTDF were considered to act as a mathematical proxy for view. Upon initial inspection, the most promising are listed below in Table 11.

Table 11: View through proxy parameters.

Description	Justification	Value
Ratio of direct transmission and diffuse transmission	Direct transmission represents view; the higher the diffuse transmission, the lower the view.	τ-direct/τ-diffuse
Direct transmission multiplied by total transmission	Direct transmission represents view; the lower the total transmission, the lower the overall view.	τ-direct/τ-total
Total transmission	Total transmission suggests how much light passes through the façade (but could be in directions that do not provide view)	τ-total
Ratio of direct transmission and diffuse transmission normalized by total transmission	Direct transmission represents view; the higher the diffuse transmission, the lower the view; the lower the total transmission, the lower the overall view.	(τ-direct/τ-diffuse)/τ-total
Direct transmission (no distortion)	Direct transmission represents view, inherently represents the quantity of light transmitted, diffuse light does not contribute to view.	τ-direct

This table shows the range in possible definitions, all related fundamentally to the transmissivity of the surface for a given direction. Each showed promise to be a sound approximation for view for different reasons, as described in the justification column of the table. But in many cases, the quantities obtained for a sample complex fenestration system exceeded the equivalent quantity of a hole representing a perfectly clear view. Since there cannot be a more perfect view than a hole, these parameters were one-by-one eliminated as possible definitions for view.

Finally, the quantity of light transmitted with no reflection or distortion was mathematically shown to be indicative of view in a particular direction. Weighting this quantity among all the view directions of the room gives more credit to view directions that are more likely to occur, and provides an overall definition of view through the facade.

7.2.2 Calculating View Through

In order to identify the quantity of light passing through a fenestration surface with no distortion or reflection, the hole was again used as a representative of perfectly clear view. However, this time the comparison is used not to inform us about potential parameters, but to calculate the parameter itself.

For each position/window relationship angle, there is a direct line of sight through the façade surface for which a light source would be directly transmitted to reach the analysis point. This can be calculated analytically with the following two equations, where the subscript $_1$ refers to incident angles and the subscript $_2$ refers to emerging angles. θ and φ refer to the elevation and azimuth angles, respectively, of the light rays.

$$\theta_1 = \theta_2 \qquad \textbf{38}$$

$$\phi_1 = \phi_2 - 180 \qquad \textbf{39}$$

Given this relationship, the BTDF quantity associated with the $(\theta_1, \varphi_1, \theta_2, \varphi_2)$ for the hole represents perfect transmission for that particular position/window angle. This is the maximum allowable transmission, governed by common sense and the first law of thermodynamics.

However, since the BTDF of a hole does not exhibit one hundred percent transmission in the single direction and zero in all others, this must be taken into account. Transmission is very localized around the direct line of sight, but light is spread over about ten of the 145 emerging directions. Thus, the BTDF of a complex fenestration system must be compared with the pattern of transmission exhibited by the BTDF of the hole in order identify which components are associated with direct transmission. This relationship can be calculated analytically for each $(\theta_1, \varphi_1, \theta_2, \varphi_2)$ combination using Equation 40.

$$BTDF_{sample,direct}(\theta_1, \phi_1, \theta_2, \phi_2) = \frac{BTDF_{hole}(\theta_1, \phi_1)}{\max(BTDF_{hole}(\theta_1, \phi_1))} \cdot BTDF_{sample}(\theta_1, \phi_1) \qquad \textbf{40}$$

This calculation results in a modified version of the BTDF for each $(\theta_1, \varphi_1, \theta_2, \varphi_2)$ combination that is the direct component of the BTDF. Then, using the previously established relationship for calculation of transmitted flux, the direct component of flux transmission can be determined using Equation 41. Finally, Equation 42 calculates the hemispherical transmission of direct, non-distorted light through the fenestration surface.

$$\Phi(\theta_1,\phi_1,\theta_2,\phi_2) = \begin{cases} 2\pi \cdot BTDF_{sample,direct} \cdot (1-\cos(\alpha)) \cdot \cos\theta_2,\ for\,\theta_2 = 0 \\ BTDF_{sample,direct} \cdot \sin(\theta_2) \cdot \cos(\theta_2) \cdot d\theta \cdot d\phi, else \end{cases} \tag{41}$$

$$\tau_{direct} = \sum_{\theta_2=0}^{\theta_2\max} \sum_{\phi_2=0}^{360-d\phi_2} \Phi(\theta_1,\phi_1,\theta_2,\phi_2) \tag{42}$$

Using the preceding three equations, a direct hemispherical transmission value is calculated for each of the 30,000 angle relationships. Averaging these values across all relationships as done in Equation 43 normalizes the angle-dependent hemispherical transmission by the likelihood of view point occurrence.

$$VTP = \frac{\sum_{i=1}^{i=300} \tau_{direct,\,sensor,i}}{30{,}000} \tag{43}$$

The analytical workflow that describes the calculation procedure for the VTP is shown in Figure 38.

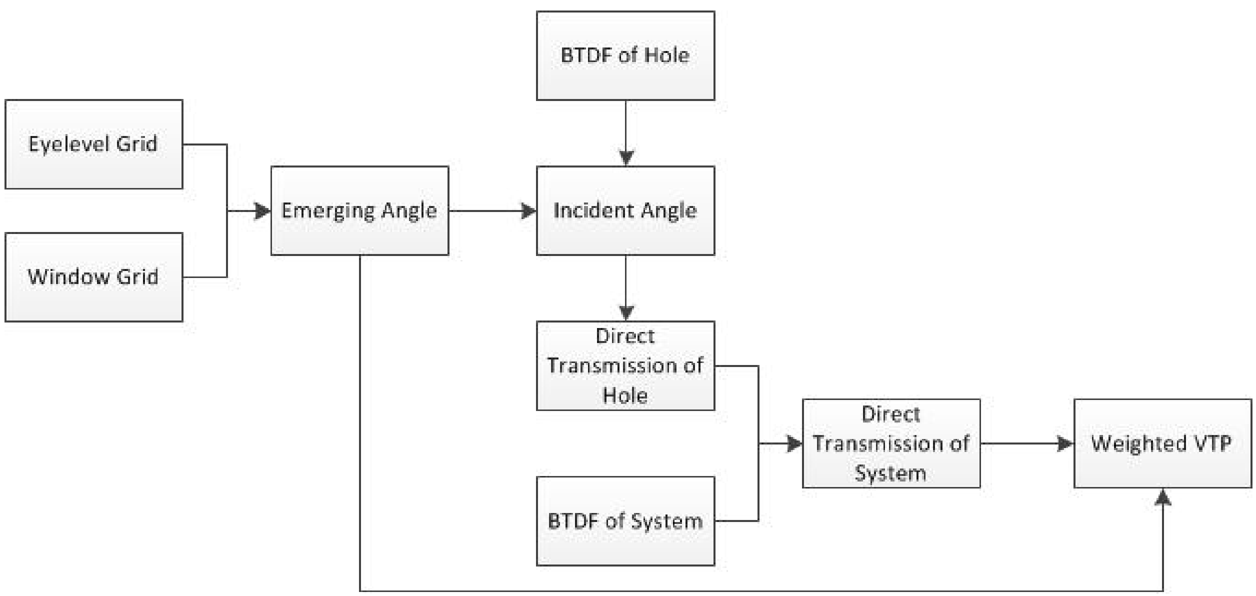


Figure 38: Workflow for calculation of the VTP metric.

The entire calculation procedure, from BTDF analysis to weighted VTP, is conducted analytically in Matlab. The input requirements are the eyelevel grid coordinates, the window grid coordinates, the BTDF of the hole and the BTDF of the system being analyzed. The VTP is reported as a single value.

7.3 Reduction Approach

Although the VTP is already calculated analytically, the calculation procedure takes some time due to the 30,000 view angles evaluated in the generic test module. A study was conducted to determine whether the resolution of both or either the window grid and/or eyelevel grid produced the same VTP results. It was found that the resolution could be reduced to fewer view angles but doing so affects the final VTP value such that small differences are no longer represented. For example, the holographic element achieves a VTP of 0.260 and the prismatic panel achieves a VTP of 0.194. This small absolute difference becomes even smaller when the grid resolution is reduced, threatening inaccurate ranking of view for other systems that were not evaluated in this study.

Furthermore, reduction of the grid resolution does not decrease calculation time significantly, thus providing even less justification for affecting accuracy. The VTP is calculated using Matlab in less than three minutes in its full resolution case, using a single processor. Space requirements are also not a concern because stored data is minimal. Finally, this resolution enables the same sensor grid used for the ECD and REI metrics to be used for the VTP, maintaining consistency in parameters and increasing the ease of access to the metrics. Ultimately, although a reduction approach was explored, it was not pursued for the final definition of the VTP.

7.4 Validation Study

The VTP validation study was conducted to determine whether the quantitative calculation and final metric reflect user opinions of view. Therefore, a statistically significant user study was proposed to determine the relative view perception of the sample complex fenestration systems.

102 random participants were asked to rate their opinions of view through a fenestration sample. Each sample was handheld and participants were permitted to hold, move, and rotate the samples as they desired. Participants were aware that these materials would replace or be added – in the case of shades – to windows and that distance to the façade and angle of view might change. They were asked to provide their "overall opinion of view" on a sliding scale from "no view" (as if it were a wall) to "full view" (as if it were a hole in the wall). The pictures below shows the study set up. The study was conducted at ÉPFL, in both English and French (see Appendix C).

Figure 39: View study setup and participant viewing samples.

This data was collected and quantified on a scale from zero to ten, where zero represents no view and ten represents full view. The graph below shows the raw average of each of nine fenestration sample evaluated. The full set of data is available in Appendix C.

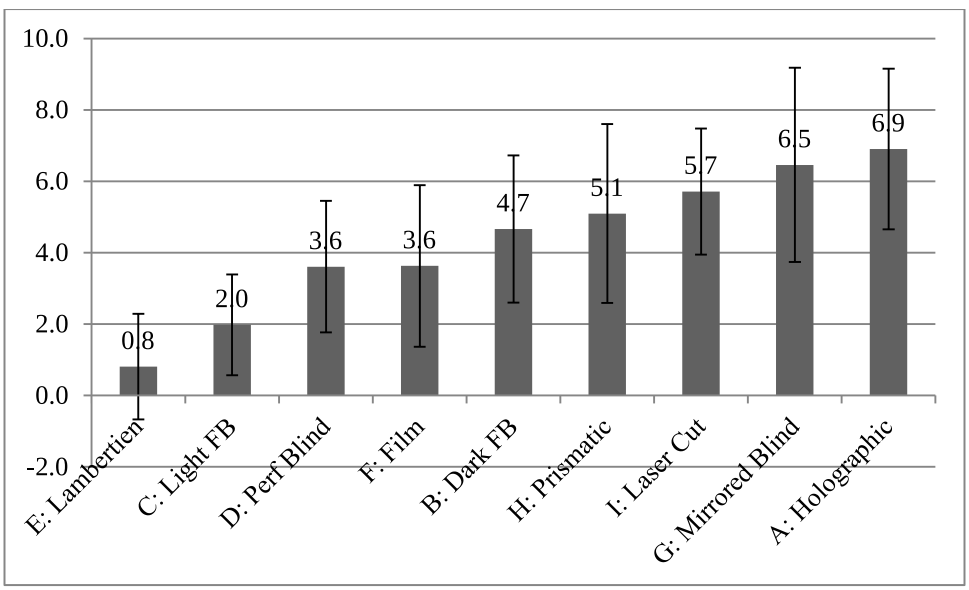


Figure 40: Average perception of view from 100 participants.

It is interesting to note how small the perceptions in view varied between each other, and yet the full set of samples exhibits a substantial range in view opinions. This suggests that is view a very gradual quantity in perception. The large error bars provide context for just how subjective view is. On the other hand, the range of average view perceptions indicates that this set of samples exposed the users to a sufficiently diverse degree of views to perceive. Samples A, C, E, G, and H were the five sample complex fenestration systems for which the BTDFs were analyzed to calculate the VTP.

When normalized to the same scale (0 to 1) and compared with the results for VTP, the relative rankings match with the relative rankings of the user study results, as shown in Figure 41. The error bars indicate one standard deviation associated with the user study opinions. There is overlap in the standard deviation ranges, but more often than not, this was the ranking provided by the user. In other words, users who fall in the lower range for one system tend to rate other systems lower, maintaining a consistent ranking.

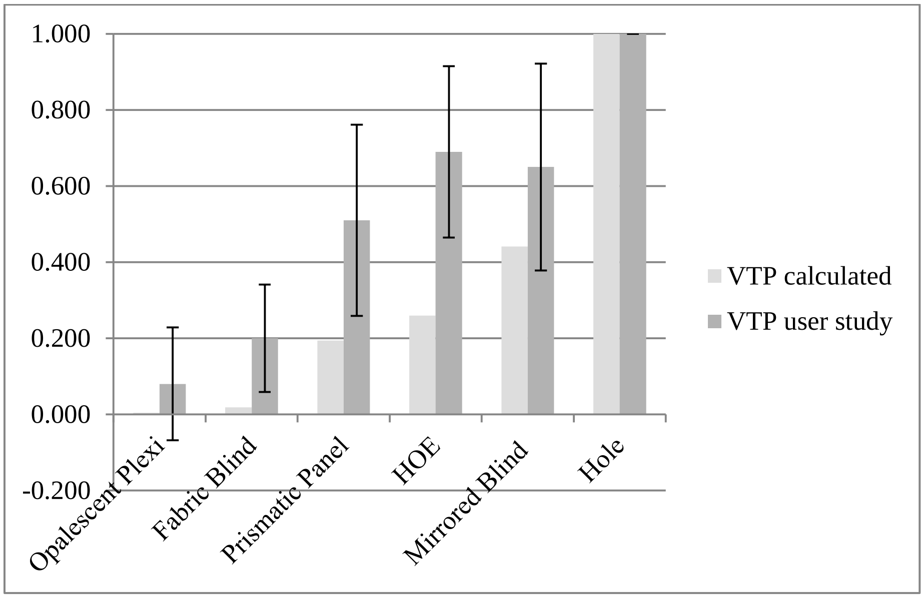


Figure 41: Comparison between VTP calculated and VTP user study.

Although the consistent rankings shown above are encouraging in suggesting that the VTP is an accurate measure of user perceived view through – at least for the five fenestration samples studied – the VTP metric would be strengthened if it were even more accurate analytically. While a more extensive study would require the BTDF analysis and user study on many more CFS samples, the initial correlation study indicates that this may be achievable. As shown in the graph below, the perceived and calculated VTP values are correlated with an R^2 value of 0.92 in a logarithmic relationship.

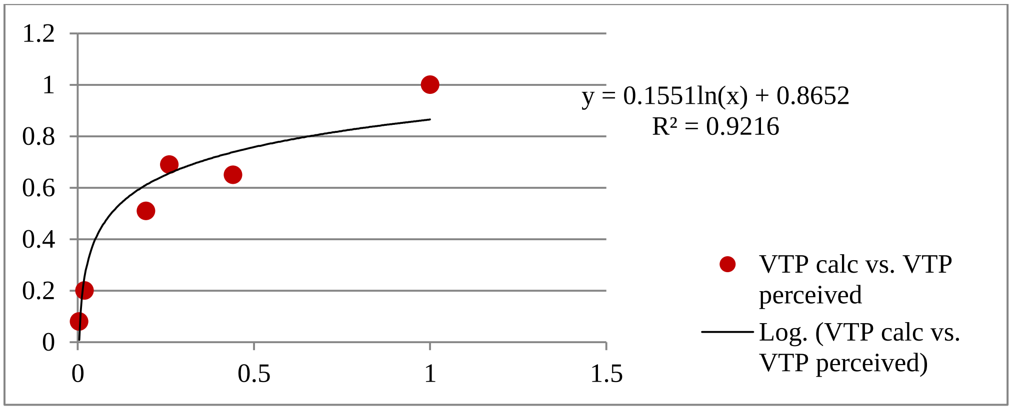


Figure 42: Analytical correlation between perceived view through and calculated VTP.

A consistent relationship between the two over a larger set of samples would further validate the potential of the VTP as a metric for view through.

7.5 VTP Definition and Label Concept

The VTP of the five sample complex fenestration systems is reported in its final form below. The hole achieves a perfect VTP indicating that it is, indeed, a clear view whereas the Opalescent Plexiglass achieves a score very close to zero, indicating that no view is perceived.

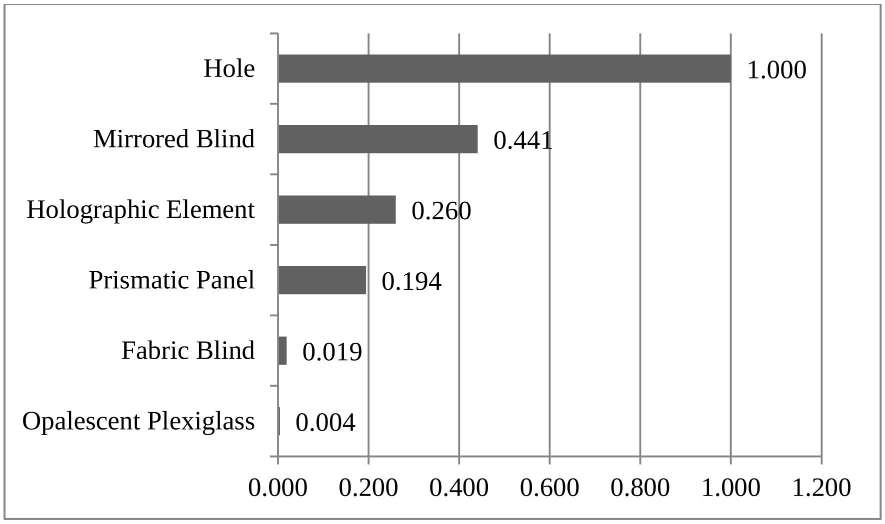


Figure 43: VTP values for five complex fenestration systems.

During the user study validation, it was apparent that users were extremely concerned with the difference between no view due to blockage and not enjoying the view due to distortion or reflections. Two samples that achieve the same VTP value may do so through different view disruption mechanisms, and it might be relevant for a user to understand which is dominant.

The ways in which view is disrupted due to the fenestration system can be assigned into two broad categories: blockage and distortion. A screen would be the result of blocking while a reflective system would occur due to distortion. These are quantified in two equally broad categories: opaqueness measured by inverse of total hemispherical transmission and distortion measured by the quantity of nondirect transmission.

In the visual label concept, each of these parameters is an axis, and the VTP is reported as a single value. The scale shows how much of the disruption is due to blockage and distortion. Figure 44 shows the VTP label idea for each of the five complex fenestration systems evaluated in this work. It also shows how a hole would be plotted on the origin of the two axes, indicating a perfectly clear view through.

