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A comparison of two light-redirecting fenestration systems using a modified modeling technique for Radiance 3-phase method simulations

Luis Santos[a,*], António Leitão[b], Luisa Caldas[c]

[a] Univ. of California, Berkeley, College of Environmental Design, Department of Architecture, Center for the Built Environment, USA
[b] INESC-ID, Instituto Superior Técnico, Universidade de Lisboa, Portugal
[c] Univ. of California, Berkeley, College of Environmental Design, Department of Architecture, Lawrence Berkeley National Laboratory, USA

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ABSTRACT

This paper compares two different macroscopic light-redirecting fenestration systems (LRFS) using Radiance's three-phase method. The goal is to assess the potential of simplified daylight metrics that are less computationally expensive, such as Daylight Factor (DF), in the optimization of LRFS. This work compares a highly specular LRFS optimized for DF (Lasy_S) with a validated commercial LRFS (LightLouver) using a Double Clear Glazing window as the control case. The comparison uses two different locations representative of two different annual sky conditions: London, UK - overcast; Phoenix, AZ, USA – clear. Useful Daylight Illuminance (UDI) and annual Daylight Glare Probability (DGP) are the metrics used to evaluate daylight availability and visual comfort. To facilitate the efficient modeling of customized macroscopic LRFS in the three-phase method workflow, this work extends Radiance's *genblinds* routine, making it able to generate complex venetian blinds systems based on multiple-curved sections. With the modified *genblinds*, the Lasy_S system is properly remodeled for the three-phase method for an accurate comparison of the different systems. The analysis shows that Lasy_S is a light-weighted and low-maintenance LRFS that outperforms LightLouver in terms of useful annual illuminance levels in both locations, being more effective in cloudier skies due to the metric used in the optimization. Nevertheless, albeit the system mitigates glare, it is not as successful as the commercial LRFS. This indicates that DF and annual horizontal illuminance metrics are unable to properly inform an optimization process on glare performance, thus being more appropriate for initial exploratory optimizations. Hence, to fully address glare, daylight optimization procedures based on DF should be complemented with more detailed glare simulations that do not require unreasonable computational resources.

1. Introduction

Research presented in this paper is part of a larger project that addresses the application of Generative Design Tools to the design and optimization of light redirecting systems which must also double as shading devices. Light-redirecting fenestration systems (LRFS) are usually highly specular so that they maximize the amount of light reflected into the interior of the space, which means that they can also be a significant source of glare. To avoid this problem, in the context of typical office building applications, the light redirecting devices were applied only in the glazing area between 2 m and 3 m high, thus redirecting light to the ceiling, and avoiding the user's visual field. Furthermore, these systems can be visually obstructive, which represents another reason for removing them from the view area of the facade.

Simultaneously, the proposed system should be simple enough for mass production at low cost. It should be easily integrated into the existing market of standard office building solutions, largely based on interior venetian blinds. Since the amount of daylight savings that can be achieved by light-redirecting systems is not too significant, it is perceived that unless the proposed system responds to these additional requirements, it will probably not become a feasible, marketable product.

The solution adopted was an in-between glass system, made of 16 mm louvers placed inside a standard double-glazed unit. The 16 mm width assumes an air gap of 18–20 mm. The louvers are made from lightweight extruded aluminum, with 6063 alloy and T6 temper, using an extra-thin profile fabrication. On the top side, the louvers are coated with high-reflectance 3 M film, both in the visible (99.3% VR) and infrared spectrum, that prevents overheating inside the insulating glass unit.

Part of the research consisted on finding an optimized double

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[*] Corresponding author at: Department of Architecture. Univ. of California, Berkeley, 384 Wurster Hall, Berkeley, CA 94720-1800, USA.

E-mail addresses: luis_sds82@berkeley.edu (L. Santos), antonio.menezes.leitao@ist.utl.pt (A. Leitão), lcaldas@berkeley.edu (L. Caldas).

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curvature profile for the louvers, with a geometry able to redirect incident daylighting at the façade level deep into the space. Due to the very small scale of the louver section, it was decided that including more than two curves in the louver section might lead to significant difficulties in the manufacturing process, thus increasing production costs. The minimum number of points to describe a double curvature section is five, which was also the number of points selected for the optimization process. The project used the Radiance lighting simulation software (Ward and Rubinstein, 1988) connected with a Genetic Algorithm (GA) to perform a global and initial search of high-performance louver curvatures for light redirection into the space. To avoid computationally expensive simulations, that would make the optimization close to infeasible, this initial optimization approach used Daylight Factor (DF) simulations to inform the procedure on daylight performance. After this initial search, the optimized system was simulated in more detail using annual illuminance metrics.

A main limitation of Radiance in fully simulating specular or highly reflective daylight-redirecting systems is the use of backward ray tracing. The accurate simulation of an LRFS requires forward ray tracing, a method that starts at the light source (sun and sky) and traces each ray through the daylight-redirecting system into the room (Ward and Shakespeare, 1998). To overcome this limitation, two extensions added front-forward ray tracing to capabilities to Radiance: (i) the three- and/or the five-phase method (McNeil and Lee, 2013a) and (ii) photon mapping (Schregle et al., 2015). This paper uses an extension to the base software known as the Radiance three-phase method, to use forward ray tracing capabilities to accurately simulate the optical properties of any macroscopic fenestration system.

