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END-USE EFFICIENCY (Y WANG, SECTION EDITOR)

Dynamic Shading in Buildings: a Review of Testing Methods and Recent Research Findings

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Abstract

Purpose of Review The use of dynamically operated shading has been shown to provide energy savings and occupant visual and thermal comfort needs. As the literature in this area continues to grow, including development and evaluation of a range of shading devices, control strategies, and simulation and experimental test methods, a review is merited to assess the current state of the art.

Recent Findings While roller shades and venetian blinds are most common, there are a growing number of additional shading types considered, as well as more complex control logic, some of which directly integrates occupant feedback. In addition, the majority of dynamic shading evaluation continues to be through simulation-based methods; however, there is an increasing amount of research using experimental methods. Some research has also explored combination simulation and experimental methods to simplify the number of sensors needed and associated complexity.

Summary Improvements to control logic and ranges of test scenarios continue; however, there is still significant need for further studies in this area.

Keywords Shading control · Energy simulation · Full-scale testing · Energy savings · Occupant comfort

Introduction

Buildings in the USA consume approximately 40% energy and 72% of electricity [1]. As we face an increasing need to reduce this energy use, recently, significant research efforts have focused on how to reduce the total consumption in buildings. Modern buildings have a high potential for improved energy savings; however, at the same time, buildings and their systems also have the responsibility of providing a comfortable and productive environment for occupants, including fulfilling thermal comfort and lighting needs [2]. As occupants spend nearly 90% of their time in buildings [3], a balance between comfort, daylight provision, and energy conservation is needed.

Fenestrations serve multiple purposes, in that they admit solar radiation and daylight into a building, permitting both natural light and heat gain into the indoor building space. Through thermal heat transfer, solar heat gain, air leakage, and daylighting [2], fenestrations can both positively and negatively affect a building's energy use, mostly associated with the heating ventilation and air conditioning (HVAC) and lighting systems. Many interior building spaces, particularly in modern commercial buildings, have sufficient daylight to reduce or eliminate electric lighting in perimeter zones for certain periods of operation due to a significant percentage of window area on the exterior facade. Utilizing daylighting strategies, it has been found that electrical lighting energy use can be significantly reduced; it is estimated that 1 quad of energy could be saved in the US commercial building stock alone [4], but technology solutions currently developed have not been able to achieve significant reductions in artificial

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lighting across a broad range of conditions. However, too much natural light can also produce glare and discomfort for the occupants' work surfaces and field of view, and can also cause occupant discomfort from radiation from window surfaces with significantly different temperatures than the interior environment. Thus, ideally, fenestrations and their associated systems should provide sufficient daylighting, while minimizing energy use and maintaining occupant thermal and visual comfort.

Currently, many buildings use some form of shading device to aid in controlling the amount of daylight and solar gains entering indoor perimeter spaces. Shading devices can be installed on either the exterior or interior of a fenestration; however, the most common is interior shading, due to easier installation and maintenance, and generally lower costs. Exterior shading devices are most easily installed during construction where access to the exterior facade of a building is more easily facilitated, as compared to interior shading devices that can typically be installed at any time. In most cases, in the current building stock, shading devices are manually controlled by occupants to adjust the shading device's slat angles and/or height. Previous research has shown that occupants are very likely to change the position of the internal shading devices when undesired direct sunlight reaches their work area. However, even after the unwanted conditions dissipate, occupants are not as likely to immediately change the shading device position back to once again allow more daylight once conditions improve [5]. Thus, while interior shading devices provide a means to control the daylight in a building, currently, they are not optimally controlled for improved natural daylighting, reduced energy use, and/or occupant visual or thermal comfort.

In light of these challenges, a body of research has developed in the area of dynamic shading devices, the properties and position of which are controlled in real time or near real time. Given the significant amount of literature being published in this area and the associated research efforts, a review of the recent state of the art in these areas is merited. In addition, as sensors and connected devices become more common, improved connectivity and data are becoming more easily accessible which can enable further use of dynamically controlled shading devices. This review provides review and discussion of methodologies and findings from recent efforts. It also identifies challenges, inconsistencies, and further research needs in this domain. This research is organized into several sections; we focus first on overall innovations in shading device types and control strategy development, followed by a review of the modeling and experimental testing methods used, metrics measured, and important findings. Assessment of consistencies and inconsistencies in methodologies of testing, as well as gaps that merit further investigation, is also discussed.

Shading Device Types and Properties

A shading device, in combination with a fenestration, determines the overall thermal and optical characteristics of the overall fenestration systems [6, 7]. This combination is often called a complex fenestration system (CFS). The potential of dynamic shading to provide energy saving from heating, cooling, and lighting energy use reductions while still providing daylight and visually comfortable conditions on the building interior has been studied significantly in recent literature.

