Practical and Policy-Relevant Performance Metrics for Complex Fenestration Systems

Shreya Dave
Student Member ASHRAE

Marilyne Andersen, PhD

ABSTRACT

The selection of a fenestration system for a building is critical, as it impacts energy performance, occupant comfort, and ambiance of a space. Complex Fenestration Systems (CFS) address these criteria using a wide variety of novel technologies but are difficult to define or be characterized. Existing metrics for fenestration systems are unable to reveal the dynamics or degree of variety over climate conditions or time of year that define CFS because they rely on a single and arbitrarily-defined set of environmental conditions to calculate. Although the optical characteristics of a CFS can be predicted using its Bi-Directional Transmission Distribution Function (BTDF) – a mathematical dataset that describes the angular distribution of light flux as it passes through a material – this information is too abstract to be meaningful to the building industry. A set of metrics that uses the BTDF in an intuitive way could allow the performance and physical characteristics of these technologies to become more accessible, ultimately allowing the various benefits of daylighting to be realized. The proposed approach 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), anhd the View Through Potential (VTP), were derived from these three criteria to express, in relative terms, a façade's contribution to building energy use, the fraction of time and space for which it achieves comfortable daylight conditions, and the degree of transparency as it relates to an occupant's view through the façade, respectively. 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. In order to successfully implement these metrics, a simple and repeatable calculation process was identified first through a series of sensitivity analyses compromising on relevance or accuracy, and then by defining input conditions that are able to reduce calculation or simulation time substantially. Using both approaches, each of these metrics was further and applied to five sample façades that cover a broad range of Complex Fenestration System types, including a validation study for the VTP metric. A visual representation of this information in a condensed format was then investigated so as to allow straightforward comparisons amongst systems and a synthetic understanding of their performance. A graphical, label-like structure could indeed provide an initial suggestion for the use of these metrics in the rating and standard-setting environments.

Shreya Dave is a Masters' student in the Department of Mechanical Engineering and Engineering Systems Division, Massachusetts Institute of Technology, Cambridge, Massachusetts. **Marilyne Andersen** supervises this work and is an Associate Professor of Sustainable Construction Technologies at the School of Architecture, Civil and Environmental Engineering (ENAC) of the Ecole Polytechnique Fédérale de Lausanne (EPFL) in Lausanne, Switzerland. She was formerly an Associate Professor at the Massachusetts Institute of Technology.

1. INTRODUCTION

The total energy performance of a building is inherently related to the structure's façade, an important component of which is the fenestration system. In addition to enabling the substitution of electric lighting with natural daylight, the material properties and thermal performance of the fenestration system affect the load of the heating and cooling systems. All three together account for over half of a building's energy consumption, or about 20% of the US overall energy use (EIA, 2008). Fenestration systems in general also contribute to improved building spaces in ways beyond energy consumption including the quality and quantity of light, and occupant visual comfort is very important for daily tasks. The presence of comfortable daylight has been qualitatively linked to improved morale, worker productivity, and health (Libby, 2003). Conversely, the presence of uncomfortable daylight (e.g. glare on computer screens) usually results in closing blinds and subsequently no daylight, thus the delivery of daylight must be controlled. Windows also provide occupants with a view and a visual connection to the outdoors, a concept that is typically desirable for an interior space (Boyce, 1998). Ultimately, buildings are created for occupant comfort and sacrificing this for improved energy performance – such as, for example, strictly limiting window area – may not be an effective way to promote efficiency.

Complex Fenestration Systems (CFS) use a wide variety novel technologies to exert greater control over the performance of the fenestration system and thus have the potential to reduce energy consumption associated with the fenestration system by up to 41% (Arasteh, 2003). The great potential of these systems is, however, not being realized due to barriers to market entry associated with their complexity, dynamic performance capabilities, and lack of understanding of appropriate implementations. CFS aim to achieve improved overall performance in a variety of unique ways but until there is a means to communicate these benefits, their use will be limited.

