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Fener: A Radiance-based modelling approach to assess the thermal and daylighting performance of complex fenestration systems in office spaces

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ABSTRACT

A new Radiance-based modelling approach called Fener is presented. The motivation is to be able to perform detailed analyses of complex fenestration systems (CFS) from the energetic and daylighting points of view in a computationally efficient manner, so the benefits of innovative products can be easily quantified. The model couples daylighting and thermal simulations in a time-step basis, so that shading control strategies that depend on thermal variables, such as indoor air temperature and energy load, can be simulated without iterating between full-year simulations of a thermal model and a daylighting model. Fener is a single-zone energy model that uses the three-phase method and bi-directional scattering distribution functions (BSDF) to predict the transmitted solar irradiance and indoor illuminance of office spaces with CFS. An evaluation of the model is presented. Fener is tested against EnergyPlus and classic Radiance for different fenestration systems and sky conditions. Cooling and heating energy demand, transmitted solar irradiance and indoor illuminance are compared. As an exemplary application, Fener is used to assess the performance of an innovative perforated lamella system together with a control strategy that depends on indoor air temperature.

1. Introduction

Complex fenestration systems (CFS) refer to any light transmitting window technology that incorporates at least one non-clear (non-transparent) layer or one layer with swichable properties. Examples include translucent insulating panels, shading devices, such as venetian blinds and roller shutters, and electrochromic glazing. CFS, combined with a suitable control strategy, have the potential to improve the thermal and visual comfort of indoor spaces as well as to save energy for lighting, cooling and heating. Recent energy reduction requirements are forcing the architectural-engineering community to integrate daylighting and shading technologies in their designs. However, the prediction of the light scattering properties of CFS remains an open research field. There is still a need for the integration of advanced methods for thermal and daylighting simulation in order to facilitate the development of new products and the adoption of commercially available technologies.

In recent years, a number of modelling strategies have been proposed in order to represent the light scattering properties of CFS. Kuhn et al. [1] presented a "Black-Box" model to predict solar gains through CFS in building simulation programs. The model requires angularly resolved solar heat gain coefficients, which can be analytically derived or obtained through calorimetric measurements [2]. The model then introduces the radiant and convective effect of solar heat gains into the energy balance of the building through a two-layer approach.

Other modelling initiatives keep the separation between the thermal and optical problems of the fenestration system. While the thermal problem can be solved by a layer-by-layer heat transfer equation, the optical problem is addressed by using bi-directional scattering distribution function (BSDF) data. Klems [3,4] developed a calculation method to generate BSDF data of multi-layered fenestration systems from the angularly resolved data of single layers, which could be independently measured or calculated. Measurements of BSDF data can be carried out with a goniophotometer [5], although just a few of these devices currently exist that can fully characterize a CFS. Alternatively, one can generate BSDF data through ray-tracing. The Radiance-based program genBSDF computes these datasets from the geometry of macroscopic systems and surface properties of the base materials

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[7]. The Klems' method was implemented in the Window 6 program (http://windows.lbl.gov/software/window/6/).

BSDF data can be used within Radiance [8] in order to simulate the daylighting performance of CFS. One way to do this is by applying the three-phase method [9]. This approach, based on the daylight coefficient method, separates the light transport between the outdoor and the indoor environments into three phases: exterior transport, fenestration transmission through a BSDF dataset and interior transport. The three-phase method has some advantages over classic Radiance and Daysim [11] for the evaluation of CFS, especially for systems composed of small structures and for specular or refracting shading surfaces. This is due to the fact that the calculation of the light transmission through a fenestration system is not restricted to the backward raytracing method but can be calculated by other methods such as photogoniometry and Photonmapping. The separation of the light transport in three phases, as opposed to Daysim's one-phase, brings computational efficiency when the fenestration system can switch among multiple states during a dynamic simulation (e.g. a Venetian blind system).

BSDF data is also used in building energy calculations. The building simulation program, EnergyPlus [12], allows the user to provide BSDF data as the optical representation of the fenestration system, while keeping the layer-by-layer heat transfer definition. EnergyPlus includes a daylighting engine, DElight, based on the radiosity method [6]. DElight is suitable for simple building geometries with CFS but does not support dynamic shading control. In addition, specularly and light-redirecting surfaces cannot be handled accurately by the radiosity method.