The impact on energy and visual performance of shading devices depends, first, on their physical properties as well as those of the fenestration(s) they cover. In recent literature, various types of static and dynamic shading devices have been developed and tested, including, most commonly, venetian blinds [7–13], roller shades [14–20], and louvers [21, 22], mostly on the interior side of the fenestration, but also some have studied their use on the exterior and/or a combination of both. Elzeyadi et al. [23] studied less traditional devices, including dynamic egg-crates, optical element panels, thermal change planes, weaved panels, and automated movable screens. Internal light shelves [23] and grid shading [24] have also been investigated for impact on building energy use and comfort. Recent research has also included studies on the use of photovoltaics integrated into shading devices, including PV-integrated overhangs [25], and dynamic building-integrated photovoltaics [26]. Of these shading devices studied, however, roller shades and venetian blinds are the most common in current literature. Among the 50+ papers reviewed on dynamic shading and fenestrations published within the last 3 years, 18 covered venetian blinds (35%), 6 of which included exterior blinds (12%) and 14 interior blinds (27%). Seventeen discussed roller shades (33%), and 5 covered a range of other shading devices (10%). The newer types of shading devices proposed in some of the recent literature are not as ubiquitous currently, and thus perhaps have not received as much focus. However, given that these alternative methods have found to be comparable or better in terms of performance compared to the traditional shading types (e.g., [23]), these findings appear to point to the need for further study of such devices.

Shading Control Strategy Development

While the physical properties and types of roller shades and venetian blinds appear to not have changed significantly over time, the control strategies' implementation has undergone significant development for the early 2000s to the present time. Controls during the early 2000s were either only based on direct sunlight, on the theoretical position of the sun, or on outdoor irradiation sensor data using open-loop controls. Since using such control strategies were found not to be adequate in maintaining occupant comfort or take into account the variations in sky conditions [27••], the control of dynamic shading has since moved more towards the use of closed-loop controls based on indoor sensors [7, 11, 17].

In general, recent efforts have used data on weather, interior environment, and/or building system performance as input into a control strategy, the logic of which is used to determine how and when to adjust the shading device for improved energy use, lighting levels and glare, occupant comfort, or a combination of these. Recently, many control studies have focused more on occupant visual comfort, such that the dynamic shading controls would provide an acceptable work environment to the occupants [11, 17, 28–31]. There has been more limited focus on the impact of dynamic shading controls on thermal comfort. The studies focused on visual discomfort, known as discomfort glare, use model-based controllers using simulation models [12, 17] or in some cases luminance mapping using vision sensing technology [32•] as tools to determine better ways to effectively prevent glare and to maintain visual comfort.

To assess the effectiveness of automated shading controls, established daylighting metrics and associated thresholds have been used. More recently, in addition to using these metrics, some studies have focused on more in-depth testing with real occupants, to assess occupant visual comfort through laboratory- and field-based studies using occupant satisfaction surveys [10, 11, 33]. The results are in many cases compared to the established daylighting metrics and thresholds of discomfort, some of which have found conflicting results between the established metrics and comfort thresholds and what occupants have reported as acceptable (e.g., [11, 33]).

Recent studies have also integrated the use of dynamic shading with daylight-linked lighting controls such that daylight is used to reduce artificial lighting energy and associated internal gains. Lighting control is used for electric interior lights to maintain a work plane setpoint of 500 lx in most cases [14, 15, 17, 21, 28, 34, 35] and a setpoint of 300 lx in others (e.g., [16]), utilizing natural daylight combined with artificial light. Most of the studies with lighting control have utilized continuous dimming controls for the internal electric lights [15, 35–39] while some have used on/off controls [19, 40] or stepped dimming control [28]. This is understandable given that continuous dimming gives the largest range of possible scenarios to achieve maximum daylight with minimum lighting energy use.

In general, most studies have also focused on commercial rather than on residential buildings for dynamic shading and lighting controls studies. Of those papers that specifically focus on one building type, 5 cover residential (15%) and 29 cover commercial (85%). Given that lighting energy use represents an overall lower percentage of consumption in residential buildings than in commercial, the lighting energy savings in residential buildings is not necessarily considered as impactful [16]. However, as more people work from home, telecommute, or stay at home during the day, evaluation in residential buildings may be important to consider more carefully moving forward.

Dynamic Shading Testing and Evaluation Methods

To support control strategy and algorithm development, a range of methodologies have been utilized to assess performance of dynamic shading devices and associated controls strategies, including computer simulation-based and experimental-based testing methods. In addition, a range of evaluation criteria and performance measures have been created and used to assess system performance. Simulation methods have developed and improved significantly in recent years; the number of research efforts using experimental test methods has also increased, although it is still limited in comparison to simulation-based research. Of the papers reviewed, over 30 (59%) used simulation-based methods for part or all of the study, whereas 17 (33%) tested using experimental methods. In some cases, both simulation and experimental methods were used (16%), as discussed further below.

