A comprehensive method to determine performance metrics for complex fenestration systems

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ABSTRACT: The ability to accurately and concisely describe the performance of complex fenestration systems (CFS) is essential to their effective implementation into the building industry. CFS are a diverse category of daylighting technologies that manipulate the light that is permitted to enter a building space. The variety and degree of dynamics that exist in the range of such technologies require a robust and flexible set of metrics that can communicate performance simply and informatively. This paper presents an approach for processing their detailed optical properties - expressed as Bi-Directional Transmission Functions (BTDF) - into a comprehensible set of metrics that can convey useful information about a system's adherence to visual comfort and energy-efficiency objectives. These metrics can then inform non-technical members of the building industry about the performance capabilities of a façade. This paper describes the novel method by which performance is evaluated, accounting for spatial and temporal variation in environmental condition.

Keywords: Daylighting, energy efficiency, metrics, complex façades.

1. INTRODUCTION

Solar radiation is a natural and inevitable source of light and heat for buildings. Buildings in the United States account for about 40% of total energy use, 18% of which is attributed to lighting and 33% of which is attributed to heating and cooling [1]. Intelligent use of this resource by fenestration technologies provides an opportunity to reduce a building's energy load attributed to window by about 41% [2]. Ultimately however, buildings are designed to provide shelter and comfort for occupants, a goal that cannot be ignored in light of optimizing energy efficiency. Complex fenestration systems (CFS) manipulate light in a number innovative ways in order to achieve balanced performance objectives. In order to facilitate the implementation of complex fenestration systems in efficient building design, a comprehensive set of metrics that relates a product with relative performance is crucial.

1.1. Problem Context

While existing metrics are a suitable comparison for heat transfer and visible light transmission for conventional glazings, they are far too limited to provide useful or even relevant information for more complex glazings or for shading systems. These façade systems require a detailed description of their optical properties, typically expressed mathematically as Bi-Directional Transmission Function (BTDF) data in order to communicate their actual performance characteristic [3]. A standard BTDFs format consists of 145 incident angles relating to 145 emerging angles [4]. The challenge is to develop a robust method to manipulate this mathematical representation into a form that is not simply a set of technical specifications, but one that can inform the user concisely of annual and spatial performance in terms of energy use and occupant comfort. Furthermore, due to the variation in technologies, it is important that, despite their necessary brevity, these metrics can still reflect information to the extent that the user can differentiate or rank them according to performance priorities.

1.2. NFRC Rating System

The technical specifications for windows, doors, and skylights are mandated in the United States by the National Fenestration Rating Council (NFRC). The NFRC's standards require that fenestration manufacturers report the system's U-factor, solar heat gain coefficient, and visible transmittance based on a single predetermined set of assumptions and environmental conditions. These qualifications are then presented as absolute values to the consumer using a concise, easy-to-understand label [5].

The NFRC specifications are appropriate for describing conventional fenestration systems. Although the established set of assumptions does not explicitly represent all realistic environmental conditions, it is reasonable to expect the user to be able to extrapolate general performance expectations using intuition about local temperatures and orientation. Complex fenestration systems, however, are much less intuitive. The complexities of these systems cannot be represented with the single set of conditions because this provides no insight for accurate extrapolation. Thus, a concise but more explicit set of performance-based metrics is required to supplement physical perception.

1.3. Daylighting Metrics

A number of metrics have been developed to describe how well a space performs with respect to occupant visual comfort in daylit spaces. Most fundamentally, quantitative light levels are defined for various work activities by the Illumination Engineering Society (IES) [6]. These illuminance levels were later incorporated into metrics that define performance for determined conditions (for a static sky type, annually, etc) such as the Daylight Factor (DF), which is defined as the proportion of outdoor light under an overcast sky that enters the space at a given location [7]. Other metrics, such as Daylight Autonomy (DA) and Useful Daylight Illuminance (UDI) use climate-based simulation capabilities to provide more realistic metrics [8, 9].

The Daylight Glare Probability (DGP) metric evaluates the quality of light in a space. It is an empirical correlation to describe the likelihood of discomfort glare due to daylight [10]. A simplified version of the DGP metric, known as DGPs, has also been identified [11]. One of the vital advantages to the DGP metric is its glare prediction for daylight specifically, as opposed to being based on electric lighting conditions.