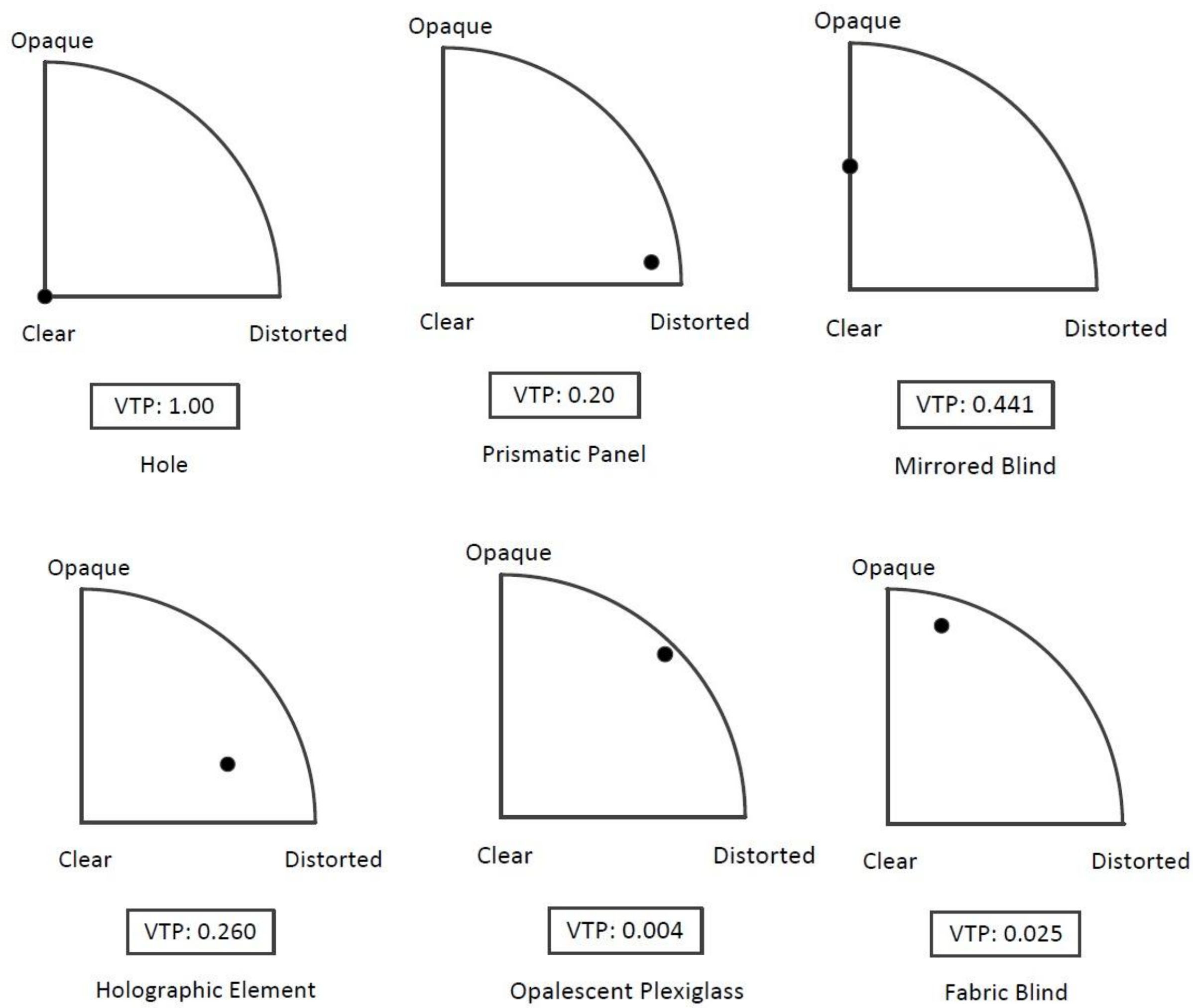


Figure 44: VTP label concept for five complex fenestration systems and a hole.

The VTP provides the user with aesthetic information about the fenestration system without relying on opinion or individual judgment. It informs a user about how clear the view through a complex fenestration is, on a scale from 0 to 1, where 0 indicates no view and 1 suggests perfectly clear view. Further, it is able to tell a user whether the disruption in view is due to blockage (opacity) or other light manipulation (distortion). The VTP is calculated analytically from the BTDF and is the first view parameter to be able to do so quantitatively.

Chapter 8
Policy Applications

The goal of the performance metrics developed in this work is to integrate them into the building industry, connecting engineering principles and designer preferences in ways that can promote overall improved performance. Ideally, benchmarks will evolve as more fenestration systems are evaluated, BTDFs will become more standard because there is a specific use for their information, and manufacturers will be able to compete on specifications that speak to the realistic performance of their products. This chapter summarizes the efforts that have already begun in this process and the goals and milestones for the next few months. The research presented here provides an initial foundation and a considerable amount of understanding to the industry and policy making organizations within it.

In this chapter, we discuss our involvement in the NFRC Daylighting Potential Task Force and present a policy memo that has already been submitted to the Task Force. A forthcoming presentation at the ASHRAE Winter Conference and followup memo will propose a timeline and outline milestones in the incorporation of these metric concepts into the NFRC rating system. We also more broadly treat the potential, but unexplored, role of these metrics in a bottom-up adoption approach. Finally, a brief assessment of role of quantitative metrics in the policy realm is provided.

8.1 NFRC Task Group

Over the past seven months, we have been engaged with the NFRC Daylighting Rating Task Group in order to understand the goals and methodology that is currently ongoing to create more representative metrics of complex fenestration systems. The goal of the Task Group was to develop a metric that speaks to the daylighting benefits, in terms of light, of a fenestration system, both simple and complex. This goal is code-driven, with various standards bodies recognizing the limitations of describing fenestration systems in the context of only energy. Where energy metrics have been established and utilized, daylighting as a concept is not perceived quantitatively, partially because the codes do not require such analysis. Currently, it is up to the discretion of the architect or engineering firm constructing a building to conduct any form of daylighting analysis. However, with the introduction of a daylighting metric, a more holistic decision of fenestration system can occur more frequently.

The workflow of achieving this goal follows standard NFRC procedures. The discussion is extended to people working in the field, from academia, private research, as well as stakeholders from the industry. As an example, glazing manufacturers are directly affected by a code's window-to-wall requirement because their sales then depend solely on the code's value. These firms are likely to support a daylighting metric that encourages additional fenestration sales. Meanwhile, an advocate for building energy efficiency may prioritize energy consumption as an end goal. The policy memo included in Appendix A was submitted to this Task Group in March of 2011 so the relevant participants were aware of the efforts of this independently funded research.

In order to accomplish these goals, the scope of the Task Group was divided into two phases, the first being more immediately critical and achievable. They are outlined exactly as follows in the March 8, 2011 Daylighting Potential Task Group Agenda:

- *Phase One: To create a rating system for daylighting potential utilizing the existing NFRC VT rating combined with known, bright day incident illuminance values.*
- *Phase Two: To create a rating system to allow designers to utilize a standardized measurement of the appropriate illumination characteristics of fenestration products considering directional effects for incident and emitted illumination, illumination quality, illumination quantity, illumination distribution and other complex variables as needed.*

The fundamental goal of Phase One is to define a practical sky that can be considered "bright day illuminance." The sky will then inform the standard for incident sun, and using the visible transmittance at normal incidence, a daylighting potential value can be obtained. The goal of Phase Two is to incorporate the BTDF into the structure of the Phase One metric, taking into account the angular dependency of a fenestration system and also the angular distribution of light within a space. The details of a standard space or sky have not been addressed currently.

In the course of this work, the Task Group has explored the pros and cons of a simple versus complex daylighting potential metric. The pros of Phase One include simplicity, ease of calculation, and placing all systems on the same scale. Conversely, it does not address distributional aspects, orientation of the façade, climate of the building location, or any issues related to glare. As a result, the simplified approach has been widely criticized by members of the daylighting industry. Avoiding the oversimplification of Phase One by the approach suggested in Phase Two, however, requires a new level of complexity for the

NFRC. Integrating the BTDF into the standards definition would require research and preparation, and the ability to finance such a project is to be determined. Still, this approach would address issues of glare, solar heat gains, lighting distribution, and the potential to reduce the amount of post-construction analysis required in the building.

Simultaneously, on October 4, 2011, the NFRC issues a Request for Proposal (RFP) the calls for a goniophotometric device that can be standardized for use in evaluating complex fenestration systems. This initial step to developing standardization around BTDFs is crucial for the practical implementation of each of the metrics proposed in this work; including introducing the device, building a test facility, developing a calibration protocol, and validate the testing method (NFRC, 2011). Whereas this research assumes that an accurate database of BTDFs will exist for manufactured complex fenestration systems, this RFP provides a mechanism to do so.

The results of this thesis are being presented at the ASHRAE 2012 Winter Conference on January 24th 2012 in preparation for delivery to the NFRC Task Group. The stakeholder structure of the group means that the metrics will undergo revision and deliberation for some time, but the authors are confident in the level of rigor that led to the definition and development thus far. Having considered and addressed the concerns introduced by the Task Group, this work presents a solid foundation for discussion such that the process is expedited and complex fenestration products are integrated sooner.

8.2 Manufacturer Adoption

Manufacturers may also adopt the metrics, label design, and suggested testing approach in a more ad hoc manner. While the stakeholder process of the NFRC Task Groups is effective in setting metrics that are vetted and fair, the improvement energy efficiency without compromising other design goals is a strong consideration in buildings today. The metrics proposed here were developed for complex fenestration systems, but can certainly be applied to describe annual performance of standard fenestration system. Much of the information communicated in these metrics for standard fenestration systems is easily deduced from the traditional metrics in use, but they do exist as a “market” for adoption.

The benefit of objective and descriptive performance metrics is the ability for manufacturers to compete on criteria that are relevant to the systems they are producing. Because this lack of information transfer in the market is more imminent to those who stand to lose business from it, these manufacturers may choose to characterize their systems using the BTDF method given the specific use for this information that these metrics provide. Where top-down policy will take time, a bottom-up approach in an industry with a relatively small number of players may become more effective in the meantime.

8.3 Policy Considerations

This brief discussion relies on two fundamental themes of the use of metrics in the policy framework, particularly in the way in which these performance metrics were developed. The first speaks to the structure of top-down policy in any country, but specifically in the building industry of the United States. The second addresses the role that numbers have in the polis as compared to the quantitative world of engineering and the issues that must be considered in their use.

8.3.1 Measures in a Top-Down Approach

First, we must recognize that the definition of performance is subject to debate (Reiner, 2002). Where there are opposing, or simply different, view points, opinions, perceptions, and goals, the factors that characterize performance are certainly relevant for discussion. In the building industry, most obvious is the tension between architects and engineers. But also present are misaligned incentives between owner and occupant, landlord and tenant; where up-front cost battles comfort, control, or operating costs. Although the approach of many top down mechanisms is to alter the market in a way to align these incentives, this is often the solution to the wrong problem; ignoring tradeoffs is exactly the wrong approach (Reiner, 2002). In this vein, three performance metrics have been developed, where a fourth quantitative metric is cost, such that tradeoffs are clear, can be identified, and priorities can be achieved. These instead align incentives with particular preference in a way that is transparent, instead of with each other.

Second, we reiterate the concern of altering the purpose for which measures are used without reevaluating what is being measured. Reiner notes that measures that may be appropriate for ex-post assessment or bureaucratic accountability may actually not be the best incentives for regulatory control (Reiner, 2002). In this context, the performance metrics developed here were developed with both in mind, but recognize that many of the previously defined metrics are simply not well-suited for regulatory control. For example, assessment of a space's daylight factor might provide an intermediary participant in the building design with useful information, but because it does not measure the space as it truly behaves, cannot be used effectively in ex-post assessment. This crucial discrepancy was identified early and addressed with the use of performance metrics, as was discussed in Chapter 2.

Although the building industry may not be as prone to political swing as say, electricity generation and air pollution, it is still relevant to acknowledge the importance of creating metrics outside the policy realm. Measurements are inherently linked to benefits and penalties when applied from a top down approach; manufacturers are going to see their complex fenestration technologies succeed or fail as compared to others when evaluated comparatively. Similarly, every number presented involves some decision about where to draw the line (Stone, 1997). When this is able to be done so outside the political realm, but within the industry's body of knowledge, the measurement is often more effective.

Finally, although numbers describe quantifiable and worthy characteristics, Reiner wisely states, "All too often, performance measures will come to be used in regulatory programs and regulatory indicators become measures of progress" (Reiner, 2002). His statement reiterates the need to recognize the purpose for which performance metrics were developed, but further, warns against the net zero building that nobody wants to inhabit. Just because energy consumption is a fairly common performance measure for a building, ignoring other aspects in the regulatory sphere in order to measure progress is dangerous and potentially devastating for the industry.

8.3.2 Numbers in the Polis

A second discussion is centered around the role of numbers in the polis. These observations are less warnings, and more factors to be aware of as performance metrics such as the ones proposed permeate the industry.

First, it is crucial to remember that measures are always double-edged swords (Stone, 1997). What is a cost to one party is an earning or saving to another. Similarly, buildings experience inherent tradeoffs, whether it be between performance and cost or various aspects of performance. Moreover, in many cases, simply measuring a factor heightens awareness for the particular characteristic. Being able to quantify visual comfort on a scale similar to that of energy consumption for a fenestration system forces users to think about all three performance criteria. Whether this induces decisions that are beneficial to energy consumption or not, the presence of information theoretically allows a more rational choice. And in the free market perspective, priorities are not questioned, but lack of information often skews the costs of achieving these priorities. Again, the metrics proposed here provide a language to increase access to information.

A second characteristic of the polis is the natural desire to manipulate measures or "teach to the test" (Stone, 1997). Where factors are not being measured, and the heightened awareness does not exist, the issue is far less present. Although this is not suggesting that intentional falsification of numbers is occuring, participants in the polis certainly do change behavior in response to being measured. Educators teach to standardized tests not because they are less interesting in their students' learning, but because if they are going to learn something, it might as well serve a purpose. This extricable feature of social measurement is just as present in the building industry. As suggested previously, there is a difference between achieving LEED credit in the spirit of LEED or in the easiest manner possible. Further, existing traditional metrics for fenestration systems incentivize manufactures to create systems that perform best at impossible environmental conditions. The role of annual performance in these metrics needs not be reiterated, but the approach taken precludes many potential reactive solutions that are not in the spirit of performance.

In summary, the presence and dominance of numbers in society is not an indicator that everything can be measured in an unbiased and worthy manner. Numbers can be manipulated, measures can be forged, and the ultimate goal or end point can easily be forgotten. Despite the introduction of quantitative performance measures in this work, we urge our colleagues to recognize the dynamic and social role that buildings play in our society and not rely on metrics, binary scales, or predetermined definitions of performance to cloud creativity and desire to improve the built space in any number of innovative ways.

Chapter 9
Conclusion

Advanced façades that use daylight in novel ways are not science fiction; they exist today. With today's energy challenges, conservation and efficiency are often considered the lowest hanging fruit, but often neglected in the economics of energy efficiency are the challenges of implementation when user comfort, behavior, and desires are involved. Providing the information for users to make informed decisions about the technologies that affect their daily life, consciously placing priorities on aspects such as comfort, view or energy, paves the way to create a demand for efficient technologies. Just as users may or may not be willing to compromise on the performance of a vehicle in favor of energy efficiency, users, occupants or designers, must have the power of choice to determine priorities for their interior space.

9.1 Achievements

The conclusion of this work is really the beginning of the next phase of the project. While the metrics have been defined, developed, and analyzed, the goal of this research is to engage manufacturers and standards organizations to determine the feasibility of these metrics in practice. Although the interests of these stakeholders have been considered throughout the technical development of the metrics, it will require a concerted effort to follow through with metrics to prepare them for public consumption.

Three relative performance metrics have been proposed in this research to provide users with information about the tradeoffs and performance characteristics of daylighting technologies, specifically, complex fenestration systems. Each is based on the bidirectional transmission distribution function (BTDF), the mathematical quantity that describes the angular behavior of light and heat transfer across a façade, but has been manipulated and packaged in a way that is useful to the building industry. The three metrics are the Relative Energy Impact (REI), the Extent of Comfortable Daylight (ECD), and the View Through Potential (VTP). The three metrics each address one critical criteria of fenestration systems: energy consumption, occupant comfort conditions, and view to the outdoors, respectively.

Each performance metric has been introduced with its full resolution calculation methodology as well as a final definition that incorporates sensitivity studies that reduce calculation time and complexity. In addition, analytical assessment of the metrics was conducted in order to identify subsidiary areas of research. A validation study that assesses the critical component of each metric was also conducted to gain insight as to the legitimacy of the definition of the performance metric. Finally, a final definition derived from the lessons learned for each metric was provided alongside an initial concept for a label or other visual representation that describes each complex fenestration system.

More specifically, the following insights were generated, categorized by metric:

Relative Energy Impact (REI):

- Proposed an energy performance metric that considers established technical specifications in their real-world annual usage.
- Established three climate zones and three orientations for which fenestration energy performance is sufficiently similar to consider collectively.
- Proposed an intermediate traditional metric that is more applicable to actual use than existing technical specifications.
- Validated the use of an independent energy model to enable decisions about the fenestration system specifically.

Extent of Comfortable Daylight (ECD):

- Proposed a unique way to describe visual comfort in terms of the fenestration system such that tradeoffs in comfort and other criteria could be identified.
- Established a single climate location and three orientations for which fenestration systems affect visual comfort similarly enough to consider collectively.
- Broke ground on an analytical explanation for comfort parameters from BTDF analysis.

- Suggested that a simple generic test module space may be an appropriate tool for evaluating visual comfort through a validation study that compares performance to a more complex space.

View Through Potential (VTP):

- Proposed the first validated approach to quantifying an occupant's perception of view from a system's BTDF.
- Presented a novel way to think about light transmission in terms of human perception that may inform other design decisions.
- Conducted a statistically significant user study that corroborates results of calculations for view through.

In addition, the following other accomplishments were required to supplement the specific outcomes of this research:

- A discussion of the need for performance metrics for daylighting systems.
- A justification for use of a relative approach to describe performance.
- A definition of generic test module and reference fenestration system for comparison.
- A method to condense measured BTDF data into a Klems basis BTDF dataset.
- A framework to reduce significant climate zones from a sensitivity analysis study.
- An innovative and visual concept to describe each performance metric on a fenestration system label.

In summary, a comprehensive methodology for calculation of three relative performance metrics has been established and reported here. The marriage of technical calculation process and practical implementation considerations primes these metrics for their real-world use. Furthermore, careful reflection on the both the priorities and approaches of engineers and designers sets these metrics apart from the many technical specifications and qualitative concepts that often spar in the building industry.

9.2 Future Work

In order to further validate these metrics in their current form, the BTDF dataset for various other real fenestration systems should be generated an analyzed to ensure that rankings and perceptions remain consistent. In addition, the metrics should be tested on complex fenestration systems that are entirely different in structure and approach to daylighting to assess their applicability to this category of systems. These technologies have substantial potential, and a method to communicate their performance enables more complex and esoteric technologies to be developed and disseminated effectively.