Simulation Methods

Simulation efforts have focused mostly on visual comfort evaluation using daylight simulation programs, and/or on energy performance and savings evaluation using energy simulation programs. Given that daylighting programs and energy simulation methods do not generally provide overlapping capabilities, many simulation-focused papers have focused on either daylighting or energy performance. When simulation is used for determining the performance of dynamic shading, accuracy in modeling of the thermal and optical transport through both the fenestration and shading device is of significant importance. Along with the accuracy, computational efficiency is also desirable, especially if the model is intended to be used as model in a model-based control strategy in real buildings where quick calculations are needed. Thus, recently, the work using simulation focuses on several different areas—(a) improving the computational methods and accuracy of models, (b) parametric studies, and (c) integration with building-level controls, and assessing building-level impacts, each of which is discussed herein.

Modeling Improvements

For (a), research has included making models more accurate and computationally efficient in terms of both shading device properties and controls [41–43]. In [21], the Radiance three-phase method [43] was used along with WINDOW7 [44] to improve characterization of optical properties and thermal and optical transport through complex fenestration systems. WINDOW7 has also been widely used for estimating the detailed properties of fenestration system both with and without shading layers [12, 14, 16, 17, 45]. Various studies have also improved on ray-tracing methods used in lighting simulation software such as DAYSIM [46], using hybrid ray-tracing and radiosity models for daylight and glare simulation [17, 45, 47, 48]. These have found to provide reasonable accuracy and less computation time compared to ray-tracing simulation.

Recent efforts have also used the shade position and lighting level output from DAYSIM as input in whole building energy simulation software to calculate the impact of daylighting on total building energy consumption [21, 49]. In many cases, this can also be facilitated using co-simulation tools that link external data as inputs into EnergyPlus. The reason for using such method was accuracy in daylight analysis being higher in daylighting software compared to energy simulation [50]. EnergyPlus uses the radiosity method for daylight calculation and considers all the light hitting the facade of a simulated building to be diffuse. Another limitation in using only whole building simulation software for shading control, specifically for roller shades, is that current simulation software only provides two possible heights for shading devices, either open or closed, to control a shading device. Hence, the implementation of advanced control strategies might be very challenging when using such software in a standalone manner.

Parametric Studies Using Simulation

Various parametric studies have also been performed using simulation, with the aim of assessing the impacts of variations in parameters such as window size, room orientation, and properties of glazing and shading devices. For such studies, using such a large number of variables would be costly and time-consuming if conducted using experimental testing. Hence, such situation simulation, if accurate, can provide significant insight on performance of different windows and glazing and shading types. A parametric study on slat dimensions and slat counts was performed [9] using a Honeybee plugin in Grasshopper based on Rhinoceros 3D [51] as an engine for Radiance, DAYSIM, and EnergyPlus. Similarly, a parametric study using ISE VE [52] studied the impact of various shading typologies on daylight metrics, glare indices, solar insolation, and solar heat gain coefficient (SHGC) [23]. A parametric study of different slat shapes to enable daylight adequacy while maximizing patient's external view access was studied by Sherif et al. [13] using Grasshopper plugin for the Rhinoceros modeling software [51]. Singh [15, 35] also studied the effect of various parameters such as different types of glazing, window-to-wall ratio, and orientation of window using roller shades [15] and venetian blinds [35].

New Approaches for Building Controls and Optimization Applications

In addition to parametric studies and model improvements, another focus includes the integration of modeled dynamic shading into the larger building controls and optimization rather than only considering the space directly interfacing with a dynamically shaded facade. For example, in [19], model predictive control (MPC) for interior roller shades was performed using EnergyPlus and the comparison of the performance of the MPC was conducted using a reactive conventional shading system. It was found that the MPC had the potential to achieve annual heating, cooling, and lighting energy savings of 12, 49, and 54% respectively, as compared to a conventional building control system. In another study [36], optimization was conducted using a genetic algorithm and EnergyPlus simulation on the operation schedules of window blinds to minimize overall building HVAC and lighting energy usage while providing visual comfort. Manzan [53] optimized the geometry and location of a fixed external shading device used in conjunction with internal dynamically controlled venetian blinds to provide optimal energy savings.

Experimental Testing Methods

As discussed, the number of experimental studies in the field of dynamic shading is more limited as compared to simulation studies. Some have focused on the use of illuminance-based shading controls and others on glare-based controls in a full-scale test setup, many of which also take advantage of the use of simulation combined with experimental testing to simplify the test setup and/or number of sensors needed. Others have evaluated occupant satisfaction and interaction with the shading and controls.