1.1 A Need for New Performance Metrics

Metrics for standard fenestration systems, classified as windows, skylights and doors, are defined by the United States National Fenestration Rating Council (NFRC). These are effective in communicating information about both energy performance and visible transmittance, and provide a framework for comparison across various models. A single set of environmental conditions and solar incident angle enables a simple and representative calculation and these metrics successfully describe standard fenestration systems because they typically exhibit similarbehavior regardless of sun angle (NFRC 100, 1997). However, using a single set of environmental conditions and solar incident angle does not reveal the benefits or subtleties that characterize CFS. CFS manufacturers should not be required or encouraged to optimize the performance of their systems around a single solar incident angle to achieve a better metric rating if it compromises the annual performance of the system in a real building.

Meanwhile, existing visual comfort metrics are inherently disconnected from the fenestration system because they are highly spatially dependent. The daylighting industry has developed a set of metrics to describe occupant visual comfort, usually based on illuminance or luminance distributions and probability of discomfort glare (Wienold, 2006). These metrics thus provide a very strong prediction for occupant visual comfort when knowledge about spatial geometry is present. Simulation tools are very informative in the design of a space, but not practical to use in the selection of a fenestration system independently. In addition, tradeoffs in performance are not apparent because these descriptions are not directly comparable to other performance metrics when the behavior of the system is not intuitive, as is the case for most CFS.

In an effort to address these needs, three primary performance criteria have been identified as being most relevant to the fenestration system, energy performance, occupant visual comfort, and view through ability, for which a set of three metrics was derived. These metrics use annual climate-based data as well as the mathematical dataset that describes angular light behavior, the Bi-Directional Transmission Distribution Function (BTDF) to evaluate performance in terms of each of the criteria (CIE, 1977). While comprehensive BTDF datasets do not yet exist for all CFS, the metrics presented here provide a useful form of the unwieldy BTDF that is necessary to describe a system completely, thus providing an incentive to populate a database. Work at Lawrence Berkeley National Laboratory, the Ecole Polytechnique Fédérale de Lausanne, the Fraunhofer ISE and others on goniophotometers underlies the feasibility of creating these datasets (Andersen and deBoer, 2006).

2. THREE PERFORMANCE PERSPECTIVES FOR BALANCED OBJECTIVES

Improved communication about CFS would improve understanding of their fundamental tradeoffs between performance criteria and increases their accessibility by the building industry to ultimately support current efforts in enabling the design of spaces that achieve the needs of the user. Existing industry rules of thumb, usually important guidelines for standard fenestration systems, may not apply to the same degree for CFS. For example, the window-to-wall ratio (WWR) is used as a metric often used as a predictor of energy performance because increased window area tends to lead to increased heat loss across the façade. While very relevant for a clear window, this rule of thumb may not apply to a spectrally selective system with a south-facing orientation in a hot climate. In other words, metrics that could identify such exceptions to the rule would allow for more flexibility in the development and use of novel systems as well as the design of a space.

Three metrics that describe each of the three performance criteria mentioned previously were defined and proposed to allow users to select systems according to individual priorities and were introduced in (Dave and Andersen, 2011). The three metrics aim to address the limitations of existing metrics as they apply to CFS and provide context for benchmarks. Each has been further developed and are presented in this paper in a form that incorporates standards and policy considerations. The *Relative Energy Impact* (REI) metric is defined as the annual total relative energy load that can be attributed to the fenestration system, both with respect to heating and cooling as well as lighting, and is described in Section 3. The *Extent of Comfortable Daylight* (ECD) metric is defined as the percent of time and space that achieves comfortable daylight conditions as compared to a reference case, as described in more detail in Section 4. The *View Through Potential* (VTP) metric uses the BTDF of a system to predict the degree of view through of the façade and is explained further in Section 5.

2.1 Application Framework

Because assumptions are required to quantify both energy performance and illuminance values, a relative approach has been used. The values of the REI and ECD metrics are normalized with a reference case. The reference fenestration system is a clear double glazed window with glass panes of 3.2 millimeters and an air gap of 12.8 millimeters. This enables users to recognize how much better or worse a CFS performs as compared to an intuitive system. The VTP metric is not normalized with a clear glazing because this action does not provide further information to the user; a clear view is a concept that users are familiar with and a perfectly clear façade would achieve a VTP value of one.

The metrics proposed also require a generic test space for evaluation. The space used is a rectangular office of dimensions 3 meters wide by 9 meters deep by 3 meters high. The fenestration system occupies the top half (1.5 meters by 3 meters) of the oriented wall. This test module also has the same dimensions and characteristics as an experimentation module which is being constructed at the EPFL and will be used to obtain measured data for CFS samples.