1.4. Adopted Approach

This paper presents the methodology for calculating quantitative performance-based metrics to inform about what effects a complex fenestration system will have on the performance of the space. The complete data set will consist of analysis of five selected complex fenestration systems defined by their BTDF in each of the five orientations (north, east, south, west, and horizontal) and in fifteen climate locations that represent the variety in typical conditions of the continental United States [12]. This data will then be evaluated through a series of sensitivity analyses in order to determine the critical variables that affect ultimate performance and provide insight as to how to reduce the information into a usable form.

In this paper, the criteria most relevant to the performance of a façade system – namely relative energy impact, occupant visual comfort, and view through the façade – are defined within the context of a generic space and on an annual basis. A base case scenario of a double-glazed clear window is used to normalize assumptions and to provide an intuitive reference case with which the building industry is familiar. This base case scenario, along with a sample complex fenestration system, have been used to generate an initial dataset so as to illustrate the feasibility of the proposed methodology for a given climate location.

2. PROPOSED METHOD

Three performance criteria have been defined to assess the performance of a complex façade system: one addressing annual energy efficiency and based on simplified lighting and heating/cooling estimations to determine *Relative Energy Impact (REI)*, one related to visual comfort and approximated as a new metric named *Extent of Comfortable Daylight* (ECD), and one related to the ability to view through the system and approximated as a new metric named *View Through Potential* (VTP). These three criteria are presented in the following sections.

2.1. Reference Scenarios

The generic space modelled for all spatial comparisons is based on the geometric and material properties of a proposed experimentation module at the Ecole Polytechnique Federale de Lausanne (EPFL), which will be built for a similar purpose of assessing the effects of various façade system designs.

The generic space is a single room with one window oriented in the direction of the façade being evaluated. The window is 3 by 1.5 meters and the room is 3 meters wide, 9 meters deep, 3 meters high. The reflectances of major surfaces are 0.87 (wall), 0.87 (ceiling), and 0.13 (floor). The locations of measurement sensors form a grid at each 0.65 m^2 interval. Figure 1 provides schematic of the test space.

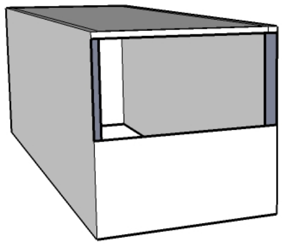

Figure 1: Test module used for spatial simulations.

The base case fenestration system is a double-glazed clear glass window with glass layers of 3.2mm thickness and an air gap of 6.4mm. In conventional NFRC metrics, the U-factor would be defined as being 3.12 W/m^2 and the overall visible transmittance is 81% [5, 14].

2.2. Relative Energy Impact

A fenestration system affects the energy performance of a space in two fundamental ways. First, the amount of light that is permitted to enter a space will, in an ideal situation ("perfect" daylight-responsive photosensors) correlate inversely to the amount of supplemental electric lighting required. Second, the heat addition associated with solar radiation and the heat loss associated with the thermal conductivity of the façade both have an impact on the heating and cooling loads within the space. This impact is complex to assess accurately but can generally be approximated with simplified calculations. Our proposed calculation procedure addresses each aspect.

Lighting

We suggest that the lighting load reduction potential be evaluated based on a set of essential assumptions to describe the behavior of the operator and presence of a dimming system. These are:

- Lights may be on, dimmed, or off.
- The test space consists of three lighting zones, the perimeter, the middle, and the deep zone.
- Lights are by default on, but if all sensors in the zone receive sufficient daylight, lights may be dimmed or off.
- Lights are turned on if the average illuminance level of the time step is below 300 Lux. Lights are off if the illuminance level is above 500 Lux. Lights are dimmed if shades are drawn due to uncomfortable glare (DGP > 0.33) [10].

- Bulbs are assumed to consume 10 watts per square meter of floor area. Dimmed bulbs consume 7 watts per square meter. Bulbs that are off consume no electricity [15].

The thresholds for lighting conditions have been derived from minimum IES recommendations and the DGP metric for discomfort glare. According to the IES Handbook, the minimum comfortable light level in an office is about 300 Lux [7]. Maximum light levels are less well defined, but too much light presents the issue of glare. Therefore, daylight is considered uncomfortable for occupants if the DGP is above 0.33 which is the point at which blinds are assumed to be drawn [10].

Estimation of the total amount of electricity is determined from simulations that integrate weather data with the façade's angle-dependent transmissivity to determine the indoor illuminance and DGP values for each moment of the year in order to suggest the amount of electricity required to light the space comfortably. It is then possible to determine a value for the annual electricity required for the space for the base case window scenario and thus each complex fenestration system as compared to the base case.