As previously mentioned, the metrics in their current form will be presented at the ASHRAE Winter Conference 2012 and to the NFRC Daylighting Potential Task Group. A representative from this work should remain engaged with the Task Group as a stakeholder in order to ensure that it is evaluated fairly and provide feedback accordingly. Simultaneously, a representative from this research should conduct outreach to manufacturers and suggest this approach for rating complex fenestration systems. This dual approach is *not* intended to be an undercut to the NFRC; rather it is a mechanism to understand which of the two methods is more appropriate in the industry. More likely, making both parties aware of it will help with refinement and awareness of the REI, ECD, and VTP as viable metrics.

Other areas for future work include further development of the heat transfer model used in the REI metric that currently requires fundamental assumptions, a careful study of more complex fenestration systems to justify the use of the generic test module for the ECD metric, and an even larger user study on more systems for the VTP metric. A substantial portion of these tasks relies on a further developed BTDF database for which data accuracy across systems is equal and a greater number of varied systems are evaluated. Although this access does not yet exist, simulation engines such as Window 6 and Radiance have begun to incorporate the structure and information of a BTDF dataset (Window 6.1, 2006; Saxena et al., 2010). In general, however, the sheer quantity of data and specific knowledge required to utilize it prevents practical implementation at any substantial level. As a result, the demand for a comprehensive database of BTDFs has not yet been established. An additional feature of the metrics presented in this work is creating such a demand by providing a relevant and practical approach to their use. The development of this framework for performance metrics that rely on the BTDF addresses the "chicken and egg" problem associated with the need for sufficient data but the barrier to generating the data without a satisfactory reason. The RFP issued by the NFRC is crucial to achieving this and enabling the pathway for these and other metrics.

Finally, future users should not be afraid of using the lessons learned in the development of these metrics and redesigning the approach if need be. As the industry evolves, so should metrics and the criteria by which we judge technologies. Just as these metrics are improvements on the existing NFRC and daylighting metrics in the industry, future metrics should evolve with the needs of the industry.

9.3 Final Remarks

The evolution of energy efficiency in buildings is one crucial driver for the development of these metrics to inform users of the tradeoffs they may or may not be willing to make with innovative fenestration technologies. Another driver is the desire to engage with the natural beauty and benefits of daylight, the most pure form of energy on the planet. The use of sunlight in this simple yet dynamic way is enchanting, constructive, and best of all, a free and bountiful resource with incredible potential.

Appendix A
General

This Appendix contains the following information:

- Policy memo to the NFRC Daylighting Task Group

Application of methodology presented in

Dave, S., Andersen, M. "A comprehensive method to determine performance metrics for complex fenestration systems." 27th Conference on Passive and Low Energy Architecture. *(forthcoming).*

March 9, 2011
Shreya Dave (sdave@mit.edu)

The paper submitted to the 27th Conference on Passive and Low Energy Architecture (PLEA) presents the calculation process that forms the foundation of further decisions and the application of this process is described as follows. There are four stages to which the procedure will be applied in order to arrive at an ultimate rating methodology.

The goal of this research is to create a ranking system that applies to any façade system that is considered to be a complex fenestration system. The process is intended to be straightforward enough that it is not a burden for the manufacturer to report these metrics and the metrics representative enough such that comparative decisions can be made by the user.

1. **Full resolution calculations:** The initial application step of analysis is to use the detailed procedure that is outline in the paper to arrive at the most accurate and specific values for each possible scenario. (All possible scenarios consist of fifteen climate locations, 56 moments of the year that have sky types determined for weather data, five orientations, and five complex fenestration systems that have been identified for their diversity.) This process is conducted using MATLAB and *Radiance* simulations for which a sample of results is presented in the paper.
2. **Input reduction:** In order to create a metric that is more universally applicable without requiring one hundred values to describe a system, inputs must be grouped into categories that predict similar results. For example, if the fifteen climate zones in the United States can be reduced to four groups of similar performance, the total number of calculations can be reduced by 75%. Similarly, if a particular metric such as the U-factor does not vary significantly over different environmental conditions, one representative set of environmental conditions may be used for a single calculation instead of 56 per climate location.
3. **Analytical calculation:** The full resolution calculation procedure requires involved simulations that, while alleviated by reduction of the number of inputs required for evaluation (thus reducing the total number of simulations required to define a system) is still time consuming and requires knowledge of simulation software. The goal of implementation as a useful metric will be hindered by a complex and involved process and so developing an analytical calculation procedure of a BTDF that bypasses the light rendering process and provides information about the general performance of a system is required. In order to make this feasible, reduction of required specificity in performance is required – in other words, a reliable relationship between BTDF and comfortable daylight conditions must be established, without the need for explicit illuminance calculations.
4. **Validation in a real space:** Each of the two previously explained simplifications from the full resolution calculations will be assessed using the sample of facades that was identified at the beginning of the project in the generic space described in the paper. In order to make validate the entire process, an independent validation will occur on a space that exists in reality. Both the full resolution calculations and the simplified calculations should then reveal the same relative metrics and inform the user of the same decision based on individual priorities.

The final metric rating system will be presented at the culmination of this project, due to be completed by October 2011. Parts I, II, and III above are scheduled to be completed by July 2011. The thesis project for which this research is being conducted will be submitted in December 2011.

Appendix B
Supplementary Information for REI Metric

This Appendix contains the following information:

- Table of full resolution REI results for each orientation.
- Ranking of full resolution REI calculation for each orientation.
- EnergyPlus validation table.

North																		
	clear_double			PrismaticPanel			OpalescentPlexi			HOE			OhenPerf (sched)			FabricGreyRed (sched)		
	HF	SHGF	EnergyLoad	HF	SHGF	EnergyLoad	HF	SHGF	EnergyLoad	HF	SHGF	EnergyLoa	HF	SHGF	EnergyLoa	HF	SHGF	EnergyLoa
alb	106870	22533	129,410.00	104570	18407	122,980.00	104570	21271	125,840.00	106840	18280	124790	106870	9737.9	116610	106870	22533	129410
bal	116330	19115	135450	113800	15613	129410	113800	17365	131160	116290	15989	131920	116330	8136	124470	116330	19115	135450
boi	128720	-27124	101590	125970	-23383	102590	125970	-47039	78930	128670	-9057.8	119220	128720	-16307	112410	128720	-27124	101590
bur	160490	-38786	121710	157020	-29178	127840	157020	-60745	96272	160440	-13097	146840	160490	-13056	147440	160490	-38786	121710
chi	143080	-787.42	142300	140010	126.32	140130	140010	-10116	129890	143030	6424.4	149020	143080	856.07	143940	143080	-787.42	142300
dul	203470	-80291	123180	199060	-63833	135220	199060	-113240	85823	203400	-39138	163630	203470	-35051	168420	203470	-80291	123180
elp	84817	65623	150440	82991	53708	136700	82991	78604	161600	84787	42318	126840	84817	29685	114500	84817	65623	150440
fai	262170	-105260	156900	256640	-83191	173450	256640	-128900	127750	262080	-61999	199290	262170	-41738	220430	262170	-105260	156900
hel	163880	-55998	107880	160400	-44466	115940	160400	-82669	77735	163820	-24599	138730	163880	-24197	139680	163880	-55998	107880
hou	68171	109040	177210	66696	89931	156630	66696	140270	206970	68147	65134	133070	68171	53091	121260	68171	109040	177210
mem	92991	63496	156490	90973	51510	142480	90973	80086	171060	92959	38050	130720	92991	28455	121450	92991	63496	156490
mia	52234	176930	229160	51109	144230	195340	51109	238670	289780	52216	96989	149040	52234	83664	135900	52234	176930	229160
pho	92914	107390	200300	90921	85026	175950	90921	137690	228610	92882	61179	153780	92914	45202	138120	92914	107390	200300
sal	105200	-62331	42865	102970	-51373	51600	102970	-85616	17357	105160	-34400	70442	105200	-33293	71903	105200	-62331	42865
sfr	84208	-126150	-41944	82394	-97833	-15440	82394	-174750	-92360	84179	-60868	23051	84208	-48038	36171	84208	-126150	-41944
	clear_double			PrismaticPanel			OpalescentPlexi			HOE			OhenPerf			FabricGreyRed		
	HF	SHGF	EnergyLoad	HF	SHGF	EnergyLoad	HF	SHGF	EnergyLoad	HF	SHGF	EnergyLoa	HF	SHGF	EnergyLoa	HF	SHGF	EnergyLoa
alb	0	0	0	-0.02152	-0.18311	-0.04968704	-0.02152	-0.05601	-0.02758674	-0.00028	-0.18875	-0.0357	0	-0.56784	-0.09891	1	1	0.00
bal	0	0	0	-0.02175	-0.18321	-0.0445921	-0.02175	-0.09155	-0.0316722	-0.00034	-0.16354	-0.02606	0	-0.57437	-0.08106	1	1	0.00
boi	0	0	0	-0.02136	0.137922	0.00984349	-0.02136	-0.73422	-0.22305345	-0.00039	0.66606	0.173541	0	0.398798	0.106507	1	1	0.00
bur	0	0	0	-0.02162	0.247718	0.05036562	-0.02162	-0.56616	-0.20900501	-0.00031	0.662327	0.206474	0	0.663384	0.211404	1	1	0.00
chi	0	0	0	-0.02146	1.160423	-0.01524947	-0.02146	-11.847	-0.08721012	-0.00035	9.158797	0.047224	0	2.087183	0.011525	1	1	0.00
dul	0	0	0	-0.02167	0.204979	0.09774314	-0.02167	-0.41037	-0.30327164	-0.00034	0.512548	0.328381	0	0.56345	0.367267	1	1	0.00
elp	0	0	0	-0.02153	-0.18157	-0.09133209	-0.02153	0.197812	0.0741824	-0.00035	-0.35513	-0.15687	0	-0.54764	-0.2389	1	1	0.00
fai	0	0	0	-0.02109	0.209662	0.1054812	-0.02109	-0.22459	-0.18578713	-0.00034	0.410992	0.270172	0	0.603477	0.404908	1	1	0.00
hel	0	0	0	-0.02124	0.205936	0.07471264	-0.02124	-0.47628	-0.27943085	-0.00037	0.560716	0.285966	0	0.567895	0.294772	1	1	0.00
hou	0	0	0	-0.02164	-0.17525	-0.1161334	-0.02164	0.286409	0.16793635	-0.00035	-0.40266	-0.24908	0	-0.51311	-0.31573	1	1	0.00
mem	0	0	0	-0.0217	-0.18877	-0.08952649	-0.0217	0.261276	0.09310499	-0.00034	-0.40075	-0.16468	0	-0.55186	-0.22391	1	1	0.00
mia	0	0	0	-0.02154	-0.18482	-0.14758248	-0.02154	0.348952	0.26453133	-0.00034	-0.45182	-0.34962	0	-0.52714	-0.40696	1	1	0.00
pho	0	0	0	-0.02145	-0.20825	-0.12156765	-0.02145	0.282149	0.14133799	-0.00034	-0.43031	-0.23225	0	-0.57909	-0.31043	1	1	0.00
sal	0	0	0	-0.0212	0.175803	0.20377931	-0.0212	-0.37357	-0.59507757	-0.00038	0.448108	0.643345	0	0.465868	0.677429	1	1	0.00
sfr	0	0	0	-0.02154	0.224471	0.63189014	-0.02154	-0.38526	-1.2019836	-0.00034	0.517495	1.549566	0	0.619199	1.862364	1	1	0.00

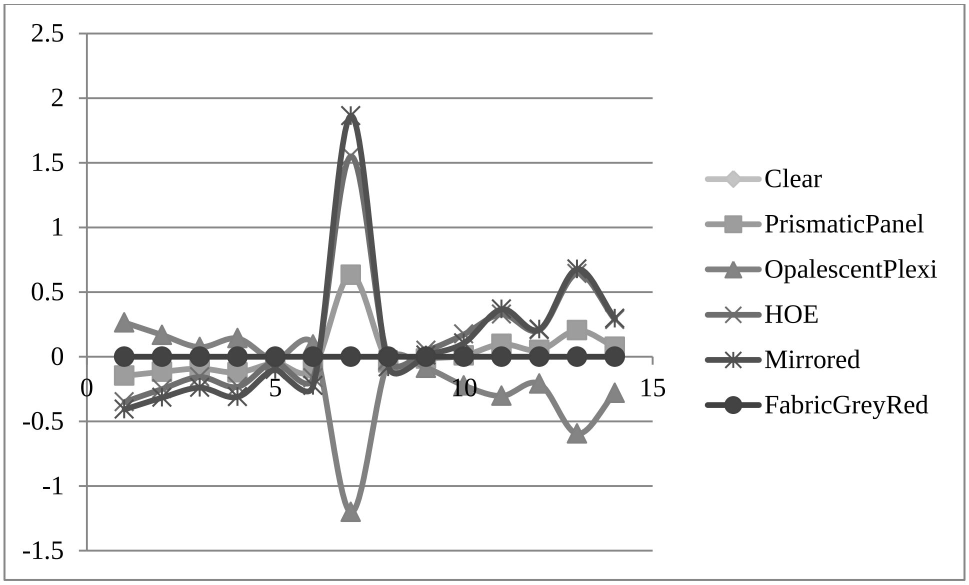
East																		
	clear_double			PrismaticPanel			OpalescentPlexi			HOE			OhenPerf (sched)			FabricGreyRed (sched)		
	HF	SHGF	EnergyLoa	HF	SHGF	EnergyLoa	HF	SHGF	EnergyLoa	HF	SHGF	EnergyLoa	HF	SHGF	EnergyLoa	HF	SHGF	EnergyLoa
alb	105660	13428	119090	103410	23281	126700	103410	5158.8	108570	105630	15861	121170	105660	1358.4	107020	105660	13428	119090
bal	113030	-1034.9	112000	110640	7228.7	117870	110640	-2803.2	107840	112990	1323	113970	113030	3205.5	116240	113030	-1034.9	112000
boi	129490	-87543	41946	126710	-75490	51220	126710	-89942	36769	129440	-67948	61099	129490	-25967	103520	129490	-87543	41946
bur	157630	-196800	-39169	154280	-169130	-14852	154280	-165590	-11309	157580	-162490	-5390.2	157630	-54688	102940	157630	-196800	-39169
chi	140070	-35802	104270	137130	-25457	111670	137130	-36776	100350	140030	-22387	117220	140070	-8791.4	131280	140070	-35802	104270
dul	197890	-286790	-88894	193710	-237860	-44143	193710	-236640	-42921	197830	-232610	-35380	197890	-69824	128070	197890	-286790	-88894
elp	84721	174050	258770	82900	162910	245810	82900	133240	216140	84692	153280	237720	84721	41854	126580	84721	174050	258770
fai	258810	-389550	-130750	253420	-345650	-92228	253420	-296980	-43559	258720	-334530	-76578	258810	-96492	162310	258810	-389550	-130750
hel	160590	-223080	-62487	157260	-191200	-33944	157260	-195150	-37893	160540	-183460	-23402	160590	-70385	90205	160590	-223080	-62487
hou	68279	225580	293850	66799	189970	256770	66799	194810	261610	68255	186190	254240	68279	55278	123560	68279	225580	293850
mem	92046	151870	243920	90069	147480	237550	90069	131770	221840	92014	139280	231010	92046	45972	138020	92046	151870	243920
mia	53831	435340	489170	52635	372750	425380	52635	376720	429360	53812	353390	407030	53831	90437	144270	53831	435340	489170
pho	93539	343480	437020	91520	311370	402890	91520	277750	369270	93507	303280	396500	93539	71788	165330	93539	343480	437020
sal	105630	-100330	5303	103390	-79242	24149	103390	-103280	114.09	105600	-74252	31024	105630	-33287	72345	105630	-100330	5303
sfr	82469	-468790	-386330	80729	-396380	-315660	80729	-393780	-313050	82441	-389540	-307350	82469	-129280	-46812	82469	-468790	-386330

	clear_double			PrismaticPanel			OpalescentPlexi			HOE			OhenPerf			FabricGreyRed		
	HF	SHGF	EnergyLoa	HF	SHGF	EnergyLoa	HF	SHGF	EnergyLoa	HF	SHGF	EnergyLoa	HF	SHGF	EnergyLoa	HF	SHGF	EnergyLoa
alb	0	0	0	-0.02129	0.733765	0.063901	-0.02129	-0.61582	-0.08834	-0.00028	0.181189	0.017466	0	-0.89884	-0.10135	0	0	0
bal	0	0	0	-0.02114	7.984926	0.052411	-0.02114	-1.70867	-0.03714	-0.00035	2.278384	0.017589	0	4.097401	0.037857	0	0	0
boi	0	0	0	-0.02147	0.137681	0.221094	-0.02147	-0.0274	-0.12342	-0.00039	0.223833	0.456611	0	0.70338	1.467935	0	0	0
bur	0	0	0	-0.02125	0.1406	0.620823	-0.02125	0.158587	0.711277	-0.00032	0.174339	0.862386	0	0.722114	3.628099	0	0	0
chi	0	0	0	-0.02099	0.28895	0.07097	-0.02099	-0.02721	-0.03759	-0.00029	0.3747	0.124197	0	0.754444	0.259039	0	0	0
dul	0	0	0	-0.02112	0.170613	0.50342	-0.02112	0.174867	0.517167	-0.0003	0.188919	0.601998	0	0.756533	2.440705	0	0	0
elp	0	0	0	-0.02149	-0.064	-0.05008	-0.02149	-0.23447	-0.16474	-0.00034	-0.11933	-0.08135	0	-0.75953	-0.51084	0	0	0
fai	0	0	0	-0.02083	0.112694	0.294623	-0.02083	0.237633	0.666853	-0.00035	0.14124	0.414317	0	0.752299	2.241377	0	0	0
hel	0	0	0	-0.02074	0.142908	0.456783	-0.02074	0.125202	0.393586	-0.00031	0.177604	0.62549	0	0.684485	2.44358	0	0	0
hou	0	0	0	-0.02168	-0.15786	-0.12619	-0.02168	-0.1364	-0.10972	-0.00035	-0.17462	-0.1348	0	-0.75495	-0.57951	0	0	0
mem	0	0	0	-0.02148	-0.02891	-0.02612	-0.02148	-0.13235	-0.09052	-0.00035	-0.0829	-0.05293	0	-0.69729	-0.43416	0	0	0
mia	0	0	0	-0.02222	-0.14377	-0.1304	-0.02222	-0.13465	-0.12227	-0.00035	-0.18824	-0.16792	0	-0.79226	-0.70507	0	0	0
pho	0	0	0	-0.02158	-0.09348	-0.0781	-0.02158	-0.19136	-0.15503	-0.00034	-0.11704	-0.09272	0	-0.791	-0.62169	0	0	0
sal	0	0	0	-0.02121	0.210186	3.553837	-0.02121	-0.0294	-0.97849	-0.00028	0.259922	4.850273	0	0.668225	12.64228	0	0	0
sfr	0	0	0	-0.0211	0.154461	0.182927	-0.0211	0.160008	0.189682	-0.00034	0.169052	0.204437	0	0.724226	0.878829	0	0	0