When evaluating daylight, 56 representative moments have been used to represent daylight conditions for a statistical year. These moments consist of seven times of day during eight days of the year, spaced equally around the "extremes" of solstices. Climate data is averaged within each day and time bin to produced information associated with each of the 56 sun positions. This approach has been validated for use in the daylight simulation engine Lightsolve as providing sufficient information about annual performance and is used as a proxy for hourly calculations (Kleindsienst, 2008).

Five systems were selected to cover a great variety of behavior patterns to aid in the development of the widely-applicable metrics. These systems are (a) a prismatic panel that offers little view to the outside but redirects light towards the ceiling of the space; (b) exterior mirrored blinds that can be adjusted and can block high-angle direct light while simultaneously directing some to the ceiling; (c) a holographic optical element that refracts incoming direct and diffuse light at particular angles; (d) an opalescent plexiglass which diffuses light in a lambertien manner; and (e) an interior fabric blind that blocks most incident light. **Figure 1 shows** a photograph of each sample fenestration sample as well as a RADIANCE rendering for a single moment of the year for each system.

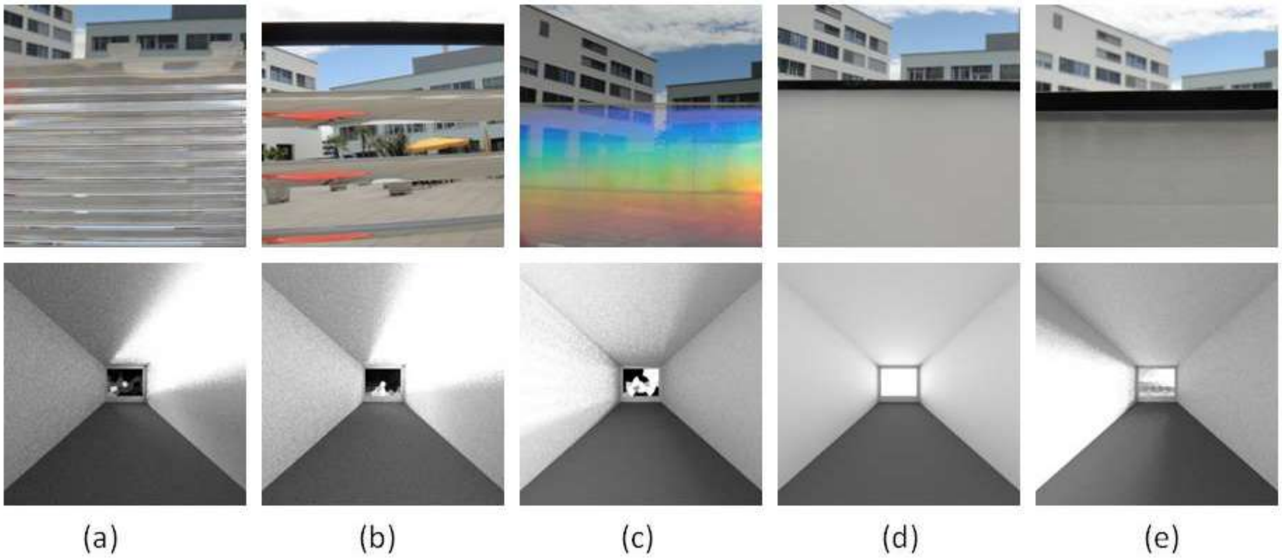

Figure 1 *Five façade samples used for determining performance metrics; (a) Prismatic Panel (b) Mirrored Blinds (c) Holographic Optical Element (d) Opalescent Plexiglass and (e) Fabric Blinds.*

3. RELATIVE ENERGY IMPACT

The *Relative Energy Impact* (REI) provides information to the user about the energy performance of a fenestration system, both in heat transfer and in lighting energy efficiency. The initial values for the REI metric of five sample façade systems were calculated using annual climate data, system material properties, the BTDF, and heat transfer models using Matlab. For each moment of the year, the instantaneous net heat transfer across the façade is calculated. This net heat transfer for all moments of the year can be shown visually on a temporal map such as the one **shown in Figure 2 (left)**. These quantities are combined into a single value using an equation that is based on the degree day method to determine whether the net heat transfer is contributing to or decreasing the overall energy load of a building, in an approach similar to the one introduced by (ASHRAE 90.1, 1999, Karlsson, 2001) and **shown in Figure 2 (right)**. The quantity calculated for a façade is compared to that of the reference case and presented as the percent difference, where a negative value indicates better performance.