Heating and Cooling

The *2001 ASHRAE Handbook of Fundamentals* defines energy flow through a fenestration product, neglecting humidity difference, as being the difference between heat flow in due to solar heat gain and heat flow out across the surface of the fenestration [16]. This net heat flow is calculated for each moment of the year.

At each moment, the Solar Heat Gain Coefficient is calculated by first determining the solar position for each hour and applying the associated solar transmittance derived from the BTDF. It is then multiplied by the corresponding total incident irradiance using a global vertical irradiance model proposed by Hay and McKay [17]. The U-factor is calculated as a function of the hourly exterior temperature based on the heat transfer model embedded in LBNL's WINDOW 6 software [18]. Previous versions of WINDOW are used to calculate the single U-factor value for submission to the NFRC certification.

The hourly climate data used both for the Solar Heat Gain Factor and U-Factor calculations determined from the typical-meteorological-year values (TMY3) provided by the US Energy Information Administration [18]. These represent the typical weather for a representative city in each of fourteen climate zones [19, 12]. At each climate location, 56 representative moments have been calculated to represent the year [22]. Weather data is binned and averaged into 56 periods and all calculations are based on this data set.

The AHSRAE Degree-Day method for annual energy load suggests binning days into Heating Degree Days (HDD) or Cooling Degree Days (CDD) [16]. Karlsson et al. propose a simple annual energy model derived from this heat flow equation that allows for comparison of window performance [20]. Using the structure proposed by Karlsson et al. and the assumptions of the Degree-Day method, we propose a method that first determines whether the net heat transfer is contributing to the energy load or to the energy efficiency of the space. Each day is identified as being a HDD or a CDD, so that the energy flow due to the fenestration is applied as contributing to or reducing the building's heating or cooling system accordingly. Summing these load contributions and reductions for the year yields a single number that characterizes the CFS's contribution to annual energy performance.

2.3. Occupant Visual Comfort

While occupant comfort is a very subjective concept, quantitative suggestions have been made to define lighting conditions based on the avoidance of visual discomfort. Drawing on the literature as before, a minimum illuminance threshold of 500 Lux represents the lowest acceptable light levels for an office space [7]. Intolerable glare has been identified as a DGP of greater than 0.42 [10]. We propose a definition for the *Extent of Comfortable Daylight (ECD)* metric as the percentage of floorplan over the year which experiences comfortable daylight conditions within this range. The upper threshold in the ECD metric is thus defined with respect to uncomfortable and intolerable glare, and the lower threshold with respect to suitable illuminances. In order to simulate the threshold of acceptance, credit is assigned on a linear basis of semi-discomfort range from 200 to 500 Lux and 0.33 to 0.42 DGP. All light levels are determined from Radiance simulations, and the data analysis is conducted with MATLAB.

If both the minimum illuminance target and maximum glare probability are achieved at a given time, the sensor location receives a credit of 1. If not, it receives a credit of 0, with fractional credits for the buffer range. Thus, for each moment of the year, we can identify how much of the space is "comfortably lit" as a percent of area. The ECD of a space will then represent a condensed version of information in the form of a single number for the year in a manner similar to the condensing process in Gagne's Goal Based Illuminance calculation [21]. As with the energy efficiency calculations, the ECD metric will be reported as a comparison to the base case window scenario. This provides a physical reference for how a complex fenestration is performing relative to a standard and intuitive alternative.

Temporal maps are a visual means to represent data for an entire year. Horizontally, these images show annual performance and vertically they show performance along the hours of the day indicating when a space is lit comfortably, too little or too much [22].

2.4. View Clearness

The ability to see an accurate image through a window component has been identified as being a critical aspect of performance for its acceptance by occupants [24]. One simple and relevant way to characterize view is to define full, partial, or no view to an occupant inside. View is a function of the light that is transmitted directly and without distortion. We propose to define the *View Through Potential (VTP)* metric as being the percentage of space which receives direct and 'undistorted' light, thus corresponding to a rough estimation of how much of the space will benefit from various levels of view. Quantitative thresholds for these qualitative definitions are being determined through sampling a larger set of fenestration systems that are correlated with particular levels of view. As before, the metric will ultimately be reported with respect to a clear double-glazed window in order for the user to correlate quantitative values with qualitative experience.