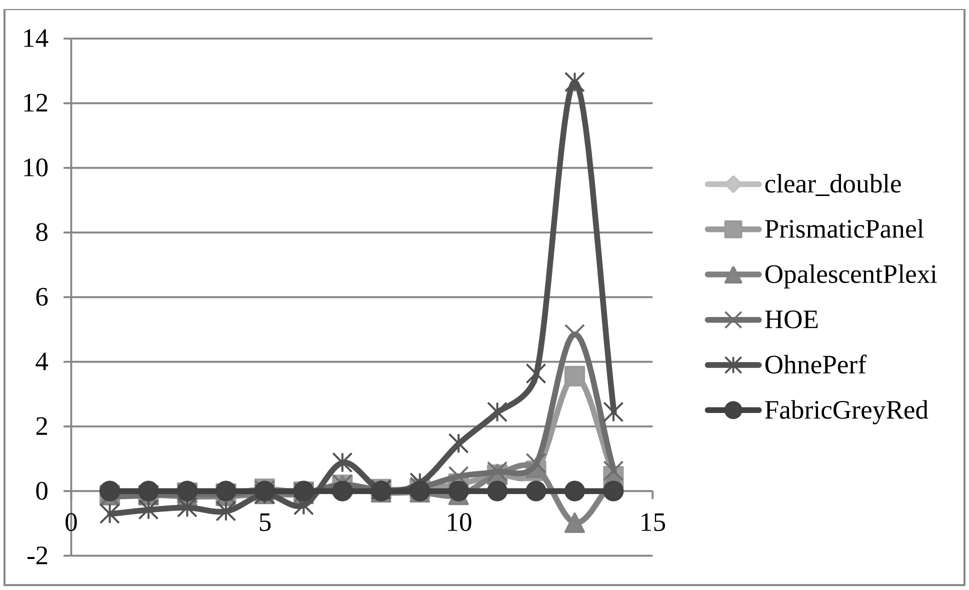
South																		
	clear_double			PrismaticPanel			OpalescentPlexi			HOE			OhenPerf (sched)			FabricGreyRed (sched)		
	HF	SHGF	EnergyLoa	HF	SHGF	EnergyLoa	HF	SHGF	EnergyLoa	HF	SHGF	EnergyLoa	HF	SHGF	EnergyLoa	HF	SHGF	EnergyLoa
alb	105590	-504480	-398890	103350	-547050	-443710	103350	-358100	-254760	105560	-557440	-452210	105590	-116820	-11231	105590	-504480	-398890
bal	113200	-366150	-252950	110800	-388610	-277800	110800	-248570	-137770	113160	-396660	-283840	113200	-84217	28982	113200	-366150	-252950
boi	129440	-441580	-312130	126670	-439970	-313300	126670	-314090	-187420	129400	-447750	-318750	129440	-100980	28462	129440	-441580	-312130
bur	157730	-460590	-302860	154370	-436570	-282190	154370	-332490	-178120	157680	-447460	-290260	157730	-107950	49784	157730	-460590	-302860
chi	143300	-338300	-195000	140210	-358810	-218600	140210	-232130	-91916	143250	-358140	-215330	143300	-79657	63641	143300	-338300	-195000
dul	198410	-632440	-434030	194210	-580140	-385930	194210	-459330	-265120	198340	-596270	-398530	198410	-139570	58841	198410	-632440	-434030
elp	84477	-360470	-276000	82665	-385160	-302500	82665	-209230	-126570	84448	-407570	-323380	84477	-67344	17133	84477	-360470	-276000
fai	257220	-655640	-398420	251910	-610830	-358920	251910	-467970	-216060	257140	-604190	-347810	257220	-146590	110630	257220	-655640	-398420
hel	162080	-623310	-461230	158680	-592100	-433420	158680	-448030	-289340	162030	-596760	-435220	162080	-152560	9521.7	162080	-623310	-461230
hou	68030	-40963	27066	66560	-75914	-9354.3	66560	27575	94135	68006	-93565	-25770	68030	-4724.3	63305	68030	-40963	27066
mem	92067	-183210	-91140	90090	-238520	-148430	90090	-98013	-7923.6	92035	-253420	-161670	92067	-36589	55478	92067	-183210	-91140
mia	53093	496320	549420	51930	357150	409080	51930	399560	451490	53075	369820	422730	53093	87056	140150	53093	496320	549420
pho	93410	131830	225240	91396	-25764	65632	91396	114440	205830	93378	-11924	81165	93410	9325.8	102740	93410	131830	225240
sal	108450	-357160	-248710	106090	-352250	-246160	106090	-255910	-149820	108410	-347150	-239080	108450	-72370	36080	108450	-357160	-248710
sfr	83407	-766670	-683260	81627	-697560	-615940	81627	-615740	-534110	83379	-706290	-623170	83407	-196080	-112670	83407	-766670	-683260
	clear_double			PrismaticPanel			OpalescentPlexi			HOE			OhenPerf			FabricGreyRed		
	HF	SHGF	EnergyLoa	HF	SHGF	EnergyLoa	HF	SHGF	EnergyLoa	HF	SHGF	EnergyLoa	HF	SHGF	EnergyLoa	HF	SHGF	EnergyLoa
alb	0	0	0	-0.02121	-0.08438392	-0.11236	-0.02121	0.29016	0.361328	-0.00028	-0.10498	-0.13367	0	0.768435	0.971844	0	0	0
bal	0	0	0	-0.0212	-0.06134098	-0.09824	-0.0212	0.321125	0.455347	-0.00035	-0.08333	-0.12212	0	0.769993	1.114576	0	0	0
boi	0	0	0	-0.0214	0.003645998	-0.00375	-0.0214	0.288713	0.399545	-0.00031	-0.01397	-0.02121	0	0.771321	1.091186	0	0	0
bur	0	0	0	-0.0213	0.052150503	0.068249	-0.0213	0.278122	0.411873	-0.00032	0.028507	0.041603	0	0.765627	1.16438	0	0	0
chi	0	0	0	-0.02156	-0.06062666	-0.12103	-0.02156	0.313834	0.528636	-0.00035	-0.05865	-0.10426	0	0.764537	1.326364	0	0	0
dul	0	0	0	-0.02117	0.082695592	0.110822	-0.02117	0.273718	0.389167	-0.00035	0.057191	0.081792	0	0.779315	1.135569	0	0	0
elp	0	0	0	-0.02145	-0.06849391	-0.09601	-0.02145	0.419563	0.541413	-0.00034	-0.13066	-0.17167	0	0.813177	1.062076	0	0	0
fai	0	0	0	-0.02064	0.068345433	0.099142	-0.02064	0.286239	0.457708	-0.00031	0.078473	0.127027	0	0.776417	1.277672	0	0	0
hel	0	0	0	-0.02098	0.050071393	0.060295	-0.02098	0.281208	0.372677	-0.00031	0.042595	0.056393	0	0.755242	1.020644	0	0	0
hou	0	0	0	-0.02161	-0.85323341	-1.34561	-0.02161	1.673168	2.47798	-0.00035	-1.28413	-1.95212	0	0.884669	1.338912	0	0	0
mem	0	0	0	-0.02147	-0.301894	-0.62859	-0.02147	0.465024	0.913061	-0.00035	-0.38322	-0.77386	0	0.800289	1.608712	0	0	0
mia	0	0	0	-0.0219	-0.28040377	-0.25543	-0.0219	-0.19495	-0.17824	-0.00034	-0.25488	-0.23059	0	-0.8246	-0.74491	0	0	0
pho	0	0	0	-0.02156	-1.19543351	-0.70861	-0.02156	-0.13191	-0.08617	-0.00034	-1.09045	-0.63965	0	-0.92926	-0.54386	0	0	0
sal	0	0	0	-0.02176	0.01374734	0.010253	-0.02176	0.283486	0.397612	-0.00037	0.028027	0.03872	0	0.797374	1.145069	0	0	0
sfr	0	0	0	-0.02134	0.090143086	0.098528	-0.02134	0.196864	0.218292	-0.00034	0.078756	0.087946	0	0.744245	0.835099	0	0	0

West																		
	clear_double			PrismaticPanel			OpalescentPlexi			HOE			OhenPerf (sched)			FabricGreyRed (sched)		
	HF	SHGF	EnergyLoa	HF	SHGF	EnergyLoa	HF	SHGF	EnergyLoa	HF	SHGF	EnergyLoa	HF	SHGF	EnergyLoa	HF	SHGF	EnergyLoa
alb	103150	-51557	51593	101000	-51017	49988	101000	-47146	53859	103110	-54531	48274	103150	-15375	87771	103150	-51557	51593
bal	110890	-29889	81001	108590	-25003	83586	108590	-27775	80814	110850	-29855	80668	110890	-7973.9	102920	110890	-29889	81001
boi	125200	-154430	-29230	122600	-128840	-6236.3	122600	-129040	-6434.8	125160	-125150	-364.5	125200	-47133	78068	125200	-154430	-29230
bur	153310	-261230	-107920	150140	-223590	-73446	150140	-204320	-54174	153260	-221140	-68337	153310	-76265	77047	153310	-261230	-107920
chi	137880	-70602	67278	135030	-55563	79466	135030	-61956	73073	137840	-59819	77610	137880	-21721	116160	137880	-70602	67278
dul	192760	-420500	-227740	188800	-377610	-188810	188800	-331800	-143000	192690	-366060	-173930	192760	-126620	66137	192760	-420500	-227740
elp	82294	202670	284964	80576	177960	258530	80576	146170	226740	82266	169890	251910	82294	57911	140210	82294	202670	284964
fai	254110	-390680	-136570	248930	-338230	-89296	248930	-305620	-56692	254030	-327940	-74647	254110	-115160	138960	254110	-390680	-136570
hel	159470	-321730	-162260	156180	-295090	-138900	156180	-260510	-104320	159420	-280890	-121950	159470	-100780	58687	159470	-321730	-162260
hou	66184	278290	344474	64795	256660	321450	64795	233660	298450	66162	240310	306270	66184	91554	157740	66184	278290	344474
mem	89495	184270	273765	87628	164730	252360	87628	139350	226980	89465	156590	245790	89495	52636	142130	89495	184270	273765
mia	51141	617540	668681	50063	574230	624290	50063	520670	570740	51124	547420	598390	51141	202390	253530	51141	617540	668681
pho	91392	634410	725802	89464	557190	646650	89464	452990	542460	91361	543370	634460	91392	175970	267360	91392	634410	725802
sal	104150	-178650	-74500	101970	-157540	-55568	101970	-153880	-51912	104110	-153660	-49863	104150	-53451	50696	104150	-178650	-74500
sfr	81467	-720160	-638693	79770	-656550	-576780	79770	-565190	-485420	81440	-639010	-557820	81467	-216720	-135250	81467	-720160	-638693
	clear_double			PrismaticPanel			OpalescentPlexi			HOE			OhenPerf			FabricGreyRed		
	HF	SHGF	EnergyLoa	HF	SHGF	EnergyLoa	HF	SHGF	EnergyLoa	HF	SHGF	EnergyLoa	HF	SHGF	EnergyLoa	HF	SHGF	EnergyLoa
alb	0	0	0	-0.02084	0.010474	-0.03111	-0.02084	0.085556	0.043921	-0.00039	-0.05768	-0.06433	0	0.701786	0.701219	0	0	0
bal	0	0	0	-0.02074	0.163472	0.031913	-0.02074	0.070728	-0.00231	-0.00036	0.001138	-0.00411	0	0.733216	0.270602	0	0	0
boi	0	0	0	-0.02077	0.165706	0.786647	-0.02077	0.164411	0.779856	-0.00032	0.1896	0.98753	0	0.694794	3.670818	0	0	0
bur	0	0	0	-0.02068	0.144088	0.31944	-0.02068	0.217854	0.498017	-0.00033	0.153466	0.366781	0	0.708054	1.713927	0	0	0
chi	0	0	0	-0.02067	0.213011	0.181159	-0.02067	0.122461	0.086135	-0.00029	0.152729	0.153572	0	0.692346	0.726567	0	0	0
dul	0	0	0	-0.02054	0.101998	0.170941	-0.02054	0.210939	0.372091	-0.00036	0.129465	0.236278	0	0.698882	1.290406	0	0	0
elp	0	0	0	-0.02088	-0.12192	-0.09276	-0.02088	-0.27878	-0.20432	-0.00034	-0.16174	-0.11599	0	-0.71426	-0.50797	0	0	0
fai	0	0	0	-0.02038	0.134253	0.346152	-0.02038	0.217723	0.584887	-0.00031	0.160592	0.453416	0	0.705232	2.0175	0	0	0
hel	0	0	0	-0.02063	0.082802	0.143966	-0.02063	0.190284	0.357081	-0.00031	0.126939	0.248428	0	0.686756	1.361685	0	0	0
hou	0	0	0	-0.02099	-0.07772	-0.06684	-0.02099	-0.16037	-0.13361	-0.00033	-0.13648	-0.11091	0	-0.67101	-0.54208	0	0	0
mem	0	0	0	-0.02086	-0.10604	-0.07819	-0.02086	-0.24377	-0.17089	-0.00034	-0.15021	-0.10219	0	-0.71435	-0.48083	0	0	0
mia	0	0	0	-0.02108	-0.07013	-0.06639	-0.02108	-0.15686	-0.14647	-0.00033	-0.11355	-0.10512	0	-0.67226	-0.62085	0	0	0
pho	0	0	0	-0.0211	-0.12172	-0.10905	-0.0211	-0.28597	-0.25261	-0.00034	-0.1435	-0.12585	0	-0.72262	-0.63164	0	0	0
sal	0	0	0	-0.02093	0.118164	0.254121	-0.02093	0.138651	0.303195	-0.00038	0.139882	0.330698	0	0.700806	1.680483	0	0	0
sfr	0	0	0	-0.02083	0.088328	0.096937	-0.02083	0.215188	0.239979	-0.00033	0.112683	0.126623	0	0.699067	0.788239	0	0	0

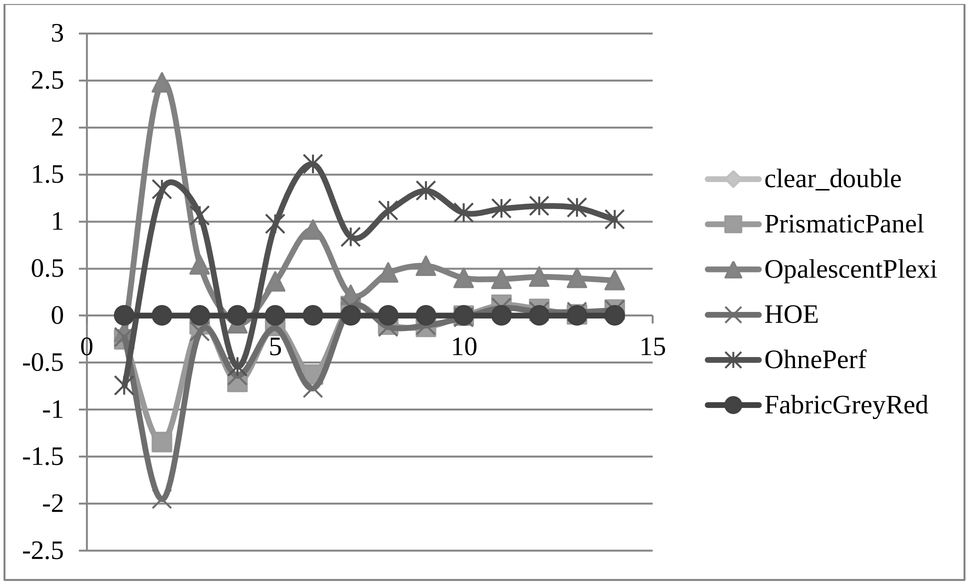
North:


2.5
2
1.5
1
0.5
0
-0.5
-1
-1.5
0
5
10
15
Clear
PrismaticPanel
OpalescentPlexi
HOE
Mirrored
FabricGreyRed

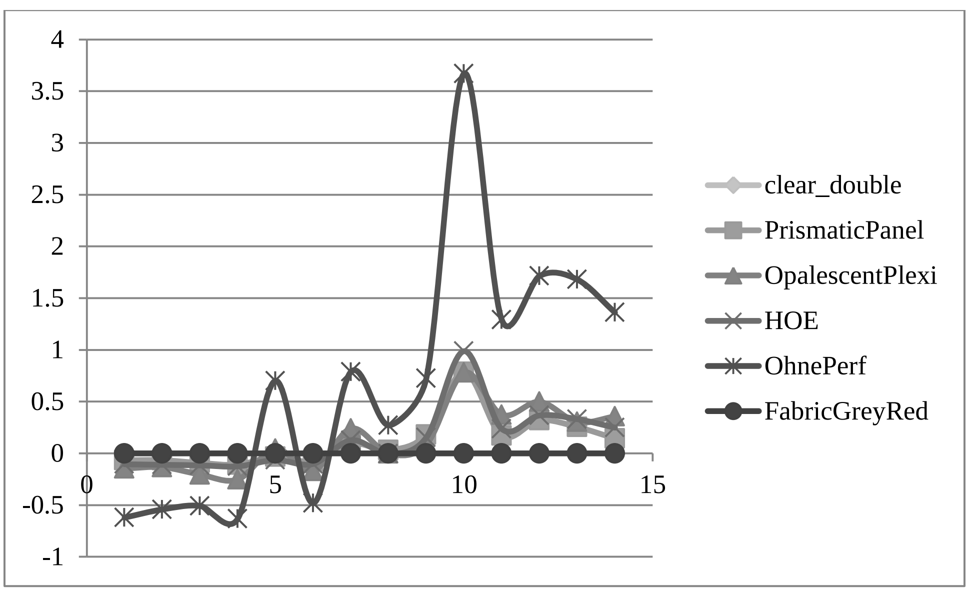
East:


14
12
10
8
6
4
2
0
-2
0
5
10
15
clear_double
PrismaticPanel
OpalescentPlexi
HOE
OhnePerf
FabricGreyRed

South:


3
2.5
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
-2.5
0
5
10
15
clear_double
PrismaticPanel
OpalescentPlexi
HOE
OhnePerf
FabricGreyRed

West:


4
3.5
3
2.5
2
1.5
1
0.5
0
-0.5
-1
0
5
10
15
clear_double
PrismaticPanel
OpalescentPlexi
HOE
OhnePerf
FabricGreyRed

Energy Plus Results												
Input Parameters				per meter squared of building area						End use breakdown		
Direction	System	Surface area window (m2)	Surface area building (m2)	Total Energy (MJ)	Lighting Electricity (MJ)	HVAC Electricity (MJ)	HVAC Natural Gas (MJ)	HVAC total (MJ)	Heating (GJ)	Cooling (GJ)	Fans (GJ)
North	clear	16.7	511.2	1550.82	181.64	83.76	92.28	176.04	35.65	9.5	33.31
North	diffusing	16.7	511.2	1548.53	181.64	82.63	93.63	176.26	36.34	9.17	32.26
North	shade	16.7	511.2	1542.53	181.64	79.33	98.41	177.74	38.78	8.3	32.26
South	clear	16.7	511.2	1540.36	181.64	82.71	85.91	168.62	32.39	10.47	31.8
South	diffusing	16.7	511.2	1537.99	181.64	81.23	88.23	169.46	33.58	9.83	31.69
South	shade	16.7	511.2	1535.78	181.64	77.07	98.84	175.91	39	8.06	31.34
East	clear	11.2	511.2	1600.49	181.64	101.29	84.51	185.8	31.68	11.68	40.14
East	diffusing	11.2	511.2	1581.26	181.64	94.62	87.41	182.03	33.16	10.68	37.65
East	shade	11.2	511.2	1543.67	181.64	80.43	95.84	176.27	37.47	8.44	32.68
West	clear	11.2	511.2	1599.46	181.64	100.8	85.06	185.86	31.96	11.19	40.33
West	diffusing	11.2	511.2	1582.94	181.64	95.04	87.41	182.45	33.16	10.36	38.22
West	shade	11.2	511.2	1539.33	181.64	78.87	96.64	175.51	37.88	8.33	31.98

Appendix C
Supplementary Information for ECD Metric

This Appendix contains the following information:

- Sun positions and binned climate data for Memphis, TN for 56 moments.
- Table of full resolution ECD results for each orientation.
- Ranking of full resolution ECD calculation for each orientation.
- ECD full resolution values compared to single-climate value.
- ECD single-climate value compared to single-sky-type value.