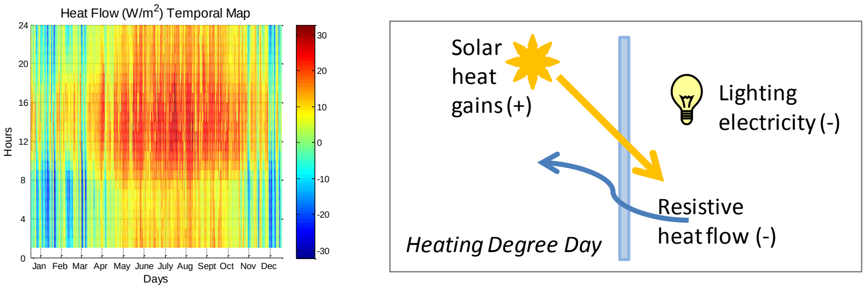

Figure 2 *A temporal map shows the net heat transfer across a façade for all hours of the year (left). The REI metric uses this data to determine a façade's contribution or load to the building's energy system (right)*

The second component to energy performance attributed to the fenestration system is lighting electricity. Lighting load is predicted by evaluating the illuminance levels in the room. However, because the metric is intended to provide information about the fenestration system and not advise on artificial lighting options, this component of the metric is calculated as a potential. The normalized value will lie between zero and one, where zero indicates that lights will be required at all daylit moments in the year at all zones of the space and one indicates that no artificial lighting is needed when there is daylight. The generic test module is assumed to consist of three zones, all of which contain dimmable lights. Rather than combining the two aspects of energy performance into a single value as was suggested previously (Dave and Andersen, 2011), the quantitative REI value provides only information about the relative heat transfer due to the façade. The lighting information is used to visually provide more information as is visually shown in Section 7.

In order to simplify the calculation procedure of the REI metric from annual simulations, a relationship to existing heat transfer metrics, namely the NFRC-defined U-factor and the Solar Heat Gain Coefficient, was desired. However, when the REI was calculated for the façade systems using their single-condition, constant values, its error suggested that a more effective set of climate-based environmental conditions could be established. Therefore, using the initial REI calculation procedure, three climate zones in the United States were identified by categorizing consistent rank of system performance and ultimately are defined based on latitude. For each climate zone, a set of conditions was derived to result in an accurate REI value such that they can be the basis for a revised approach to calculating energy metrics for fenestration systems. REI rankings for each sample system by climate zone, shown here for one orientation as an example, **are in Table 1 below**.

Table 1. REI Environmental Conditions and Values for Sample Systems (Oriented North)

	Climate Zone 1	Climate Zone 2	Climate Zone 3
Clear	0	0	0
Prismatic Panel	0.098	-0.116	-0.090
Opalescent Plexiglass	-0.303	0.168	0.093
Holographic Optical Element	0.328	-0.249	-0.163
Mirrored Blinds (exterior)	0.367	-0.316	-0.22
Fabric Blinds (interior)	0	0	0

In order to ensure that the REI metric is relevant with respect to the total building energy performance, ongoing work with the U.S. Department of Energy’s EnergyPlus simulation engine is being conducted to validate the energy calculations that lead to the REI. A variety of fenestration systems will be evaluated in the context of total energy performance for a real space. The results from both the EnergyPlus simulation and the REI methodology will then be compared, with the goal of guaranteeing that the ranking of fenestration systems is maintained for both approaches.

4. EXTENT OF COMFORTABLE DAYLIGHT

The *Extent of Comfortable Daylight* (ECD) metric is calculated using vertical and horizontal illuminance data for the generic test module, (**shown in Figure 3, left**). This data obtained by using the façade’s BTDF data in a method known as Dynamic Radiance (Saxena, 2010). The thresholds for comfortable lighting conditions consist of a minimum illuminance range and a maximum *Daylight Glare Probability* (DGP) range (IES, 1993, Wienold, 2006). Each moment of the year achieves a score, a value between zero and one where a value of one indicates that the space is entirely within comfortable lighting conditions, **shown in Figure 3 (center)**. The relationship between time and space that achieve comfortable conditions can be considered in the sample graph **in Figure 3 (right)**. The score for each sensor is combined into a total spatial score for each moment and subsequently into a single score for the whole year, normalized with the reference case.