In order to determine quantitative values, we use the visible spectrum BTDF data which provides local information about the ratio of visible light transmitted through the surface. We propose a quantitative method to analyze the BTDF of each sample as a comparison to a perfectly clear view. The ratio of the undistorted light to the total amount of light transmitting provides a quantity for how much scattering occurs. Moreover, a hole can be assumed to transmit light with no distortion, and thus has been selected as the reference case (not to be confused with the base case clear double-glazed window). Quantitatively, the BTDF of a "hole" sample – no fenestration surface – indicates how light behaves at each incident condition. The BTDF of each fenestration system can then be compared to the unmodified behavior as represented by the hole BTDF, as shown pictorally in Figure 3.

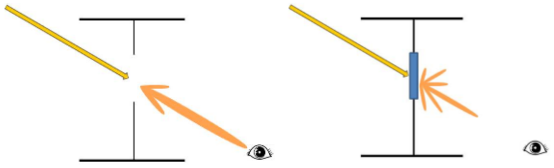

Figure 3: The quantity of direct undistorted light that reaches each sensor location will be compared for each system (e.g. right) to a "hole" reference case (left).

Each sensor location perceives each point on the window with a unique angle of reference. Figure 4 shows the range in possible view angles for a single sensor location. Each location on the window grid will be associated with unique BTDF ratio for a given sensor location. The average of these will then be the overall ratio associated with that particular sensor location.

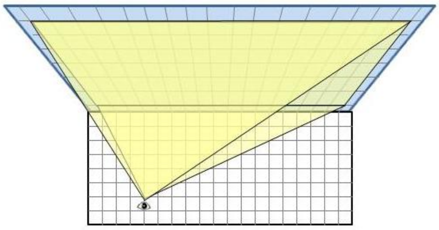

Figure 4: Angles of view must be defined for each part of the window at each sensor location.

For each sensor location, the overall ratio of the system's BTDF to the value of the hole's BTDF will indicate how clearly an occupant can see outside. If this ratio approaches 1, a clear view is achieved and if this ratio approaches 0, no view is achieved. From these qualifications, each sensor location will receive a credit between 0 and 1 if it is provided with no, partial, or full view. Again, the total credit that a system receives will be compared with the base case clear double-glazed window to provide increased intuition for the user.

3. METHOD FEASIBILTY

A requirement to the feasibility of any method, but particularly those relying on parallel ongoing research like ours, is ensuring that the tools or calculation procedures used to produce the desired outcomes are validated to be consistent and accurate. The use of BTDF data in *Radiance* calculations has been attempted [13] but the inclusion of BTDFs for time-efficient annual simulations is still a work-in-progress [25]. To determine which seems likely to produce the most reliable results in our approach, both methods have been applied for comparison and for a clear window without angular dependence; the processes have been shown to provide equivalent results.

3.1. Base case results

Using the methods presented in Section 2, the base case scenario data set was constructed and is presented here to demonstrate the feasibility of the process.

Relative Energy Impact

The Solar Heat Gain Factor was calculated as a function of angle-dependent transmissivity and local weather conditions for each hour of the year. Using the temporal map form as presented previously, it is possible to view the heat flow due to solar irradiation for each hour in a single graphical representation as in Figure 5, which shows the angle dependence of the solar heat gain factor for a south facing CFS façade in Miami, FL. This graph does not speak to whether the solar heat gain factor is contributing to cooling loads or reducing the heating load but clearly shows the times of the year which a south facing façade receives direct sunlight due to solar angle.

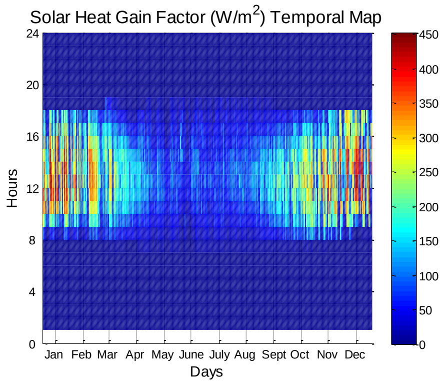

Figure 5: Temporal map of Solar Heat Gain Factor in Watts per square meter of façade area for a sample CFS.

Similarly, the hourly resistance heat flow across the façade can be calculated as a function of weather conditions. As is clear in Figure 6, there is little variation over the course of each day in amount of heat flow across the system although it does vary with season.