Binned Cliamte Data: Memphis, TN (35.15, 90.05, -6)										
	Julian Date	Hour	Altitude (degrees)	Azimuth (degrees from South)	Direct Normal Radiation (W/m2)	Diffuse Horizontal Radiation (W/m2)	Zenith Luminance (cd/m2)	Outdoor Temperature (degrees C)	Outdoor Wind Speed (m/s)	Wind Direction (degrees from North)
1	23	8	9.09	58.07	122.04	28.36	371.83	1.78	5.00	172.30
2	23	10	26.97	34.97	298.48	80.39	1157.47	3.04	5.14	183.56
3	23	11	32.65	20.05	346.43	114.57	1737.51	4.06	5.13	185.22
4	23	12	35.15	3.28	394.55	138.39	2128.15	5.36	5.28	197.63
5	23	14	29.45	-29.58	410.71	135.90	2225.97	6.32	5.44	206.00
6	23	15	22.17	-43.05	367.61	109.39	1690.19	6.57	5.30	198.59
7	23	17	2.44	-63.81	234.92	56.81	831.07	6.20	5.02	189.22
8	68	7	7.08	79.02	99.57	31.09	722.41	8.04	3.48	147.30
9	68	9	29.91	58.47	317.87	129.28	3585.32	10.65	4.23	151.63
10	68	11	46.67	26.44	378.64	188.17	6250.43	12.82	4.46	158.62
11	68	12	49.96	4.43	405.72	220.74	8181.63	14.53	4.72	174.26
12	68	14	42.60	-38.14	416.45	210.29	7347.16	15.85	4.71	177.38
13	68	16	23.20	-65.61	395.07	160.74	4824.15	15.89	4.58	183.94
14	68	17	11.64	-75.56	286.99	82.60	2204.11	14.94	4.26	177.38
15	113	6	7.32	99.87	88.09	30.01	726.30	14.86	3.47	148.77
16	113	8	31.75	82.52	331.75	126.07	3524.86	17.26	4.65	168.77
17	113	10	54.76	56.87	439.57	218.17	8216.74	19.66	5.17	192.83
18	113	12	67.11	-0.91	466.93	264.07	13405.58	21.39	5.10	197.10
19	113	14	54.26	-57.74	450.14	243.21	10995.51	22.27	5.20	193.62
20	113	16	31.16	-82.98	396.28	184.01	5772.39	22.28	4.92	188.41
21	113	18	6.73	-100.28	199.59	71.59	1794.57	20.99	4.22	166.52
22	159	6	13.11	108.80	123.18	45.47	1056.74	21.39	2.82	184.04
23	159	8	37.10	93.51	383.84	151.26	4148.79	24.48	3.77	201.84
24	159	10	61.37	72.45	487.23	240.87	10090.92	27.02	4.33	216.95
25	159	12	77.63	-1.28	527.27	280.45	18911.42	28.39	4.59	220.43
26	159	14	60.91	-73.06	508.16	270.69	15150.99	29.09	4.98	217.87
27	159	16	36.62	-93.83	421.24	209.40	6837.73	28.86	4.73	209.50
28	159	18	12.65	-109.10	234.87	97.04	2376.67	27.34	4.24	211.77
29	205	6	10.07	107.50	94.52	37.40	871.35	23.56	2.20	133.69
30	205	8	34.18	91.64	350.20	138.99	3734.61	26.33	3.03	160.64
31	205	10	58.32	69.95	475.30	233.43	9337.87	29.22	3.37	180.92
32	205	12	74.82	6.04	500.79	296.01	19240.64	31.02	3.59	192.84
33	205	14	60.87	-66.27	491.43	282.06	15836.10	31.80	4.12	195.25
34	205	16	36.92	-89.73	429.12	217.65	6741.91	31.42	4.30	193.83
35	205	18	12.70	-105.72	239.26	103.86	2424.11	29.93	3.81	172.70
36	250	7	16.22	86.36	86.04	30.42	637.61	22.13	2.23	112.17
37	250	8	28.34	76.96	331.50	108.57	2667.61	24.59	2.81	128.04
38	250	10	50.38	50.39	520.12	197.26	6350.94	27.81	3.40	157.32
39	250	12	61.22	-0.77	562.26	239.76	10184.78	29.85	3.71	160.87
40	250	14	49.90	-51.28	531.73	226.95	8676.01	30.68	3.76	168.12
41	250	16	27.75	-77.46	462.10	184.71	5229.46	30.58	3.79	181.96
42	250	17	15.61	-86.80	321.33	106.65	2525.07	29.67	3.60	180.43
43	296	7	8.55	69.84	97.13	33.38	823.83	12.26	2.30	118.72
44	296	8	19.65	59.86	292.69	105.00	2767.34	14.82	3.09	133.83
45	296	10	37.54	32.99	430.33	165.20	4879.01	17.51	3.44	154.82
46	296	11	42.54	14.86	504.37	197.61	6328.65	19.90	3.46	168.87
47	296	13	40.38	-24.66	504.14	184.35	5736.38	21.10	3.55	178.94
48	296	15	24.60	-54.41	442.78	134.24	3809.43	21.17	3.55	199.50
49	296	16	14.00	-65.24	283.76	69.95	1756.81	20.14	3.16	200.00
50	342	8	10.24	52.74	81.76	16.41	380.11	5.58	3.61	155.53
51	342	9	19.26	41.87	272.11	74.94	2144.82	7.73	4.65	183.55
52	342	10	26.39	28.98	364.96	129.98	4043.40	9.95	5.13	192.13
53	342	12	32.18	-2.12	380.72	155.59	5037.94	11.38	5.09	202.98
54	342	13	30.02	-18.10	375.01	154.37	4868.09	12.29	5.06	215.85
55	342	15	17.07	-44.87	343.10	131.74	3922.87	12.27	4.86	210.53
56	342	16	7.66	-55.27	231.87	69.40	1871.06	11.61	4.45	206.81

North	clear_double			PrismaticPanel			OpalescentPlexi			HOE			OhenPerf (sched)			FabricGreyRed (sched)		
	Low	Comf	High	Low	Comf	High	Low	Comf	High	Low	Comf	High	Low	Comf	High	Low	Comf	High
alb	0.55532	0.43233	0.012349	0.47941	0.51625	0.004341	0.40863	0.57085	0.020521	0.72354	0.27436	0.002106	0.5431	0.45688	1.41E-05	0.5431	0.45688	1.41E-05
bal	0.5483	0.44114	0.010553	0.51148	0.4859	0.00262	0.46989	0.52434	0.005772	0.75302	0.24456	0.002419	0.5483	0.45051	0.001188	0.5483	0.45051	0.001188
boi	0.5817	0.40934	0.008953	0.54102	0.4564	0.002585	0.49834	0.49487	0.006792	0.76615	0.23182	0.00203	0.58162	0.41775	0.000634	0.58162	0.41775	0.000634
bur	0.56275	0.43407	0.003187	0.52835	0.46971	0.001934	0.49301	0.5066	0.000392	0.77571	0.22429	1.38E-06	0.56275	0.43605	0.001202	0.56275	0.43605	0.001202
chi	0.56913	0.42593	0.004938	0.52713	0.47046	0.002402	0.49326	0.50603	0.000714	0.77389	0.22605	5.82E-05	0.56913	0.4295	0.001366	0.56913	0.4295	0.001366
dul	0.56826	0.42601	0.005726	0.52855	0.46559	0.005859	0.49441	0.50311	0.002486	0.77286	0.22666	0.000482	0.56755	0.43211	0.000346	0.56755	0.43211	0.000346
elp	0.55427	0.43356	0.012165	0.47357	0.52007	0.006354	0.39718	0.57908	0.023734	0.71276	0.28466	0.002579	0.53604	0.46381	0.000148	0.53604	0.46381	0.000148
fai	0.76466	0.23421	0.001125	0.69786	0.30089	0.001259	0.65378	0.346	0.000219	0.88248	0.11708	0.000437	0.76234	0.23762	3.76E-05	0.76234	0.23762	3.76E-05
hel	0.58402	0.408	0.007978	0.53817	0.45469	0.00714	0.50123	0.49572	0.003055	0.77478	0.22386	0.001363	0.58281	0.41717	1.81E-05	0.58281	0.41717	1.81E-05
hou	0.52214	0.45757	0.020291	0.46121	0.53097	0.007822	0.41038	0.57129	0.018338	0.70052	0.29739	0.002089	0.5101	0.48862	0.001276	0.5101	0.48862	0.001276
mem	0.53591	0.4521	0.011994	0.49163	0.50438	0.003991	0.44405	0.54627	0.009683	0.73642	0.26154	0.002044	0.5321	0.46712	0.000775	0.5321	0.46712	0.000775
mia	0.4753	0.4897	0.035003	0.40893	0.57316	0.017908	0.34577	0.61992	0.034303	0.66582	0.33169	0.002484	0.44274	0.55705	0.000207	0.44274	0.55705	0.000207
pho	0.5437	0.44762	0.00869	0.499	0.49818	0.002818	0.44788	0.54316	0.008962	0.72978	0.26806	0.002158	0.54139	0.45791	0.000699	0.54139	0.45791	0.000699
sal	0.58532	0.41236	0.002314	0.55547	0.44267	0.00186	0.52271	0.47673	0.000568	0.79389	0.20611	0	0.58532	0.41408	0.000592	0.58532	0.41408	0.000592
sfr	0.54372	0.44765	0.00863	0.49848	0.498	0.003518	0.4478	0.54324	0.008959	0.73011	0.26801	0.001873	0.54143	0.45794	0.000626	0.54143	0.45794	0.000626

	clear_double			PrismaticPanel			OpalescentPlexi			HOE			OhenPerf			FabricGreyRed		
	Low	Comf	High	Low	Comf	High	Low	Comf	High	Low	Comf	High	Low	Comf	High	Low	Comf	High
alb	1	1	1	0.863304	1.194111	0.351543	0.735846	1.320403	1.661754	1.302924	0.634608	0.170564	0.977995	1.056785	0.00114	0.977995	1.056785	0.00114
bal	1	1	1	0.932847	1.101464	0.248271	0.856994	1.188602	0.546982	1.373372	0.554382	0.229262	1	1.02124	0.112603	1	1.02124	0.112603
boi	1	1	1	0.930067	1.114966	0.288728	0.856696	1.208946	0.758572	1.317088	0.566326	0.226741	0.999862	1.020545	0.070821	0.999862	1.020545	0.070821
bur	1	1	1	0.938872	1.082107	0.606828	0.876073	1.167093	0.123044	1.378427	0.516714	0.000432	1	1.004561	0.377106	1	1.004561	0.377106
chi	1	1	1	0.926203	1.104548	0.486382	0.866691	1.188059	0.144584	1.359777	0.530721	0.011781	1	1.008382	0.276573	1	1.008382	0.276573
dul	1	1	1	0.93012	1.092909	1.023104	0.870042	1.180982	0.434215	1.360046	0.532053	0.084106	0.998751	1.014319	0.060344	0.998751	1.014319	0.060344
elp	1	1	1	0.854403	1.199534	0.522318	0.716582	1.33564	1.951007	1.285944	0.656564	0.212018	0.96711	1.069771	0.012192	0.96711	1.069771	0.012192
fai	1	1	1	0.912641	1.284702	1.119232	0.854994	1.477307	0.194487	1.154082	0.499893	0.388601	0.996966	1.01456	0.033423	0.996966	1.01456	0.033423
hel	1	1	1	0.921492	1.114436	0.894954	0.858241	1.215	0.382959	1.326633	0.548676	0.170811	0.997928	1.022475	0.002274	0.997928	1.022475	0.002274
hou	1	1	1	0.883307	1.160413	0.385466	0.785958	1.24853	0.90375	1.341633	0.649933	0.102927	0.976941	1.067858	0.062905	0.976941	1.067858	0.062905
mem	1	1	1	0.917374	1.115638	0.332758	0.828591	1.208295	0.807337	1.374149	0.5785	0.170385	0.992891	1.033223	0.064651	0.992891	1.033223	0.064651
mia	1	1	1	0.860362	1.170431	0.511613	0.727477	1.265918	0.980002	1.400842	0.677333	0.070965	0.931496	1.137533	0.005914	0.931496	1.137533	0.005914
pho	1	1	1	0.917786	1.112953	0.324277	0.823763	1.21344	1.031336	1.342248	0.598856	0.248326	0.995751	1.022988	0.08039	0.995751	1.022988	0.08039
sal	1	1	1	0.949002	1.073504	0.803517	0.893033	1.156101	0.245299	1.356335	0.49983	0	1	1.004171	0.255911	1	1.004171	0.255911
sfr	1	1	1	0.916795	1.112476	0.40765	0.823586	1.213537	1.038101	1.342805	0.598704	0.217088	0.995788	1.022987	0.072534	0.995788	1.022987	0.072534
mean	1	1	1	0.910305	1.135613	0.553776	0.824971	1.23919	0.746895	1.33442	0.576206	0.153601	0.988765	1.03476	0.099252	0.988765	1.03476	0.099252

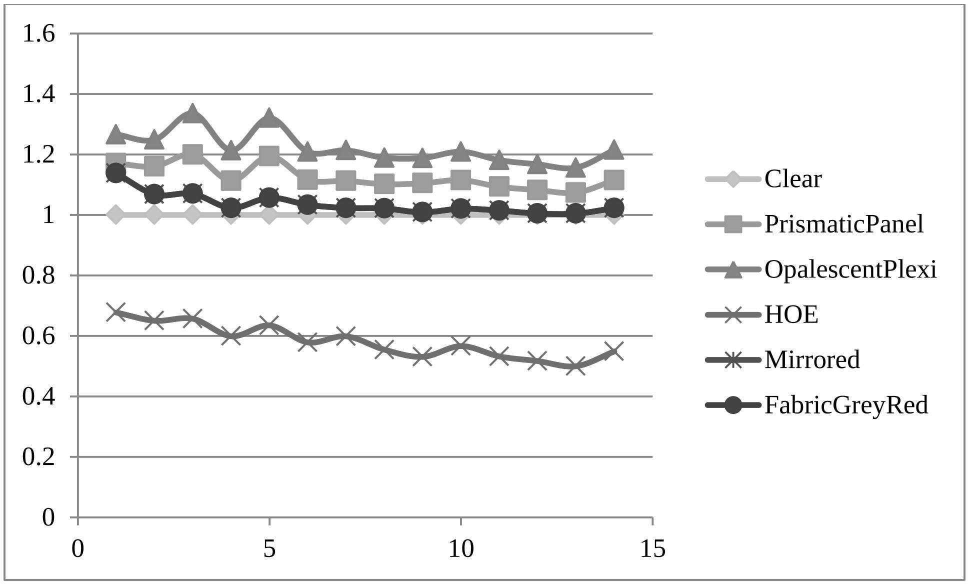
East	clear_double			PrismaticPanel			OpalescentPlexi			HOE			OhenPerf (sched)			FabricGreyRed (sched)		
	Low	Comf	High	Low	Comf	High	Low	Comf	High	Low	Comf	High	Low	Comf	High	Low	Comf	High
alb	0.54263	0.4371	0.020272	0.33394	0.60668	0.05938	0.2767	0.61274	0.11056	0.50653	0.47099	0.022482	0.54263	0.45601	0.001355	0.54263	0.45601	0.001355
bal	0.56447	0.41916	0.016371	0.37522	0.58021	0.044577	0.31003	0.60473	0.085237	0.53795	0.44214	0.019912	0.56447	0.43357	0.001964	0.56447	0.43357	0.001964
boi	0.59208	0.39208	0.015837	0.39919	0.55292	0.047889	0.33477	0.57019	0.09504	0.54679	0.43074	0.022475	0.59208	0.4058	0.002113	0.59208	0.4058	0.002113
bur	0.56536	0.42169	0.012957	0.39453	0.5672	0.038263	0.32762	0.60733	0.06505	0.56759	0.42411	0.008303	0.56536	0.43288	0.00176	0.56536	0.43288	0.00176
chi	0.56409	0.42285	0.013066	0.39141	0.5716	0.036986	0.3242	0.61575	0.060044	0.56324	0.42938	0.007383	0.56409	0.43413	0.001789	0.56409	0.43413	0.001789
dul	0.58221	0.40296	0.014829	0.3939	0.55989	0.046205	0.3183	0.59202	0.089676	0.55195	0.42959	0.018463	0.58215	0.41436	0.00349	0.58215	0.41437	0.003479
elp	0.52803	0.44889	0.023086	0.32659	0.61352	0.059884	0.2679	0.61601	0.11609	0.50279	0.47091	0.026305	0.52803	0.47145	0.000526	0.52803	0.47145	0.000526
fai	0.7058	0.29001	0.004187	0.60563	0.38282	0.011545	0.5432	0.43542	0.021387	0.73119	0.26738	0.001434	0.7058	0.29164	0.002556	0.7058	0.29164	0.002556
hel	0.59692	0.38648	0.016601	0.40441	0.55018	0.045411	0.33522	0.57229	0.092486	0.5554	0.42308	0.021528	0.59692	0.40133	0.001746	0.59692	0.40145	0.001625
hou	0.53147	0.44685	0.021674	0.35921	0.57968	0.061113	0.30136	0.60254	0.096102	0.51907	0.46246	0.018468	0.53147	0.46614	0.002385	0.53147	0.46614	0.002385
mem	0.54711	0.43628	0.016607	0.36354	0.588	0.048458	0.29508	0.61744	0.087477	0.53321	0.45036	0.016425	0.54711	0.45013	0.002757	0.54711	0.45013	0.002757
mia	0.50419	0.46625	0.029563	0.32396	0.60006	0.075985	0.28255	0.60991	0.10755	0.49228	0.48003	0.027687	0.50419	0.49307	0.002741	0.50419	0.49307	0.002741
pho	0.55229	0.42936	0.018358	0.36364	0.58253	0.053829	0.30343	0.59925	0.097317	0.52668	0.45076	0.022554	0.55229	0.44522	0.002491	0.55229	0.44522	0.002491
sal	0.59298	0.39388	0.01314	0.42584	0.53872	0.035436	0.34929	0.58256	0.068155	0.58413	0.40884	0.007026	0.59298	0.4032	0.003813	0.59298	0.4032	0.003813
sfr	0.55244	0.42883	0.01873	0.36381	0.58251	0.05368	0.30328	0.59978	0.09694	0.52728	0.4507	0.022024	0.55244	0.44504	0.002518	0.55244	0.44504	0.002518