The calculation of vertical and horizontal illuminance values is a time consuming process, and in order to make the calculation of these metrics more accessible, efforts were made to reduce the dependency on the simulation process. First, it was found that the ECD metric could be calculated using a single set of climate conditions resulting only in a maximum of 3.3% error in ECD value in all orientations (revised from previous analysis in Dave and Andersen, 2011). Analytical correlations between many inputs and the ECD value were explored and developed but investigation showed that although the ECD value can be predicted in perfect accuracy using a regression formula for each façade, climate conditions, and the BTDF, the high degree of variation in systems and operation does not permit a single equation to suffice for all CFS.

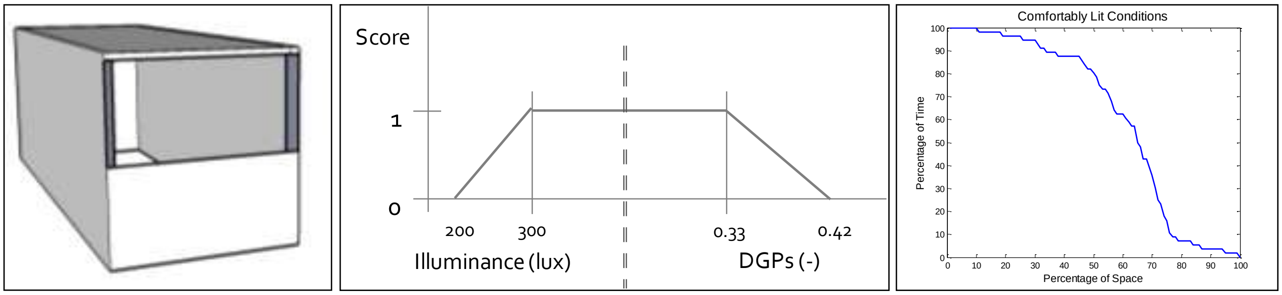

Figure 3 *Each location in the generic test module (left) receive a score between zero and one that indicates its daylight conditions (see scale, center). The relationship between time and space of a façade achieving comfortable conditions can then be visualized in the graph (right) or quantified in the ECD metric.*

With the constraint of analytical calculation removed, it is beneficial to use more of the information that is revealed by analysis of illuminance measurements insofar as this information is useful to a user. Since each moment of the year is given a score for the space, the system's percent of space and time that is uncomfortable can be deconstructed to too little light or too much. Using this concept more information can be communicated to the use about the likelihood of discomfort. **Table 2 shows** the ECD value for the five sample systems as well as the deconstruction of its performance for a sample orientation.

Table 2. ECD Values for Sample Façades (Oriented South)

	% too low	**% comfortable**	**% too high**	**ECD**
Clear	0.10	0.74	0.14	1.00
Prismatic Panel	0.34	0.57	0.08	0.97
Opalescent Plexiglass	0.15	0.72	0.12	0.81
Holographic Optical Element	0.31	0.60	0.09	1.20
Mirrored Blinds	0.09	0.92	0.00	1.21
Fabric Blinds	0.10	0.90	0.00	1.21

Finally, the ECD metric must apply to spaces beyond the rectangular generic test module. Radiance models will be used to evaluate a range of fenestration systems that have been validated to provide accurate results. The illuminance results from this Radiance simulation will be used to calculate an ECD. Achieving a consistent ECD ranking among fenestration systems will enable the use of the generic test space as the basis for ECD calculation for all systems going forward.