ComFen (http://windows.lbl.gov/software/comfen/comfen.html), a widely available simulation platform to evaluate fenestration systems in office spaces, uses EnergyPlus's daylighting engine for annual daylighting simulations. The DIVA plug-in for Rhino (http://diva4rhino.com/) uses Daysim as the calculation engine to obtain climate-based daylighting metrics. Similarly, OpenStudio (https://www.openstudio.net/) offers an integrated interface, in which the user can carry out a daylighting analysis based on the three-phase method and pass a resulting artificial lighting schedule to EnergyPlus. This kind of interfaces, which handles different calculation engines from a single definition of the building properties, can also be found in Adeline [10]. ESP-r (http://www.esru.strath.ac.uk/Programs/ESP-r.htm) offers time-step coupling capabilities with Radiance and Daysim, but the run time is inefficient and does not support BSDF data. However, none of the reviewed methods that couple daylighting and thermal simulation models are able to efficiently assess control strategies for CFS that depend on thermal variables.

The present study proposes a new modelling approach, called Fener. The main contribution is to be able to couple daylighting and thermal simulations in a time-step basis, so that shading control strategies that depend on thermal variables, such as indoor air temperature and energy load, can be simulated without iterating between full-year simulations of a thermal model and a daylighting model. Fener is a single-zone "shoe-box" energy model that uses the three-phase method to predict the solar transmission and indoor illuminance of office spaces with CFS. It allows for detailed analyses of facade systems from the energetic and daylighting points of view. Fener can also be used as a shading controller simulator, whose output in terms of shading operation can then be used in standard building simulation programs (e.g. EnergyPlus).

In this paper, a description of Fener is presented. Special attention is paid to the calculation of solar transmission and illuminance. Then, the model is evaluated against EnergyPlus and Radiance for different seasons and fenestration systems for a weather dataset for Frankfurt/Main (Germany). A case study evaluating a new lamella system combined with a thermally dependent control strategy is presented at the end.

2. Model description

2.1. Mission

The mission of Fener is to provide a simulation platform for the evaluation of fenestration technologies applied to office spaces independently of the complexity of the fenestration system. Fener keeps a simple geometric definition, a rotatable rectangular shoebox space, while allowing a flexible definition of fenestration systems and their control through the use of BSDF data. Although building typologies could be extended in the future, the shoebox approximation is often used by the building performance simulation community to showcase the impact of facade design parameters [13]. Fener allows the user to define and control any number and size of windows in each of the four facades and the ceiling (including windows in more than one surface).

The computational cost of Fener is equivalent to the one of Daysim, which is suitable for dynamic simulation, allowing interactive comparisons of fenestration technologies. All the time-consuming raytracing computation is carried out before the dynamic simulation and can be saved (in matrix form) for other simulations of similar scenarios.

Note that the goal of Fener is not to replace existing building energy models. Therefore, the model is limited to one thermal zone, no humidity calculation is included and infiltration/ventilation is represented by a user-defined schedule of volume air changes in the zone.

2.2. Three-phase method

The distinctive feature of Fener, as compared to other building simulation programs, is the integration of the Radiance-based three-phase method for daylighting and solar transmission calculations.

The three-phase method separates the solar radiation from the outdoor to the indoor environments into three phases: exterior transport, transmission through the fenestration system and interior transport. Each phase of energy transport is simulated independently and stored in matrix form. The resultant irradiance (or radiance, illuminance or luminance) at interior sensor points (I) is obtained by the matrix multiplication $I = VTDs$, where V is a view matrix that relates the interior sensor points with the inner BSDF patches, T is a transmission matrix that relates the inner with the outer BSDF patches, and D is a daylight matrix that relates the outer BSDF patches with the sky patches. The final part of the equation is a vector (s) that contains the average radiance of the sky patches for a given time and sky condition. The combined VTD matrix can therefore be understood as a daylight coefficient matrix that relates outdoor radiance with indoor irradiance.

Fener uses the three-phase method to calculate the indoor horizontal illuminance at a user-specified grid of sensors (at workplane height), which is then used to analyse the daylight autonomy and daylight distribution of the space. The resulting illuminance at a control sensor is passed to a lighting control algorithm in order to obtain the artificial lighting requirements. In addition, vertical illuminance can be calculated for the main viewing directions at the workplaces in order to evaluate also the annual daylight glare [14].

The three-phase method is also used to calculate the transmitted solar irradiance that is absorbed by indoor surfaces. A pair of sensor grids (one facing towards the surface and another one facing in the opposite direction) is placed 1 mm away from the surfaces. The solar irradiance absorbed by a surface is the average of the irradiance difference between sensors looking at opposite directions.

The three-phase method has some advantages over classic Radiance and Daysim for the evaluation of CFS. Systems such as small venetian blinds or highly reflective systems require very time