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Efficient modeling of optically-complex, non-coplanar exterior shading: Validation of matrix algebraic methods

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ABSTRACT

It has long been established that shading windows with overhangs, fins, and other types of non-coplanar systems (NCS) is one of the most effective ways of controlling solar heat gains in buildings because they intercept solar radiation prior to entry into the building. Designers however often specify non-opaque materials (e.g., louvers, fritted glass, expanded metal mesh) for these systems in order to admit daylight, reduce lighting energy use, and improve indoor environmental quality. Most simulation tools rely on geometric calculations and radiosity methods to model the solar heat gain impacts of NCS and cannot model optically-complex materials or geometries. For daylighting analysis, optically-complex NCS can be modeled using matrix algebraic methods, although time-efficient parametric analysis has not yet been implemented. Determining the best design and/or material for static or operable NCS that minimize cooling, heating, and lighting energy use and peak demand requires an iterative process. This study describes and validates a matrix algebraic method that enables parametric energy analysis of NCS. Such capabilities would be useful not only for design but also for development of prescriptive energy-efficiency standards, rating and labeling systems for commercial products, development of design guidelines, and development of more optimal NCS technologies.

A facade or “F” matrix, which maps the transfer of flux from the NCS to the surface of the window, is introduced and its use is explained. A field study was conducted in a full-scale outdoor testbed to measure the daylight performance of an operable drop-arm awning. Simulated data were compared to measured data in order to validate the models. Results demonstrated model accuracy: simulated workplane illuminance was within 11–13%, surface luminance was within 16–18%, and the daylight glare probability was within 6–9% of measured results. Methods used to achieve accurate results are discussed. Results of the validation of daylighting performance are applicable to solar heat gain performance. Since exterior shading can also significantly reduce peak demand, these models enable stakeholders to more accurately assess HVAC and lighting impacts in support of grid management and resiliency goals.

1. Introduction

Annual primary energy use in buildings was 41 EJ or 39 quadrillion Btu (39×10^{15} Btu) in the United States in 2010 and is projected to increase to 47 MJ (45 quad) by 2035. The residential sector accounts for 54% of total building energy use while the commercial sector accounts for the remaining 46%. Of the total aggregate load for both sectors, 0.797 EJ (0.756 quad) of cooling load is attributable to solar heat gains through windows. These same solar gains offset the need for heating by 0.574 EJ (0.544 quad) and have the potential to reduce lighting energy use in the commercial sector by 1.06 EJ (1 quad) through daylighting [1–4].

Prior studies have quantified the solar control benefit of exterior (outdoor) coplanar and non-coplanar shading (NCS) systems on reducing energy use and peak demand [5–11]. These systems intercept solar radiation prior to entry into the building and can thus be more effective than between-pane and interior (indoor) shading systems. Poorly designed solar control technologies however can decrease cooling load at the expense of increased heating load and lighting energy use. Industry has an intuitive understanding of these tradeoffs between solar control and daylighting (e.g, blocking sunlight reduces daylight). This is evidenced both with commercially available products and design practice: use of opaque shading elements with no transmissive properties is less typical;

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awnings, canopies, and architectural solutions are more often specified with fabrics, louvers, perforated metal, expanded metal mesh, fritted glass, and other materials to partially block direct sunlight and allow filtered daylight to come through. Operable shading such as drop arm awnings or adjustable louvers provide further opportunities to reduce energy use and peak demand through daily or seasonal adjustments in order to minimize both heating and cooling loads.

Historically, simulation tools have used geometrical calculations and/or radiosity methods to quantify the effect of NCS on window heat gains and daylighting [12–17]. Kirimtat et al. [18] provided a detailed comprehensive review of simulation modeling tools for shading systems. The key drawback of these tools is that the underlying method excludes many of the optically-complex materials that are specified for exterior shading (e.g., fritted glass, perforated metal, etc.). With the introduction of matrix algebraic models, such as the two-, three-, and five-phase methods [19–27], simulation tools have been able to employ time-efficient ray-tracing methods to determine annual energy performance of optically-complex shading and daylighting systems at a fraction of the time needed for full ray-tracing calculations.