	clear_double			PrismaticPanel			OpalescentPlexi			HOE			OhenPerf			FabricGreyRed		
	Low	Comf	High	Low	Comf	High	Low	Comf	High	Low	Comf	High	Low	Comf	High	Low	Comf	High
alb	1	1	1	0.61541	1.387966	2.929163	0.509924	1.40183	5.453828	0.933472	1.077534	1.109017	1	1.043262	0.066856	1	1.043262	0.066856
bal	1	1	1	0.66473	1.384221	2.722925	0.549241	1.442719	5.206585	0.953018	1.054824	1.216297	1	1.034378	0.119968	1	1.034378	0.119968
boi	1	1	1	0.674216	1.410222	3.023868	0.565413	1.45427	6.001137	0.923507	1.098602	1.419145	1	1.034993	0.133422	1	1.034993	0.133422
bur	1	1	1	0.697839	1.345064	2.953076	0.579489	1.440229	5.020452	1.003944	1.005739	0.640789	1	1.026536	0.135834	1	1.026536	0.135834
chi	1	1	1	0.693879	1.35178	2.830706	0.574731	1.45619	4.595439	0.998493	1.015443	0.565016	1	1.026676	0.136913	1	1.026676	0.136913
dul	1	1	1	0.67656	1.389443	3.115854	0.54671	1.469178	6.04734	0.948026	1.066086	1.24506	0.999897	1.028291	0.235336	0.999897	1.028315	0.234621
elp	1	1	1	0.618507	1.366749	2.593953	0.507358	1.372296	5.028589	0.9522	1.049054	1.139435	1	1.050257	0.022771	1	1.050257	0.022771
fai	1	1	1	0.858076	1.320023	2.757147	0.769623	1.501397	5.107587	1.035973	0.921968	0.34256	1	1.00562	0.610513	1	1.00562	0.610513
hel	1	1	1	0.677494	1.423567	2.735438	0.561583	1.480775	5.57111	0.930443	1.094701	1.296789	1	1.038424	0.105174	1	1.038734	0.09791
hou	1	1	1	0.67588	1.297259	2.819646	0.567031	1.348417	4.433976	0.976668	1.034933	0.852081	1	1.043169	0.110026	1	1.043169	0.110026
mem	1	1	1	0.664473	1.347758	2.917926	0.539343	1.415238	5.267478	0.974594	1.032273	0.989041	1	1.031746	0.166008	1	1.031746	0.166008
mia	1	1	1	0.642536	1.286992	2.570274	0.560404	1.308118	3.637993	0.976378	1.029555	0.936542	1	1.057523	0.092707	1	1.057523	0.092707
pho	1	1	1	0.658422	1.35674	2.932182	0.549403	1.395682	5.301068	0.953629	1.049842	1.228565	1	1.036939	0.135696	1	1.036939	0.135696
sal	1	1	1	0.718136	1.367726	2.696804	0.589042	1.479029	5.186834	0.985075	1.037981	0.534726	1	1.023662	0.290198	1	1.023662	0.290198
sfr	1	1	1	0.658551	1.35837	2.86599	0.548983	1.398643	5.175654	0.954457	1.050999	1.175868	1	1.037801	0.13441	1	1.037801	0.13441
mean	1	1	1	0.679647	1.359592	2.830997	0.567885	1.424267	5.135671	0.966659	1.041302	0.979395	0.999993	1.034618	0.166389	0.999993	1.034641	0.165857

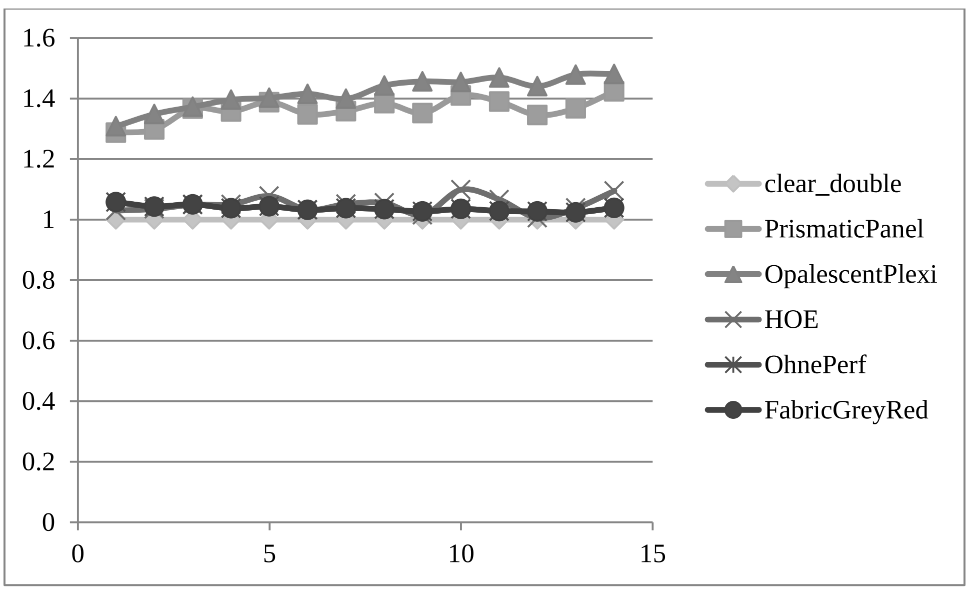
South																		
	clear_double			PrismaticPanel			OpalescentPlexi			HOE			OhenPerf (sched)			FabricGreyRed (sched)		
	Low	Comf	High	Low	Comf	High	Low	Comf	High	Low	Comf	High	Low	Comf	High	Low	Comf	High
alb	0.088837	0.7205	0.15442	0.26833	0.60856	0.10662	0.11981	0.68285	0.16692	0.2366	0.66274	0.099474	0.087477	0.91228	0.000244	0.087477	0.91172	0.0008
bal	0.10694	0.7496	0.13066	0.33074	0.56985	0.0906	0.15352	0.71773	0.12875	0.30493	0.59668	0.095647	0.10542	0.89456	1.44E-05	0.10542	0.89453	4.48E-05
boi	0.13302	0.71377	0.14476	0.31026	0.58599	0.089948	0.15172	0.70021	0.14807	0.29646	0.59256	0.10425	0.12084	0.87908	8.49E-05	0.12084	0.87903	0.00013
bur	0.11761	0.75917	0.12203	0.36616	0.54331	0.081134	0.18744	0.69966	0.1129	0.33535	0.59214	0.069711	0.11756	0.88189	0.000546	0.11756	0.88189	0.000546
chi	0.11296	0.76754	0.11575	0.37137	0.54571	0.075903	0.18606	0.7084	0.10555	0.34156	0.59424	0.062297	0.11269	0.88679	0.000522	0.11269	0.88679	0.000522
dul	0.11417	0.74044	0.14289	0.31002	0.57921	0.097735	0.15507	0.70618	0.13875	0.28317	0.61161	0.10106	0.11254	0.88713	0.000326	0.11254	0.88713	0.000334
elp	0.089841	0.74019	0.14521	0.2966	0.59795	0.097707	0.13867	0.70919	0.14089	0.26836	0.63844	0.093201	0.089627	0.90996	0.000413	0.089627	0.90969	0.000686
fai	0.23804	0.65824	0.10372	0.43076	0.51673	0.052511	0.33333	0.60087	0.065795	0.42294	0.54912	0.027946	0.23175	0.76481	0.003443	0.23175	0.76821	4.01E-05
hel	0.12569	0.7075	0.1624	0.29953	0.59114	0.09582	0.14984	0.68963	0.16053	0.28187	0.60575	0.10785	0.11816	0.88161	0.000235	0.11816	0.88156	0.000288
hou	0.097241	0.74119	0.14948	0.33867	0.56613	0.092632	0.15672	0.71127	0.13201	0.3088	0.60438	0.086824	0.096676	0.90329	3.47E-05	0.096676	0.90329	3.47E-05
mem	0.10318	0.74229	0.1434	0.34052	0.56848	0.088917	0.15704	0.7189	0.12406	0.30811	0.59989	0.091999	0.10252	0.8973	0.00018	0.10252	0.8973	0.00018
mia	0.09468	0.75416	0.14991	0.31736	0.58815	0.091164	0.1489	0.71214	0.13897	0.28073	0.61832	0.10095	0.09434	0.90504	0.000622	0.09434	0.90498	0.000681
pho	0.10065	0.74328	0.14566	0.31834	0.57946	0.093514	0.15613	0.71632	0.12755	0.2907	0.61237	0.094068	0.098658	0.90052	0.000823	0.098658	0.90041	0.000934
sal	0.12417	0.75025	0.12439	0.37759	0.53051	0.08571	0.19656	0.70188	0.10156	0.3576	0.57948	0.060715	0.12244	0.87659	0.000978	0.12244	0.87659	0.000978
sfr	0.099736	0.74021	0.14922	0.31815	0.57882	0.094217	0.1561	0.71686	0.12704	0.29111	0.6113	0.095802	0.098439	0.90084	0.000721	0.098439	0.90081	0.000749
	clear_double			PrismaticPanel			OpalescentPlexi			HOE			OhenPerf			FabricGreyRed		
	Low	Comf	High	Low	Comf	High	Low	Comf	High	Low	Comf	High	Low	Comf	High	Low	Comf	High
alb	1	1	1	3.020476	0.84463567	0.690455	1.34865	0.947745	1.080948	2.663305	0.919833	0.644178	0.984691	1.266176	0.001581	0.984691	1.265399	0.005178
bal	1	1	1	3.092762	0.760205443	0.693403	1.435571	0.957484	0.985382	2.851412	0.795998	0.73203	0.985786	1.193383	0.00011	0.985786	1.193343	0.000343
boi	1	1	1	2.332431	0.820978747	0.621359	1.14058	0.981002	1.022865	2.228687	0.830183	0.720158	0.908435	1.231601	0.000586	0.908435	1.231531	0.000898
bur	1	1	1	3.113341	0.715663158	0.664869	1.593742	0.921612	0.925182	2.851373	0.779983	0.571261	0.999575	1.16165	0.004471	0.999575	1.16165	0.004471
chi	1	1	1	3.287624	0.710985747	0.655749	1.647132	0.922949	0.911879	3.023725	0.774214	0.538203	0.99761	1.155366	0.004511	0.99761	1.155366	0.004511
dul	1	1	1	2.715424	0.782251094	0.683988	1.358238	0.95373	0.971027	2.480249	0.826009	0.707257	0.985723	1.198112	0.00228	0.985723	1.198112	0.002336
elp	1	1	1	3.301388	0.807833124	0.672867	1.543505	0.958119	0.97025	2.987055	0.862535	0.641836	0.997618	1.22936	0.002842	0.997618	1.228995	0.004727
fai	1	1	1	1.809612	0.785017623	0.506277	1.400311	0.912843	0.634352	1.77676	0.834225	0.269437	0.973576	1.161901	0.033195	0.973576	1.167067	0.000386
hel	1	1	1	2.383085	0.835533569	0.590025	1.192139	0.974742	0.988485	2.242581	0.856184	0.664101	0.940091	1.246092	0.001444	0.940091	1.246021	0.001772
hou	1	1	1	3.48279	0.763812248	0.619695	1.611666	0.959632	0.883128	3.175615	0.815418	0.58084	0.99419	1.218702	0.000232	0.99419	1.218702	0.000232
mem	1	1	1	3.300252	0.765846233	0.620063	1.522	0.968489	0.865132	2.986141	0.808161	0.641555	0.993603	1.208827	0.001259	0.993603	1.208827	0.001259
mia	1	1	1	3.351922	0.779874297	0.608125	1.572666	0.944282	0.927023	2.96504	0.819879	0.673404	0.996409	1.200064	0.004149	0.996409	1.199984	0.004544
pho	1	1	1	3.162842	0.779598536	0.642002	1.551217	0.963728	0.875669	2.888227	0.823875	0.645805	0.980209	1.211549	0.005648	0.980209	1.211401	0.006415
sal	1	1	1	3.040912	0.707110963	0.689043	1.582991	0.935528	0.816464	2.879923	0.772383	0.488102	0.986067	1.168397	0.007863	0.986067	1.168397	0.007863
sfr	1	1	1	3.189921	0.78196728	0.631397	1.565132	0.968455	0.85136	2.918806	0.825847	0.642018	0.986996	1.217006	0.004832	0.986996	1.216965	0.005023

West																		
	clear_double			PrismaticPanel			OpalescentPlexi			HOE			OhenPerf (sched)			FabricGreyRed (sched)		
	Low	Comf	High	Low	Comf	High	Low	Comf	High	Low	Comf	High	Low	Comf	High	Low	Comf	High
alb	0.53014	0.46302	0.00684	0.30457	0.63187	0.055645	0.27111	0.65728	0.049353	0.44372	0.51112	0.043497	0.52998	0.46585	0.004174	0.52998	0.46585	0.004174
bal	0.55286	0.44048	0.006656	0.32561	0.62507	0.047479	0.25279	0.6904	0.047942	0.48	0.50143	0.018513	0.55286	0.44497	0.002164	0.55286	0.44497	0.002164
boi	0.57789	0.41989	0.002218	0.33531	0.61905	0.044799	0.23705	0.70251	0.046335	0.47544	0.50487	0.019506	0.57789	0.42055	0.00156	0.57789	0.42055	0.00156
bur	0.55744	0.43537	0.007191	0.34144	0.61913	0.039434	0.29007	0.64873	0.061199	0.5197	0.47317	0.007123	0.5574	0.43959	0.003015	0.5574	0.43959	0.003015
chi	0.55806	0.43373	0.008205	0.34639	0.61233	0.041286	0.29886	0.64177	0.059372	0.51622	0.47807	0.005646	0.55806	0.43976	0.002182	0.55806	0.43976	0.002182
dul	0.56714	0.42793	0.004938	0.33251	0.61715	0.048608	0.26871	0.67759	0.043695	0.4962	0.48806	0.015508	0.56705	0.43045	0.002497	0.56705	0.43045	0.002497
elp	0.51999	0.46985	0.010158	0.31382	0.62747	0.053237	0.25575	0.67509	0.053268	0.45574	0.50539	0.038386	0.5199	0.47808	0.002014	0.5199	0.47808	0.002014
fai	0.68002	0.31544	0.004539	0.5455	0.43298	0.021521	0.5198	0.44708	0.033127	0.7213	0.27639	0.002315	0.67969	0.31872	0.001595	0.67969	0.31872	0.001595
hel	0.58067	0.41641	0.002922	0.33787	0.61162	0.050331	0.26319	0.68146	0.043093	0.4873	0.49137	0.021036	0.58064	0.41738	0.001981	0.58064	0.41738	0.001981
hou	0.51788	0.46916	0.012954	0.28436	0.65833	0.055516	0.21868	0.72239	0.051905	0.45103	0.52656	0.02229	0.51788	0.47888	0.00324	0.51788	0.47888	0.00324
mem	0.53878	0.45214	0.009079	0.31179	0.63496	0.051579	0.24781	0.69723	0.049126	0.47554	0.50649	0.017968	0.53878	0.45885	0.002373	0.53878	0.45885	0.002373
mia	0.48798	0.4932	0.018822	0.26095	0.6735	0.065555	0.19366	0.73527	0.057087	0.4178	0.54715	0.035046	0.48798	0.51004	0.001983	0.48798	0.51004	0.001983
pho	0.53686	0.45572	0.007423	0.30678	0.63966	0.051058	0.22985	0.71177	0.047488	0.46295	0.51413	0.022869	0.53686	0.46162	0.001523	0.53686	0.46162	0.001523
sal	0.58296	0.4118	0.005239	0.36284	0.60424	0.032919	0.31626	0.63739	0.046352	0.53652	0.45847	0.005007	0.58296	0.41323	0.00381	0.58296	0.41323	0.00381
sfr	0.5368	0.4556	0.007602	0.307	0.63921	0.05147	0.22987	0.71215	0.047093	0.46196	0.51549	0.022428	0.53679	0.4617	0.001514	0.53679	0.4617	0.001514
	clear_double			PrismaticPanel			OpalescentPlexi			HOE			OhenPerf			FabricGreyRed		
	Low	Comf	High	Low	Comf	High	Low	Comf	High	Low	Comf	High	Low	Comf	High	Low	Comf	High
alb	1	1	1	0.574509	1.364671	8.135353	0.511393	1.41955	7.215456	0.836986	1.103883	6.359303	0.999698	1.006112	0.610243	0.999698	1.006112	0.610243
bal	1	1	1	0.588956	1.419066	7.133478	0.457241	1.567381	7.203041	0.868213	1.138372	2.781484	1	1.010193	0.325175	1	1.010193	0.325175
boi	1	1	1	0.580232	1.474315	20.20066	0.410199	1.673081	20.89327	0.822717	1.202386	8.795599	1	1.001572	0.703206	1	1.001572	0.703206
bur	1	1	1	0.612514	1.422078	5.483494	0.520361	1.490066	8.510026	0.932298	1.086823	0.990419	0.999928	1.009693	0.419265	0.999928	1.009693	0.419265
chi	1	1	1	0.620704	1.411777	5.031994	0.535534	1.479653	7.23634	0.925026	1.102229	0.688081	1	1.013903	0.265982	1	1.013903	0.265982
dul	1	1	1	0.586293	1.442175	9.843661	0.473798	1.583413	8.848724	0.874916	1.140514	3.140543	0.999841	1.005889	0.505691	0.999841	1.005889	0.505691
elp	1	1	1	0.603512	1.335469	5.240894	0.491836	1.43682	5.243946	0.87644	1.075641	3.778893	0.999827	1.017516	0.198228	0.999827	1.017516	0.198228
fai	1	1	1	0.802182	1.372622	4.741771	0.764389	1.417322	7.298947	1.060704	0.876205	0.510113	0.999515	1.010398	0.351408	0.999515	1.010398	0.351408
hel	1	1	1	0.581862	1.468793	17.2272	0.453252	1.636512	14.74979	0.839203	1.180015	7.200164	0.999948	1.002329	0.67795	0.999948	1.002329	0.67795
hou	1	1	1	0.549085	1.40321	4.285626	0.42226	1.539752	4.00687	0.870916	1.122346	1.720704	1	1.020718	0.250116	1	1.020718	0.250116
mem	1	1	1	0.578696	1.404344	5.681383	0.459947	1.542067	5.411187	0.882624	1.120206	1.97916	1	1.014841	0.261329	1	1.014841	0.261329
mia	1	1	1	0.534756	1.365572	3.482892	0.396861	1.490815	3.032993	0.856183	1.109388	1.86197	1	1.034144	0.105345	1	1.034144	0.105345
pho	1	1	1	0.571434	1.403625	6.878073	0.428138	1.561858	6.397155	0.862329	1.128171	3.080705	1	1.012947	0.205178	1	1.012947	0.205178
sal	1	1	1	0.62241	1.467314	6.283691	0.542507	1.547814	8.847828	0.920338	1.113332	0.955772	1	1.003473	0.727323	1	1.003473	0.727323
sfr	1	1	1	0.571908	1.403007	6.770409	0.428223	1.563104	6.194654	0.860581	1.131453	2.950199	0.999981	1.013389	0.199205	0.999981	1.013389	0.199205
mean	1	1	1	0.598603	1.410536	7.761372	0.486396	1.529947	8.072682	0.885965	1.108731	3.119541	0.999916	1.011808	0.387043	0.999916	1.011808	0.387043