5. VIEW THROUGH POTENTIAL

The final metric, the *View Through Potential* (VTP), is defined as the quantity of incident light that is transmitted across a façade directly, with no distortion or diffusion. This value is considered to be a proxy for view through the façade because a fundamental concept for view perceived by humans is light that is reflected from an object and undistorted until it reaches the eye. In order to identify the direct component of the values that make up the BTDF, the CFS sample BTDF is compared to the quantitative behavior of a hole, assumed to be correlated with perfect transmission, as **shown in Equation 1**. This portion of the BTDF is used to calculate the direct integrated transmission for a view direction, and the direct transmission is equal to the sum of light flux over the emerging hemisphere. For a grid of view locations in the test space, an average direct integrated transmission value is obtained for the full surface of the façade, itself divided into a grid of coordinates, as shown in the schematic of **Figure 4 (left)**. These values are combined into the VTP value that weighs view angles according to their probability of occurring.

$$BTDF_{sample,direct}(\theta_1,\phi_1,\theta_2,\phi_2) = \frac{BTDF_{hole}(\theta_1,\phi_1)}{\max(BTDF_{hole}(\theta_1,\phi_1))} \cdot BTDF_{sample}(\theta_1,\phi_1) \qquad (1)$$

This VTP calculation approach has been validated by conducting a study of one hundred participants asked to view physical façade samples and rate their ability to see through. Participants were informed that the samples were window materials and that they could view the samples at any angle to get an “overall view”. As is apparent **in Figure 4 (right)**, although the VTP prediction for human ability to see through is not the same value as the user rating, the relative ranking is consistent, suggesting that the VTP calculation process has merit in comparisons. The user study results confirm that the definition of the VTP is acceptable as a quantitative representation of view. Because quality of view is a subjective concept – i.e. a person may prefer a blocked view to a distorted view – the VTP does not attempt to address the opinions of the user. The VTP is deconstructed to qualify the reason for lack of a clear view in Section 7 to provide additional information to the user, without making a quantitative judgment on which is preferred. As more systems are evaluated using this method, quantitative benchmarks for “full view”, “partial view”, and “no view” can be established in terms of the VTP.

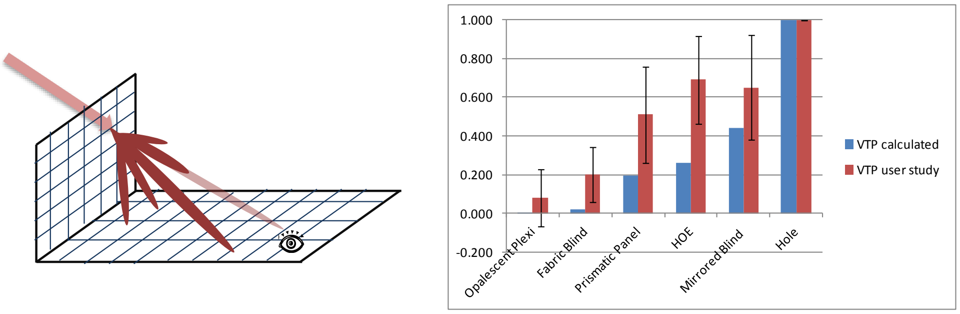

Figure 4 *A schematic of the VTP concept (left) and the results of calculation and user perception studies (right).*

6. VISUALIZING REI, ECD, AND VTP IN A CONDENSED FORM

An effective means of visualizing the proposed metrics is an important factor in understanding them logically. The metrics were designed to exist within the same framework so that tradeoffs and opportunities could be identified. Standardizing the structure of information representation is critical for the process of setting benchmarks and related guidelines based on these metrics. **Figure 5** presents a preliminary suggestion for the use of the information derived from the REI, ECD, and VTP metrics. The REI is presented in the center using a semi-circle design because the REI can be either positive (causes a load for the building) or negative (contributes to the building’s energy system). On the vertical axis is the indication of the system’s lighting load reduction potential. The scale on the left provides information about the ECD metric, deconstructed to suggest whether a system is more likely to need shading or require additional artificial lighting to achieve more comfortable conditions in the year. Finally, on the right is the VTP metric, plotted on another two axis scale which represent the system’s total transmission (opacity) and its nondirect transmission (distortion).