To assess the performance of the optimized system the paper compares it against a Double Clear Glazing window assembly (control case) and a validated commercial macroscopic LRFS using the three-phase method to perform detailed annual illuminance and glare analysis. The goal of this comparison study is to assess weaknesses and opportunities in the use of simplified daylight metrics, such as DF, in the optimization of LRFS.

To optimize research workflow and minimize the use of auxiliary software tools, file conversions, and switching between different Operating Systems (OS), the comparative study exclusively used Radiance's routines and commands, without resort to any front-end. However, it was found that it is difficult to reproduce the multiple curvature louvers using Radiance built-in modeling functions, such as *gensurf* or *genblinds*. Thus, the research conducted in this paper extended the current *genblinds* capabilities to model complex louver systems, based on multiple curvature sections, and facilitate the generation of customized Bidirectional Scattering Distribution Functions (BSDFs) in the three-phase method workflow by automating the geometry preparation for Radiance's *genBSDF* routine. The development of this improved workflow included the following stages:

- Simulation and modeling methods review, to contextualize the research;
- *Genblinds* extension to model systems based on multiple curvature sections;
- Automation of the preparation of the different fenestration components geometry for the generation of the full assembled fenestration BSDF;
- Use the new modeling workflow to accurately model and simulate the optimized LRFS with the three-phase method for a detailed comparison of the different fenestration systems.

2. Related work

The work presented in this paper addresses two main components, both in the context of the three-phase method: daylighting simulation of complex fenestration systems (CFS), and modeling techniques for those simulation techniques. The related work of each component is shortly reviewed below.

2.1. Daylighting simulations for CFS

Radiance (Ward and Rubinstein, 1988) is a highly accurate ray-tracing program that is widely regarded as the 'gold standard' for lighting simulation, being the reference software in the validation of other programs with lighting simulation abilities (Reinhart and Breton, 2009). Radiance was released in 1988 and due to the computational constraints of the time, its rendering engine is based in backward ray tracing in order to minimize computation time into a feasible range. Backwards ray tracers, such as the ones implemented in Radiance and in DAYSIM (Reinhart and Walkenhorst, 2001), are unable to simulate the performance of daylight-redirecting systems because they use probabilistic sampling methods to find the specular reflection of the sun, and the probability to find the sun with those methods is low due to the sun's small relative size. Thus, a forward ray tracing method is needed to accurately simulate CFSs (McNeil and Lee, 2013a).

Radiance is being constantly updated and one of the recent additions is the integration of Bidirectional Scattering Distribution Functions (BSDFs) and programs that generate BSDF data (*genBSDF*). These updates extended Radiance's to accurately assess and simulate any arbitrary glazing assemblies, light redirecting and/or shading systems, and other optically CFSs (Ward et al., 2011). BSDF's matrices are used as materials in Radiance to describe the optical properties of CFS (Saxena et al., 2010; Konstantoglou, 2011; McNeil and Lee, 2013a). BSDFs matrices are typically encoded in the eXtensible Markup Language (XML) format and describe the way light is distributed and scattered by a surface by splitting the light flux in two: one that treats the reflected part of light, the Bidirectional Reflectance Distribution Functions (BRDF); and another that deals with the part of the light flux that is transmitted, the Bidirectional Transmittance Distribution Function (BTDF). By providing a Radiance model of a CFS to *genBSDF*, a BSDF for that system is generated. WINDOW (Mitchell, 2008) is another software through which a BSDF of a CFS can be generated.

BSDFs are key elements in recent implementations of forward raytracing in Radiance such as the three- or five-phase method (McNeil and Lee, 2013a; McNeil, 2013). These methods are based on the daylight coefficient (*DC*) approach, which divides the sky into 145 divisions, then pre-calculates coefficients that relate the luminance of each sky division to the illuminance of a point inside the space (Tregenza, 1987). For an annual calculation, the illuminance of a specific sensor node in each time step is computed by summing up all the 145 multiplications between each sky division luminance and the respective *DC*. For example, the three-phase method breaks the luminous energy transport between the sky patches and the interior sensor nodes into three distinct phases, each one simulated independently and stored in a matrix of coefficients: (i) the Daylight matrix (D), which describes the way that energy from each Tregenza sky patch arrives into each of the directional Klems patches (Klems, 1994a, 1994b) that compose the fenestration; (ii) the Transmission matrix (T) expressed in the BSDF matrix that describes the specular and non-specular transmission of the fenestration; (iii) the View matrix (V) which characterizes how light that exits the fenestration arrives at the camera or at a grid of sensor nodes. By multiplying the three matrices, a DC is calculated. The annual illuminance (i) or luminance (l) on V is calculated by multiplying DC by a sky matrix (S) that contains the sky patches average luminance for all the hours of the year and correspondent sky conditions.

Due to its forward raytracing capabilities, the three- or five-phase methods are more accurate than annual simulation methods based on backward ray tracing (e.g., DAYSIM), and because each matrix is computed separately, it is highly flexible. For example, to test different orientations, the D matrix can be changed, while to test different fenestration systems the user only needs to change the transmission BSDF matrix, T. The three-phase method is being applied in the design, validation, and selection of CFS of LRFS and other CFS such as in (Bueno et al., 2015; J. Hu and S. Olbina, n.d.; McNeil and Lee, 2013b).