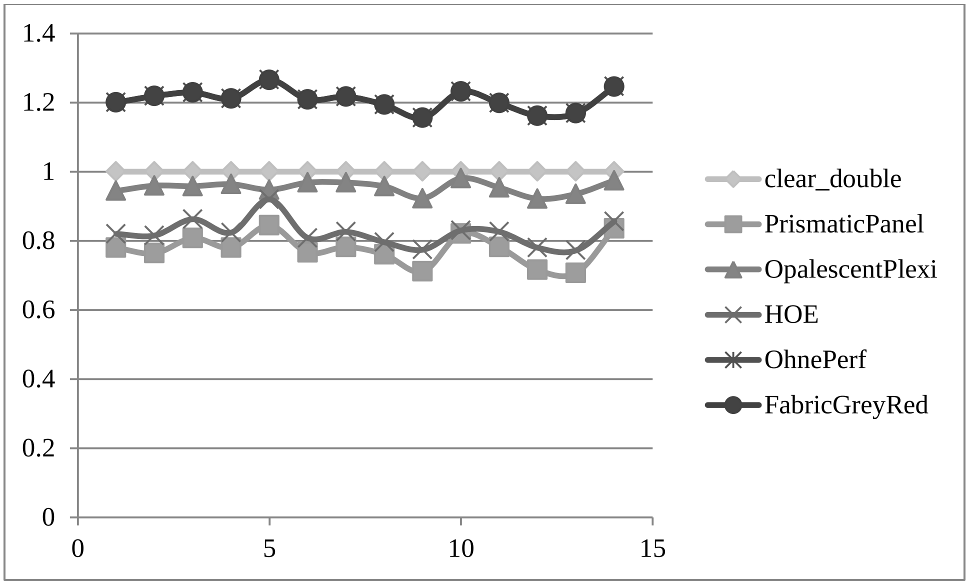
Full resolution ECD calculations: North



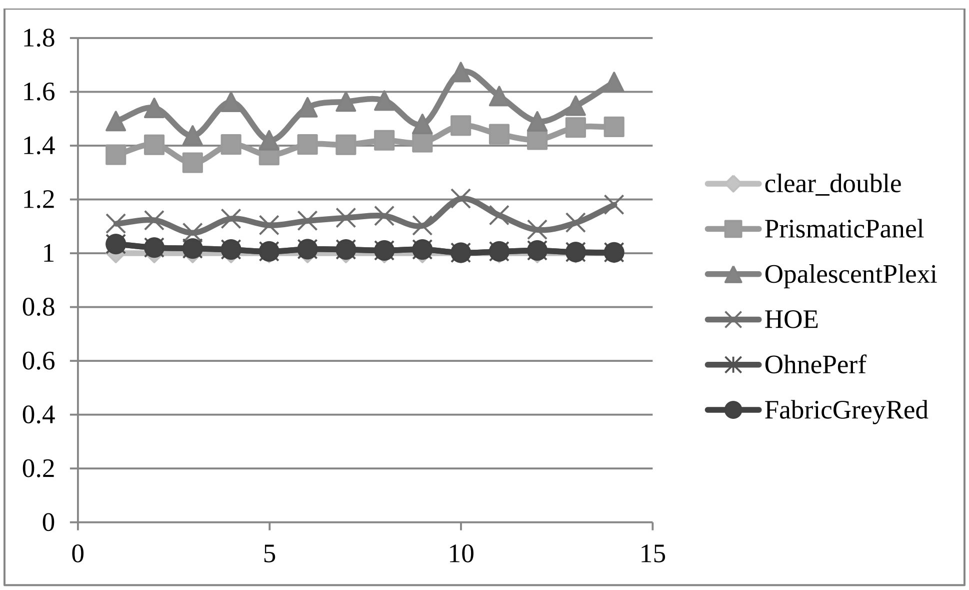
Full resolution ECD calculations: East



Full resolution ECD calculations: South



Full resolution ECD calculations: West



East vs. West

% diff between E/W							
	clear_double	PrismaticPane	OpalescentPl	HOE	OhnePerf	FabricGreyRe	max
mia	0	0.059248204	0.130547691	0.074646895	0.022353867	0.022353867	0.130547691
hou	0	0.078468904	0.132495868	0.081039929	0.02175601	0.02175601	0.132495868
elp	0	0.023151594	0.04593911	0.025026483	0.031667948	0.031667948	0.04593911
pho	0	0.033969974	0.112374614	0.071927213	0.023408289	0.023408289	0.112374614
alb	0	0.016925636	0.012560992	0.024158111	0.036255321	0.036255321	0.036255321
mem	0	0.041121633	0.085773172	0.081704192	0.016520322	0.016520322	0.085773172
sfr	0	0.032329208	0.111056625	0.073727889	0.023802374	0.023802374	0.111056625
bal	0	0.024859923	0.082829325	0.076188224	0.023657625	0.023657625	0.082829325
chi	0	0.043420369	0.015983892	0.08196421	0.012519456	0.012519456	0.08196421
boi	0	0.044438532	0.139934109	0.090208192	0.032820974	0.032820974	0.139934109
dul	0	0.037245135	0.07484467	0.067459154	0.022025427	0.022049557	0.07484467
bur	0	0.055663115	0.034015227	0.077497258	0.016543499	0.016543499	0.077497258
sal	0	0.070255096	0.045450202	0.07005081	0.01991922	0.01991922	0.070255096
hel	0	0.031272897	0.099918214	0.075010689	0.035373496	0.035672363	0.099918214
fai	0	0.039068578	0.057610675	0.050900047	0.004739716	0.004739716	0.057610675
							0.089286397

Full Resolution vs. Single-Climate

North	Full Resolution						% Difference to Single Climate					
	clear_dou	PrismaticP	Opalescer	HOE	OhnePerf	FabricGrey	clear_dou	PrismaticP	Opalescer	HOE	OhnePerf	FabricGreyRe
alb	1	1.194111	1.320403	0.634608	1.056785	1.056785	0	0.070339	0.092783	0.096988	0.022805	0.022804945
bal	1	1.101464	1.188602	0.554382	1.02124	1.02124	0	-0.0127	-0.0163	-0.04169	-0.0116	-0.01159703
boi	1	1.114966	1.208946	0.566326	1.020545	1.020545	0	-0.0006	0.000539	-0.02104	-0.01227	-0.01226983
bur	1	1.082107	1.167093	0.516714	1.004561	1.004561	0	-0.03006	-0.0341	-0.1068	-0.02774	-0.02773967
chi	1	1.104548	1.188059	0.530721	1.008382	1.008382	0	-0.00994	-0.01675	-0.08259	-0.02404	-0.02404233
dul	1	1.092909	1.180982	0.532053	1.014319	1.014319	0	-0.02037	-0.0226	-0.08029	-0.0183	-0.01829598
elp	1	1.199534	1.33564	0.656564	1.069771	1.069771	0	0.0752	0.105393	0.134942	0.035373	0.035373262
hel	1	1.114436	1.215	0.548676	1.022475	1.022475	0	-0.00108	0.005549	-0.05155	-0.0104	-0.01040168
hou	1	1.160413	1.24853	0.649933	1.067858	1.067858	0	0.040134	0.0333	0.12348	0.033522	0.033522038
mem	1	1.115638	1.208295	0.5785	1.033223	1.033223	0	0	0	0	0	0
mia	1	1.170431	1.265918	0.677333	1.137533	1.137533	0	0.049113	0.04769	0.170843	0.100956	0.100956397
pho	1	1.112953	1.21344	0.598856	1.022988	1.022988	0	-0.00241	0.004258	0.035187	-0.00991	-0.0099054
sal	1	1.073504	1.156101	0.49983	1.004171	1.004171	0	-0.03777	-0.0432	-0.13599	-0.02812	-0.02811749
sfr	1	1.112476	1.213537	0.598704	1.022987	1.022987	0	-0.00283	0.004339	0.034925	-0.00991	-0.0099069

East/West	Full Resolution						% Difference to Single Climate					
	clear_doubl	PrismaticPa	OpalescentF	HOE	OhnePerf	FabricGreyR	clear_doubl	PrismaticPa	OpalescentF	HOE	OhnePerf	FabricGreyR
alb	1	1.38796614	1.40183024	1.07753375	1.04326241	1.04326241	0	0.02983311	-0.0094738	0.04384586	0.01116239	0.01116239
bal	1	1.38422082	1.44271877	1.05482393	1.03437828	1.03437828	0	0.02705418	0.01941783	0.02184605	0.00255161	0.00255161
boi	1	1.4102224	1.45426954	1.09860233	1.03499286	1.03499286	0	0.04634665	0.02757954	0.06425576	0.00314728	0.00314728
bur	1	1.34506391	1.4402286	1.00573881	1.02653608	1.02653608	0	-0.0019992	0.01765829	-0.0257045	-0.0050493	-0.0050493
chi	1	1.35177959	1.45619014	1.01544283	1.02667613	1.02667613	0	0.00298367	0.02893663	-0.0163039	-0.0049136	-0.0049136
dul	1	1.38944312	1.46917808	1.06608596	1.02829065	1.02831547	0	0.03092899	0.03811385	0.03275598	-0.0033487	-0.0033247
elp	1	1.36674909	1.37229611	1.04905433	1.0502573	1.0502573	0	0.01409064	-0.0303425	0.01625683	0.01794205	0.01794205
hel	1	1.42356655	1.4807752	1.09470089	1.03842372	1.03873422	0	0.05624764	0.04630831	0.0604763	0.00647258	0.00677352
hou	1	1.29725859	1.34841669	1.03493342	1.04316885	1.04316885	0	-0.0374694	-0.0472155	0.00257739	0.0110717	0.0110717
mem	1	1.34775832	1.41523792	1.03227285	1.03174567	1.03174567	0	0	0	0	0	0
mia	1	1.28699196	1.30811796	1.02955496	1.05752279	1.05752279	0	-0.045087	-0.0756904	-0.0026329	0.02498399	0.02498399
pho	1	1.35674026	1.39568195	1.04984162	1.0369387	1.0369387	0	0.00666436	-0.0138182	0.0170195	0.00503325	0.00503325
sal	1	1.36772621	1.47902915	1.03798111	1.02366203	1.02366203	0	0.01481563	0.04507456	0.0055298	-0.0078349	-0.0078349
sfr	1	1.35837045	1.39864282	1.05099923	1.03780053	1.03780053	0	0.00787391	-0.011726	0.01814092	0.00586856	0.00586856

South	Full Resolution						% Difference to Single Climate					
	clear_doub	PrismaticPa	Opalescent	HOE	OhnePerf	FabricGrey	clear_doub	PrismaticPa	Opalescent	HOE	OhnePerf	FabricGrey
alb	1	0.8446357	0.9477446	0.9198334	1.2661763	1.265399	0	0.1028789	-0.02142	0.1381806	0.0474423	0.0467993
bal	1	0.7602054	0.957484	0.7959979	1.1933831	1.1933431	0	-0.007365	-0.011363	-0.015051	-0.012776	-0.012809
boi	1	0.8209787	0.9810023	0.8301834	1.2316012	1.2315312	0	0.071989	0.01292	0.0272497	0.0188402	0.0187822
bur	1	0.7156632	0.9216118	0.7799834	1.1616502	1.1616502	0	-0.065526	-0.048403	-0.034867	-0.039027	-0.039027
chi	1	0.7109857	0.9229486	0.7742137	1.1553665	1.1553665	0	-0.071634	-0.047022	-0.042006	-0.044225	-0.044225
dul	1	0.7822511	0.9537302	0.8260089	1.1981119	1.1981119	0	0.0214206	-0.015239	0.0220842	-0.008864	-0.008864
elp	1	0.8078331	0.9581189	0.8625353	1.22936	1.2289953	0	0.0548242	-0.010708	0.0672812	0.0169861	0.0166844
hel	1	0.8355336	0.974742	0.8561837	1.2460919	1.2460212	0	0.0909939	0.0064561	0.0594219	0.0308275	0.0307691
hou	1	0.7638122	0.9596325	0.8154184	1.2187024	1.2187024	0	-0.002656	-0.009145	0.0089799	0.0081696	0.0081696
mem	1	0.7658462	0.9684894	0.8081612	1.2088267	1.2088267	0	0	0	0	0	0
mia	1	0.7798743	0.9442824	0.8198791	1.2000636	1.1999841	0	0.0183171	-0.024995	0.0144994	-0.007249	-0.007315
pho	1	0.7795985	0.9637283	0.8238753	1.2115488	1.2114008	0	0.017957	-0.004916	0.0194442	0.0022518	0.0021294
sal	1	0.707111	0.9355282	0.7723825	1.1683972	1.1683972	0	-0.076693	-0.034034	-0.044272	-0.033445	-0.033445
sfr	1	0.7819673	0.9684549	0.8258467	1.217006	1.2169655	0	0.02105	-3.56E-05	0.0218836	0.0067663	0.0067327

Single-Climate vs. Single-Sky-Type

North	ECD	ECD1	% diff
clear	1	1	0
Prismatic	1.115638	1.123109	0.006697
Opal	1.208295	1.214384	0.00504
HOE	0.5785	0.578128	0.000644
Ohne	0	0	0
FGR	0	0	0

East	ECD	ECD1	% diff
clear	1	1	0
Prismatic	1.347758	1.343849	0.002901
Opal	1.415238	1.414215	0.000723
HOE	1.032273	1.029716	0.002477
Ohne	0.001449	0.00097	0.330446
FGR	0.000113	0	1

South	ECD	ECD1	% diff
clear	1	1	0
Prismatic	0.765846	0.766296	0.000587
Opal	0.968489	0.968519	3.07E-05
HOE	0.808161	0.804668	0.004323
Ohne	0	0	0
FGR	0.023965	0.03	0.251824

Appendix D
Supplementary Information for VTP Metric

This Appendix contains the following information:

- User study instruction forms (English and French)
- Full user study results.

View study forms (English and French)

View Study (English)

1. There are 9 samples on the table.
2. Please look at the sample in any way you would like.
3. Please mark on the following scales the letter corresponding to each sample's sticker ***how much of a view it would provide as a window façade***.

Sample Letter	View-Through No view … Full view
A	
B	
C	
D	
E	
F	
G	
H	
I	

L'étude de vue (Français)

1. Il y a 9 échantillons sur la table.
2. Veuillez regarder l'échantillon de la manière que vous voulez.
3. Veuillez noter sur les échelles suivantes la lettre de l'étiquette correspondant à chaque échantillon ***quelle qualité de vue cela procurerait en tant que fenêtre de façade ?***

Lettre échantillon	Vue à travers l'objet Aucune vue … Vue totale
A	
B	
C	
D	
E	
F	
G	
H	
I	

User Study Full Results (2 pages)

User	Date	A	B	C	D	E	F	G	H	I
1	Jul-19	8		2	7	0	6	9	5	5
2	Jul-19	7	3	2	7	1	6	5	6	5
3	Jul-19	9	2	2	2	1	7	9	1	6
4	Jul-19	8.5	6	2	6	1	8	6	5	6
5	Jul-19	9	3	1	2	0	1	9	8	7
6	Jul-19	6	5	2	4	2	3	2	1	5
7	Jul-19	9	6	3	5	0	6	5	8	9
8	Jul-19	9	3	2	2	1	3	7	2	4
9	Jul-19	9	8	3	4	0	3	5	2	3
10	Jul-19	8	6	5	5	0	8	3	5	4
11	Jul-19	8	7	4	2	1	3	5	7	6
12	Jul-19	5	2	1.5	1.5	0	3	2	7	7
13	Jul-19	10	3	1	4	0	4		5	4
14	Jul-19	8	7	2	4	1	4	5	6	3
15	Jul-19	10	3	2	7	1	9	9	1	7
16	Jul-19	7	6	5	6	1	4	1	3	4
17	Jul-19	8	6	3	2	1	6	4	5	7
18	Jul-19	9	8	4	6	0		9	3	5
19	Jul-19	8	3	2	4	1	1	2	4	5
20	Jul-19	6	2	0.5	4	0	3	8	2	7
21	Jul-19	8	6	2	3	0	1	6	1	2
22	Jul-19	9	7	4	4	1	7	5	8	5
23	Jul-19	5	3	2	4	1	6	1	4	8
24	Jul-19	9	3	1	2	0	4	2	7	5
25	Jul-19	9	4	2	7	0	1.5	1	1	3
26	Jul-19	7	5.5	3	6.5	0.5	4.5	4.5	3.5	5
27	Jul-19	9	4	2	5	1	2	3	4	3
28	Jul-19	5	2	1	6	0	0	3	4	4
29	Jul-19	5	5	3	4	1	1	1	1	9
30	Jul-19	9	7	4	5	1	1	3	2	4
31	Jul-19	9	5	3		1	10	1	6	7
32	Jul-19	8	4	3	4	2	4	0	6	6
33	Jul-19	10	9	1	2	0	3	4	4	5
34	Jul-19	9	5	2	3	1	4	3	3	2
35	Jul-20	4	2	2	2	0	1.5	5	3.5	3
36	Jul-20	8	3	2	7	1	8	8	9	8
37	Jul-20	9	4	2	3	1	5	9	8	6
38	Jul-20	6	3.5	2	1	0	4	9	3	7
39	Jul-20	10	8	2	2	1	4	10	8	9
40	Jul-20	2	4	5	5.5	9.5	8	2.5	8.5	4
41	Jul-20	2	5	8	5	0	1	4	3	3
42	Jul-20	9	4	2	4	1	6	8	10	8
43	Jul-20	4	8	1	3	0	2.5	9	3	4.5
44	Jul-20	7	3	2	2	2	7	9	9	6
45	Jul-20	5	4	2	3	0	2	10	5	4
46	Jul-20	9	3	1	1	0	1	9	7.5	6
47	Jul-20	3	9	0.5	2	0	2	9	7	9
48	Jul-20	7	3	2	4	1	3	8	7	5
49	Jul-20	9	3	2	6	1	3	7	7	5
50	Jul-20	6	7	2	2	1	3	8	5	6