The sole limitation of these methods is that the matrix used to map flux from the discretized sky to the surface of the window (called the daylight or "D" matrix) includes both the NCS and exterior obstructions, such as mountains or nearby buildings. This prevents parametric analysis of the NCS element in isolation from the other obstructions. Analysis of a few NCS designs (or in the case of an operable NCS with a few discrete positions) can be accomplished by computing a D matrix for each permutation of the NCS design. For most architects and engineers, this can be achieved routinely using the existing matrix-based simulation tools today. Applications involving hundreds or thousands of permutations of the NCS design and surrounding environment (e.g., window orientation, nearby obstructions, etc.) however would need an alternate approach. Such applications include development of prescriptive energy-efficiency standards to promote more optimal exterior shading. Rating and labeling of commercially available shading systems could be more easily accomplished by organizations such as the US Attachments Energy Rating Council [28] and the European Solar-Shading Organization [29]. Parametric analysis could also be applied to the development of new solar control/ daylight-redirecting NCS technologies or to develop design guidance for existing shading systems offered by manufacturers [30–33].

In this study, we describe alternate modeling approaches, called the four- and six-phase methods, that were developed to separate the flux transfer behavior of the NCS from the D matrix, enabling parametric analysis. This was accomplished with the introduction of a new facade or "F" matrix.[1] This study describes methods to construct the F matrix, then compares measured data from a full-scale outdoor testbed facility to simulations in order to validate the methods. Validation of new models is an important step toward adoption in commercial software tools. Validation provides an opportunity to examine deficiencies in the model, improve the underlying algorithms, understand the limitations of the model, and increase confidence in the use of the models for real world building applications. Results of the validation are provided. Implications of the new methods are discussed.

2. Background

The methods described in this paper use *Radiance* as the simulation engine. Radiance is a suite of tools that perform backward ray tracing and other calculations to model and render the luminous effects of fenestration and lighting systems [33]. Radiance can simulate the flux transfer of a non-coplanar shading (NCS) element using ray tracing methods. However, conventional ray tracing can take a considerable amount of time to model a single point-in-time daylit condition. In order to reduce computation time for an annual calculation, the concept of the daylight coefficient was introduced in 1983 [19], which laid out the mathematical function that relates the luminance of the sky to the illuminance of a point in a room. The concept was later realized and improved upon with the introduction of the Radiance *rcontrib* tool [34,35]. The original daylight coefficient method (also called the two-phase method) enabled efficient daylight calculations with a discretized sky luminance distribution. The three- and five-phase methods were developed later to allow parametric analysis of coplanar complex fenestration systems using bidirectional scattering distribution function (BSDF) data and enable more accurate prediction of the distribution of direct sunlight in the space [25,27]. Before the introduction of the Radiance *rfluxmtx* tool [35], users could only model coplanar, rectangular fenestration systems such as one with a double-glazed window and a venetian blind. The Radiance *rfluxmtx* tool enabled the flux transfer calculation between two non-parallel, non-rectangular surfaces, which in turn enabled the development of the four- and six-phase methods to facilitate evaluation of non-coplanar shading systems.

2.1. Modeling NCS using existing methods

There are several existing methods that can be used to simulate the daylighting performance of a NCS. The full ray tracing calculation using the Radiance *rtrace* tool is the most accurate "ground truth" approach. The Radiance two-, three-, and five-phase methods can be used to evaluate the performance of a NCS, but these methods incorporate the NCS element as a fixed part of the scene. The performance of the NCS cannot be separated and stored in a matrix to be used for example in a parametric design analysis of different glass frit patterns for an overhang or to model an operable awning.

The matrix algebraic modeling approaches are explained as follows: To derive a flux transfer matrix, there are two key components: senders and receivers. A sender is a surface with a direction that randomly sends out rays in a hemisphere. The rays interact with the objects in the scene before arriving at one or more receivers. The receivers then sort rays into bins based on the specified sampling basis. Thus, the flux transfer between a sender and a receiver is stored in a matrix with the dimension of (number of sender directions × number of receiver bins). Multiple matrices may be produced in a single run in the case of multiple receivers.

2.1.1. Two-phase method

The two-phase or daylight coefficient (DC) method can be used to calculate the annual daylighting performance of an NCS. With the two-phase method, the sky dome hemisphere is subdivided into a grid of solid angles or "patches," then the relationship between the luminance of each sky patch and the illuminance or luminance of a point in space is calculated and stored in a matrix format. In this case, the sensor point in the room is the sender and the sky dome is the receiver. Given a sky luminance distribution, the illuminance at the point in a room can be calculated by multiplying the luminance of each sky patch by the corresponding coefficient in the matrix and summing for all sky patches. The accuracy of the result increases with increased sky subdivisions. With the two-phase method, the NCS will be placed in the scene and be part of the ray tracing from the indoor sensor point to the sky. The daylight coefficient matrix needs to be re-computed when any part of the scene changes.

$$\mathbf{E} = \mathbf{V}^{*}\,\mathbf{S} \quad (1)$$

[1] Andrew McNeil (previously at LBNL) was the originator of the F-matrix concept.