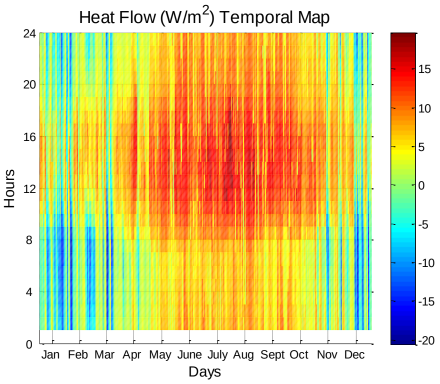

Figure 6: Temporal map of Resistance Heat Flow in Watts per square meter of façade area for a sample CFS.

Combined, the data represented by Figures 5 and 6 show the total amount of heat transfer that occurs for the space as a result of the fenestration system. The net heat flow is described pictorially in Figure 7. When there is no sunlight (at night), the heat flow across the façade dominates, resulting in near or slightly below zero heat passage. Meanwhile, direct solar irradiation results in substantial heat gains.

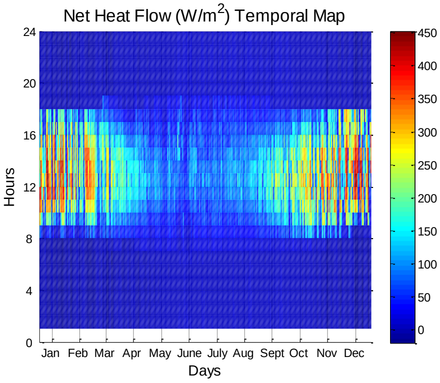

Figure 7: Temporal map of Total Net Heat Flow in Watts per square meter of façade area for a sample CFS.

Occupant Visual Comfort

While the ECD metric is a single value that represents the visual comfort performance over the year, Figure 8 shows more explicitly the profile of performance of two different façades, also in Miami, FL. For each moment of the year, the space achieves a certain value that can be represented as a percentage of sensors that achieve comfortable light conditions. Using the 56 representative moments [23], it is possible to quantitatively assess the relationship between the amount of time that achieve "comfortable conditions" as the requirement for the fraction of space that is comfortably lit the amount of time the room achieves those conditions decreases.

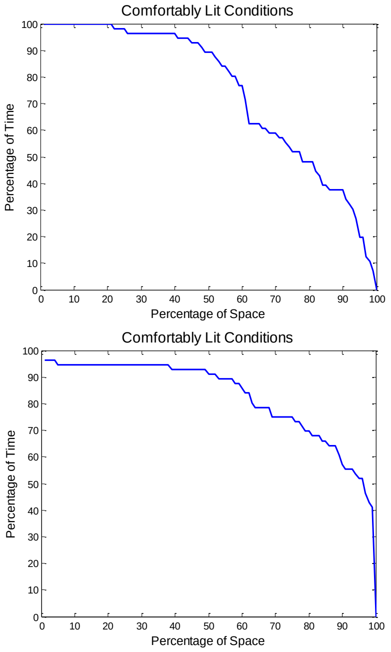

Figure 8: Percentage of time and space that achieves comfortable light levels according to the ECD metric for the base case (top) and a sample CFS (bottom).

View Clearness

Finally, the VTP metric was also calculated for the clear double-glazed window base case façade. Because the view range is within 60 degrees of normal incidence, this glazing does not exhibit any angle-dependent properties. (For a standard window, view angles greater than 60 degrees do result in a decrease in transmittance and an increase in reflectance.) As such, the VTP is equal to the façade's overall transmissivity of 82%. This façade is characterized as providing a clear view to the outside. The sample CFS is considered to provide no view to the outside and its VTP value is 8%.

4. CONCLUSION

The method proposed is the first step toward creating a comprehensive and robust set of metrics that inform the user about the technical performance of a complex fenestration system. Once the method feasibility validation has been completed, detailed technical data can be computed. Following, a phase of data analysis will identify the critical aspects of fenestration technology in actual implementation through rigorous sensitivity analyses. Being able to isolate the variables to which performance is most sensitive will enable us to condense the data into more readable forms and ultimately generate a relevant rating system.

The goal of this research is to promote utilization of complex fenestration systems to improve building energy performance by disseminating technical information in a form that is easily understandable, thereby generating demand for an energy-efficient product. By providing a standard on which manufacturers can compete, this will also stimulate innovation in a typically slow-moving industry. With improved communication, designers and engineers can engage in integrated design processes that will contribute to a transformed building industry that is mindful of the importance of energy efficient technologies and objectives.

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