51	Jul-20	8	5	2	2	1	2	6	4	4
52	Jul-20	7	5	1	5	1	7	6	5	6
53	Jul-20	4.5	3	0	4.5	0	0	4.5	2	2
54	Jul-20	8	8	2	4	1	4	8	9	8
55	Jul-20	8	4	2	3	1	7.5	8	8	7
56	Jul-20	5	2	1	3	0	2	3	7	9
57	Jul-20	9	3	2	2	1	3	9	2	5
58	Jul-20	4	3	2	5	0	5	7	6	8
59	Jul-20	5	2	1	10	0	7	10	9	8
60	Jul-20	3	6	1	2	0	4	8	5	6
61	Jul-20	7	7	3	6	1	4	9	3	6
62	Jul-21	7	3	2	6	1	6	6	6	8
63	Jul-21	7	3	2	2	0	5	7	3	6.5
64	Jul-21	10	4	1	2	0	2	9	3	5
65	Jul-21	5	2	1	1.5	0	2.5	8.5	4	7.5
66	Jul-21	4	3	2	4	1	1.5	9	6	5
67	Jul-21	4	4	4	4	1	6	10	5	5
68	Jul-21	8	3	2	7	1	5	9	4	6
69	Jul-21	4	2	1	2	1	1	5	1	4
70	Jul-21	1.5	8	9	6	10	3	5	8.5	6
71	Jul-21	10	3	1	1	0	1	5	8	6
72	Jul-21	4	7	1	3	0	3	7	4	7
73	Jul-21	9	9	3	5	1	3	10	10	8
74	Jul-21	9	7	2.5	6.5	1	3	8	7	6
75	Jul-21	8	5	0	2	0	1	10	10	8
76	Jul-21	8	1	1	2	1	3	8	2	4
77	Jul-21	8	6	1	2	1	2		3	4
78	Jul-21	2	4	1	1	1	3	4	4	3
79	Jul-21	3	2	1	2	1	2	3	2	3
80	Jul-21	7	7	1	2	1	3	9	4	6
81	Jul-21	9	3	2	3	1	5	7	5	4
82	Jul-21	5	4	0	2	0	0	8	9	5
83	Jul-21	8	8	1	2	0	2	9	2	5
84	Jul-21	7	3	1	3	1	3	5	4	6
85	Jul-21	9	5	1	1	0	2	7	8	7
86	Jul-21	4	5	0	2	0	8	9	6	7
87	Jul-21	9	6	3	4	6	3	5	8	6
88	Jul-21	7.5	5	1	1.5	0	4	9	3	8
89	Jul-21	1.5	5	1	3	0	1	9	8	7.5
90	Jul-21	9.5	9	1	3	0	5	8.5	3.5	2.5
91	Jul-21	5	3	1	2	0	0.5	6	3.5	7
92	Jul-21	7	5	2	4	1	4	8	3	8
93	Jul-21	7	3	1	2	1	2	9	6	6
94	Jul-21	3.5	2	1	2	0.5	0.5	2.5	1.5	4.5
95	Jul-21	5	8	2	2	1	1	9	2	5
96	Jul-21	8	7	3	5	1	5	9	7	5
97	Jul-21	8	5	3	4	0	5	9	5	7
98	Jul-21	8.5	3	1	5	1	5	9	8	6
99	Jul-21	5	3	1	1	0	4	8	8	8
100	Jul-21	8	8	2	3	1	4	7	6	7
101	Jul-21	6	5	1	5	0	3	7	8	8
102	Jul-21	4	3	0	5	0	0	8	7	6
Average		6.9	4.7	2.0	3.6	0.8	3.6	6.5	5.1	5.7
St Dev		2.251555	2.059258	1.414076	1.842015	1.482646	2.259041	2.717954	2.507453	1.76673

Sources

Andersen, M., 2002. Light distribution through advanced fenestration systems. *Building Research and Information*, 30(4), pp. 264-281.

Andersen, M., 2004. Innovative Bidirectional Video-Goniophotometer for Advanced Fenestration Systems. PhD Thesis, Ecole Polytechnique Federale de Lausanne.

Andersen, M., 2009. Delight in Greener Daylight: A Class Perspective on Façade Renovation.

Andersen, M., and de Boer, J., 2006 Goniophotometry and assessment of bidirectional photometric properties of complex fenestration systems, *Energy and Buildings*, 38(7), pp. 836-848.

Andersen, M., Kleindienst, S., Yi, L., Lee, J., Bodart, M., Cutler, B., 2008. Informing daylighting design with the Lightsolve approach: why and how. *Proceedings of the PLEA 2008 conference:* Dublin, Ireland.

ASHRAE, 2009. ASHRAE Handbook – Fundamentals (SI Edition). American Society of Heating Refrigeration and Air-Conditioning Engineers, Inc.

ASHRAE 90.1., 1999. ASHRAE Energy Standard for Buildings Except Low-Rise Residential Buildings. American Society of Heating Refrigeration and Air-Conditioning Engineers, Inc.

ASHRAE 189.1. 2009. ASHRAE Standard for the Design of High-Performance, Green Buildings Except Low-Rise Residential Buildings. American Society of Heating Refrigeration and Air-Conditioning Engineers, Inc.

ASME, 2004. Performance Based Codes and Standards. *American Society of Mechanical Engineers*

Aydinli, S., 1996. Short description of the spiral goniophotometer for bi-directional measurements (TU Berlin). Report for IEA SHC Task 21, ECBCS Annex 29, Subtask A, Technische Universitat Berlin (TUB), Berlin.

Bakker, L. and van Dijk, D., 1995. Measuring and processing optical transmission distribution functions of TI-materials. Private Communication, TNO Building and Construction Research, Delft.

Bodart, M. & De Herde, A., 2002. Global Energy Savings on Offices Buildings by the Use of Daylighting. *Energy and Buildings,* 34(5), pp. 421-29.

Carli, Inc., 2006. Tarcog: Mathematical Models for Calculation of Thermal Performance of Glazing Systems With or Without Shading Devices. Technical Report, 17 October, 2006.

Cappozi, Lou, 2009. Personal communication during BT Seminar Tour of Genzyme Center. Fall 2009 Semester, Cambridge, MA.

CIBSE, 1999. Lighting Guide 10: Daylighting and window design. Chartered Institution of Building Services Engineers, London, UK.

CIE, 1977. Radiometric and photometric characteristics of materials and their measurement. Commission Internationale de l'Eclairge, 38 (TC-2.3).

CIE, 1989. Guide to Recommended Practice of Daylight Measurement. Commission Internationale de l'Eclairage.

Culter, B., Sheng, Y., Martin, S., Glaser D., and Andersen M., 2008. Interactive selection of optimal fenestration materials for schematic architectural daylighting design. *Automation in Construction*, 17, pp. 809-823.

Eble-Hankins, M., and Waters, C., 2004. VCP and UGR Glare Evaluation Systems: A Look Back and A Way Forward. *LEUKOS – The Journal of the Illuminating Engineering Society of North America*, 1, pp. 7-38.

Energy Information Administration, 2008. EIA Annual Energy Outlook.

Energy Information Administration, 2004. United States Climate Zones. Accessed 25 January, 2010 <http://www.eia.doe.gov/emeu/recs/climate_zone.html>.

Energy Information Administration, 2010. EIA Annual Energy Review.

EnergyPlus Energy Simulation Software, 2010. Version 6.0.0. *Energy Efficiency and Renewable Energy, US Department of Energy:* Washington, DC.

Farley, K.M.J., and Veitch, J.A., 2001. A room with a view: a review of the effects of windows on work and well-being. Institute for Research in Construction, National Research Council Canada.

Gagne, J., and Andersen, M., 2010. A Generative Façade Design Method Based on Daylighting Performance Goals. *Journal of Building Performance Simulation.*

Hay, J., 1993. Calculating Solar Radiation for Inclined Surfaces: Practical Approaches. *Renewable Energy*, 3 (4/5), pp. 373-380.

Heschong L., Mahone D., Kuttaiah K., Stone N., Chappell C., McHugh J., Burton J., Okura S., Wright R., Erwin B., Digert N., Baker K., 1999. Daylighting in Schools: An Investigation into the Relationship Between Daylighting and Human Performance. Submitted to the Pacific Gas and Electric Company. The Heschong Mahone Group. Fair Oaks, California.

Heschong L., Mahone D., Kuttaiah K., Stone N., Chappell C., McHugh J., Burton J., Okura S., Wright R., Erwin B., Digert N., Baker K., 2003. Windows and Offices: A Study of Office Worker Performance and the Indoor Environment. CEC PIER 2003. The Heschong Mahone Group. Fair Oaks, California.

Heschong, L., 2011. Creating Consensus on Annual Daylighting Performance Metrics. MIT 31 March.

Ihm, P., Nemri, A. & Krarti, M., 2009. Estimation of Lighting Energy Savings from Daylighting. *Building and Environment*, 44(3), pp. 509-14.

Illumination Engineering Society (North America), 1982. *American National Standard: Office Lighting:* New York, NY.

Institute of Medicine, Food and Nutrition Board, 2010. Dietary Reference Intakes for Calcium and Vitamin D. Washington, DC: National Academy Press.

International Energy Agency, 2000. Daylight in Buildings – A source book on daylighting systems and components, IEA SCH Task 21/ECBCS Annex 29. Berkeley, CA.

Kanter, J., 2009. *Europe's Ban on Old-Style Bulbs*. The New York Times: New York, NY. 31 August.

Karlsson, J., Karlsson, B., and Roos, A., 2001. A simple model for assessing the energy performance of windows. *Energy and Buildings*, 33, pp. 641-651.

Keighley, E., 1973. Visual requirements and reduced fenestration in offices: A study of multiple apertures and window area. *Building Science*, 8. pp. 321-331.

Kischkoweit-Lopin, M., 2002. An overview of daylighting systems. *Solar Energy*, 73(2), pp. 77-82.

Kleindienst, S., 2010. Time-Varied Daylighting Performance to Enable a Goal-Driven Design Process. *PhD thesis in Building Technology, Department of Architecture*, MIT.

Kleindienst, S. and Andersen, M., 2010. Solar Heat Surplus and Solar Heat Scarcity: the Inclusion of Solar Heat gain in a Dynamic and Holistic Daylight Analysis. *Proceedings of the 4th National Conference of IBPSA-USA*, SimBuild: New York, NY.

Kleindienst, S., Bodart, M., Andersen, M., 2008. Graphical Representation of Climate-Based Daylight Performance to Support Architectural Design. *LEUKOS – The Journal of the Illuminating Engineering Society of North America*, 5(1) pp. 39-61.

Klems, J., 1994. A new method for predicting the solar heat gain of complex fenestration systems – I: Overview and derivation of the matrix layer calculation. In *ASHRAE Winter Meeting*, New Orleans, LA, Jan 22-26.

Klems, J., and Warner, J., 1995. Measurement of bidirectional optical properties of complex shading devices. In *ASHRAE Transactions 101 (1)*, pp. 791-801, Chicago, IL.

Klems, J., Warner, and Kelley, G., 1997. A comparison between calculated and measured SHGC for complex glazing systems. In *ASHRAE Transactions 102(1)*, pages 931-939, Atlanta, GA, Feb 17-21 (1996).

Kuller, R. and Wetterberg, L., 1996. The subterranean work environment: Impact on well-being and health. *Environment International*, 22, pp. 33-52.

Lambert, G.W. et al., 2002. Effect of Sunlight and Season on Serotonin Turnover in the Brain. *Lancet*, 360, pp.1840-42.

Leach, M., Lobato, C., Hirsch, A., Pless, S., Torcellini, P., 2010. Technical Support Document: Strategies for 50% Energy Savings in Large Office Buildings. NREL/TP-550-49213. National Renewable Energy Laboratory: Golden, CO.

Li, D., Lam, J., and Lau, C., 2002. Technical Note: A new approach for predicting vertical global solar irradiance. *Renewable Energy*, 25, pp. 591-505.

Luckiesh, M., 1944. Brightness engineering. *Illuminating Engineering*, 39, pp. 75-92.

Marceau, M., and VanGeem, M., 2007. Modeling Energy Performance of Concrete Buildings for LEED-NC Version 2.2: Energy and Atmosphere Credit 1. *Portland Cement Association*: Stokie, IL.

Mardaljevic, J., 2000. Simulation of annual daylighting profiles for internal illuminance. *Lighting Research and Technology*, 32 (3), pp. 111-118.

Mardaljevic, J., 2001. The BRE-IDMP dataset: a new benchmark for the validation of illuminance prediction techniques. *Lighting Research and Technology,* 33 (2), pp. 117-134.

McCluney, R. and Sung, J., 1999. Simulation of venetian blind optical properties with monte carlo ray tracing. Technical report, Florida Solar Energy Center: Cocoa, FL.

McGowan, R., 2011. Daylighting Subcommittee/Daylight Potential Task Force. Personal Communication, National Fenestration Rating Council.

Menchaca, A., and Glicksman, L., 2008. Coolvent: A Multizone Airflow and Thermal Analysis Simulator for Natural Ventilation in Buildings. *Third National conference of IBPSA-USA*: Berkeley, CA.

Nabil, A., and Mardaljevic, J., 2006. Useful daylight illuminances: A replacement for daylight factors, *Energy and Buildings*, 38, pp. 905-913.

National Institute of Health, 2011. Dietary Supplement Fact Sheet: Vitamin D. Office of Dietary Supplements. Accessed 25 October. Available at < http://ods.od.nih.gov/factsheets/vitamind>.

NFRC, 1997. NFRC 100: Procedure for Determining Fenestration Product U-Factor. National Fenestration Rating Council.

NFRC, 2004. 2005 IECC (Supplement to 2003 IECC) Simplified Prescription Requirements. National Fenestration Rating Council.

NFRC, 2009. NFRC 200: Non-residential fenestration products. National Fenestration Rating Council.

NFRC, 2011. National Fenestration Rating Council. Available at <www.nfrc.org>, Accessed 28 October.

NFRC, 2011. NFRC Request for Proposal: Complex Fenestration Product – Visible Transmittance Rating. National Fenestration Rating Council. 4 October.

Nicodemus, F., 1970. Reflectance nomenclature and directional reflectance and emissivity. *Applied Optics*, 9(6), pp. 1474-1475.

Nicodemus, F., Richmond, J., Hsia, J., Ginsberg, I., and Limperis, T., 1977. Geometrical Considerations and Nomenclature for Reflectance. NBS Monograph 160, National Bureau of Standards, U.S. Department of Commerce: Washington, DC.

Optics 5, 2010. Lawrence Berkeley National Labs, Department of Energy.

Osterhaus, W., 2002. Recommended Luminance Ratios and their application in the Design of Daylighting Systems for Offices. *The Modern Practice of Architectural Science: From Pedagogy to Andragogy*. Proceedings of the 35th Annual Conference of the Australia and New Zealand Architectural Science Association, pp. 1-4.

Papamichael, K., Klems, J., and Selkowitz, S., 1988. Determination and Application of Bidirectional Solar-Optical Properties of Fenestration Materials. Technical Report LBL-25124Lawrence Berkeley National Laboratory: Berkeley, CA.

Perez, R., Selals, R., and Michalsky, J., 1993. All-Weather Model for Sky Luminance Distribution – Preliminary Configuration and Validation. *Solar Energy*, 50(3), pp. 235-245.

Radiance, 2009. Radiance reference. Available at < http://radsite.lbl.gov/radiance/whatis.html>.

Rea, M.S., Figueiro, M.G. & Bullough, J.D., 2002. Circadian Photobiology: An Emerging Framework for Lighting Practice and Research. *Lighting Research and Technology*, 34(3), pp.177-90.

Reiner, D., 2002. Getting From Here to Where? *Causal Reasoning & Goal Setting in the Policy Process*. MIT Department of Political Science, PhD Dissertation.

Reinhart, C., and Andersen, M., 2006. Development and validation of a Radiance model for a translucent panel. *Energy and Buildings*, 38, pp. 890-904.

Reinhart, C.. and Voss, K., 2003. Monitoring Manual Control of Electric Lighting and Blinds. *Lighting Research & Technology*, 35(3), pp. 243-60.

Reinhart, C., and Walkenhorst, O., 2001. Validation of dynamic RADIANCE-based daylight simulations for a test office with external blinds. *Energy and Buildings*, 33 pp. 683-697.

Rogers, Z., 2006. Daylighting Metric Development Using Daylight Autonomy Calculations In the Sensor Placement Optimization Tool. Architectural Energy Corporations: Boulder, CO.

Rosen, L.N., Targum, S.D., Terman, M., Bryant, M.J, Hoffman, H., Kasper, S.F., Hamovit, J.R., Docherty, J.P., Welch, B., and Rosenthal, N.E., 1990. *Psychiatry Research*, 31(3), pp. 131-144.

Rubin M., 2010. Personal Communication. October 2010.

Ruck, N. et al., 2000. *Daylight in Buildings: A Source Book on Daylighting Systems and Components*. Lawrence Berkeley National Laboratory: Berkeley, CA.

Saxena, M., Ward, G., Perry, T., Heschong, L., and Higa, R. 2010. Dynamic radiance – predicting annual daylighting with variable fenestration optics using BSDFS. SimBuild.

Stone, D., 1997. Policy Paradox: The Art of Political Decision Making. WW Norton: New York, NY.

Talman, C.F. & Keally, F., 1930. Now the Windowless Building with Its Own Climate. *The New York Times*, 10 August.

Tertzakian, P., 2006. *A Thousand Barrels A Second: the coming oil break point and the challenges facing an energy dependent world*. McGraw-Hill. New York, NY.

Urbano Gutierrez, R. and Andersen M., 2008. D-LITE: a new perspective for searching and selecting light-control technologies as a designer. *Proceedings of the PLEA 2008 conference*, October 22-24: Dublin, Ireland.

Utzinger, M., Wasley, J., 1997. Building Balance Point. *Vital Signs Curriculum Materials Project.* University of California, Berkeley and University of Wisconsin, Milwaukee.

Vos, J., 1999. Glare today in historical perspective: towards a new CIE glare observer and a new glare nomenclature. *Proceedings of CIE 24th Session*, pp. 38-42.

Vos, J., 2003. Reflections on glare. *Lighting Research & Technology,* 35, pp. 163-176.

Ward, G., 2009. Complex Fenestration and Annual Simulation (presentation). 8th International Radiance Workshop, Cambridge, MA. 21-23 October.

Ward Larsson, G., and Shakespeare, R., 1998. Rendering with Radiance: The Art and Science of Lighting Visualization. Morgan Kaufmann Publishers.

Wienold, J., 2008. Dynamic simulation of blind control strategies for visual comfort and energy balance analysis. *Proceedings of Building Simulation 2008, the 10th International Building Performance Simulation Association (IBPSA) Conference.*

Wienold, J., and Christoffersen, J., 2006. Evaluation methods and development of a new glare of a new glare prediction model for daylight environments with the use of CCD cameras. *Energy and Buildings*, 38, pp. 743-757.

Wilcox, S. and Marion, W., 2008. *User's Manual for TMY3 Data Sets*, NREL/TP-581-4315. National Renewable Energy Laboratory: Golden, CO.

Window 6, 2010. Window 6 Research Version. Lawrence Berkeley National Laboratory: Berkeley, CA.

Window 6.1/Therm 6.1, 2006. Research Version User Manual. Lawrence Berkeley National Laboratory: Berkeley, CA.