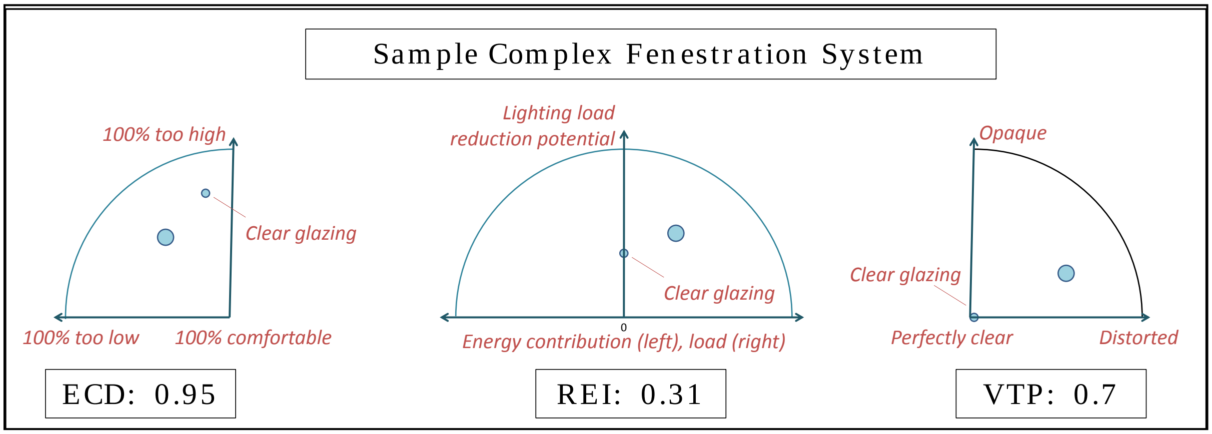

Figure 5 *An initial proposal for label structure and metric depiction for a sample system plotted on three dual axes.*

7. CONCLUSION

In an effort to address the limitations of existing means to describe complex fenestration systems, three metrics are described in this paper to address and inform users effectively of three principle performance criteria for fenestration systems: energy performance, occupant visual comfort, and view through ability, and whose initial concept can be found in (Dave and Andersen, 2011). The *REI* evaluates the fenestration system's contribution to total building energy consumption, the *ECD* describes how much of the space is provided with comfortable lighting conditions by the façade throughout the year, and the *VTP* provides a quantitative measure of how transparent a CFS is perceived by humans. Each metric was further developed to achieve a repeatable calculation procedure and presented in a concise, comprehensive, and informative structure. Ultimately, these metrics could enable the use of BTDFs in user decisions and address the barrier to market entry of CFS by drastically improving communication and information transfer about CFS throughout the building industry

ACKNOWLEDGMENTS

This work was supported by the MIT Energy Initiative Seed Grant and by the Ecole Polytechnique Fédérale de Lausanne. The authors thank Professor Leon Glicksman from MIT for his input, guidance, and support.

NOMENCLATURE

BTDF = bidirectional trans. distribution function

Φ = light flux

$\theta_{1,2}$ = incident, emerging elevation angle [rad]

$\phi_{1,2}$ = incident, emerging azimuth angle [rad]

REFERENCES

Arasteh, D., Apte J., and Huange, Y.J. 2003. Future Advanced Windows for Zero-Energy Homes. ASHRAE Trans, 109 (2).

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

ASHRAE. 2005. ASHRAE Handbook-Fundamentals. Atlanta.

ASHRAE 90.1. 1999. ASHRAE Energy Standard for Buildings Except Low-Rise Residential Buildings.

Boyce, P. 1998. Why Daylight? Proceedings of Daylight 1998 Interational Conference on Daylighting Technologies for Energy Efficiency in Buildings. 359-365.

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

Dave, S., and Andersen, M. 2011. A comprehensive method to determine performance metrics for complex fenestration systems. 27th Conference on Passive and Low Energy Architecture (PLEA).

Dave, S., and Andersen, M. 2011. Streamlining Access to Informative Performance Metrics for Complex Fenestration Systems. CISBAT 2011.

Environmental Information Administration. 2008. EIA Annual Energy Outlook.

Illumination Engineering Society of North America (IES). 1993. IES Lighting Handbook, 8th Edition.

Karlsson, J., Karlsson, A., and Roos, A. 2001. A simple model for assessing the energy performance of windows. Energy and Buildings, 33.

Kleindienst, S., Bodart, M., and Andersen, M. 2008. Graphical Representation of Climate-Based Daylight Performance to Support Architectural Design. LEUKOS – The Journal of the IED of North America. 5 (1).

Klems, J.H., Warner, J.L, and Kelly, G.O. 1997. A comparison between calculated and measured SHGC for complex glazing systems. ASHRAE Transactions, 102 (1).

Libby, B. 2003. The evangelists of natural light – Selling architects on the benefits of the sun's illumination. International Herald Tribune, June 19:7.

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

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

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