Illuminance-Based Control Evaluation

Karlsen and Heiselberg [7, 11] used vertical illuminance, solar irradiance, and cooling demand measurement as criteria to control shading devices using combination of external and internal venetian blinds. They used vertical illuminance to evaluate glare and a vertical illuminance threshold to control the slat angles. Carletti [8] controlled external venetian blinds at four pre-determined configurations based on external illuminance and temperature in residential buildings to study the impact on indoor thermal conditions. Some research has also used a combination of experimental testing and simulation. Shen and Tzempelikos [47] used full-scale experimental testing combined with simulation to study daylight-linked control which enables control of the shading device based on the transmitted illuminance from the window. Simulation determined the correlation between the transmitted illuminance and work plane illuminance such that desirable work plane illuminance could be maintained by varying the height of shading device based on the transmitted illuminance level from the window. The advantage of this method is that only one sensor was needed to control the shading device to maintain reasonable daylighting level and visual comfort throughout the room, rather than multiple sensors.

Glare-Based Control Evaluation

In order to experimentally evaluate visual comfort from dynamic shading applications, various approaches have been utilized, including, similar to those mentioned above, studies that utilize a combination of experimental testing and simulation. Bueno et al. [12] developed a controller which used real-time daylight simulation based on the three-phase method and bi-directional scattering distribution functions (BSDF) as substitute of illuminance sensors; experimental testing was used to test the prototype in rotatable test facility under multiple configurations. Several recent studies have also focused on the use of high dynamic range (HDR) photography for assessment of lighting conditions in an interior space to validate and/or calibrate simulation methods, and to provide control input data. Yun et al. [29] utilized experimental testing methods to evaluate the vertical illuminance values obtained using Evaglare. High dynamic range images (HDRIs) were taken with measured vertical illuminance in a mock-up room and a scale model then compared to Evaglare outputs. The daylight glare probability (DGP) from the HDRIs and DGPs measured in the mock-up room and the scale model were also used to determine correlations with vertical illuminance. However, the dynamic shading and lighting controls were not evaluated in the experimental test setup, and instead were performed using the DIVA-for-Rhino plugin for Rhinoceros for blind position and lighting level and EnergyPlus to calculate total consumption. Motamed et al. [32•] performed on-the-fly measurements of DGP using an HDR vision sensor to optimize the shading position and electric light control based on visual comfort. Unlike many of the experimental setups which use HDR images for assessment of lighting conditions [29, 45], here, the vision sensing technology was used for control purposes, where the discomfort glare measurement using the HDR vision sensor was used as an input of solar shading and electric light control system. In [10], shading control for an office with internal venetian blinds was performed using DGP calculations using a low-cost camera whose result was compared to the images taken with high-resolution camera. In the study, they concluded that further research and more extensive measurements are needed to verify the applicability of such system in broader context, but that the initial efforts showed promising results.

A central theme across these recent efforts appears to be a move to provide quality controls and evaluation methods but through innovations that reduce costs and improve simplicity. Given that lower cost systems that are less complex but equally reliable should be more desirable for implementation in real buildings, the results of recent efforts are encouraging. However, a challenge with comparison and evaluation of different full-scale test methods and their results is the variation in the test setups utilized to test the dynamic shading devices. For example, most experimental testing has focused on testing shading devices in the south orientation; however, several have focused on the other orientations as well. Window-to-wall ratios in the experimental test setups used also range significantly, from 32 to 70%, as have the dimensions of the rooms and the distance of the interior sensors and/or occupants from the exterior windows. Sky conditions are also an important factor that impacts performance; in many but not all of the recent experimental papers, sky conditions were reported.

Occupant Satisfaction/Interaction with Dynamic Shading

Efforts have also been made to evaluate user satisfaction and interaction with controlled shading as well as lighting system [7, 11, 30, 31, 40, 54], efforts that can really only be evaluated using experimental testing. Bakker et al. [55] controlled shading devices using various time intervals and various discrete steps with pre-determined positions for roller shades to study user satisfaction and distraction caused by shade movement. Occupant interaction with motorized roller shades and dimmable electric lights using different control interfaces and underlying variables was studied by Ahmad et al. [30]. Gunay et al. [40] developed an adaptive model which was based on lab-collected interaction of occupants with shading devices. Finally, automated blinds on a virtual window with artificial daylight were used for testing the effect of level of automation and type of system expressiveness (via interface) on user satisfaction [31].

Conclusions

Based on the results of studies assessing occupant interaction with shading and lighting controls, occupants consciously and actively close shading devices upon perception of glare and switch on lights whenever insufficient daylight occurs; however, they often fail to turn off the lighting or open shading devices when the conditions leading to visual discomfort disappear [40]. Hence, automated control of shading has continuously shown to be preferential to manual control. The results from various studies showed that automated shading devices have been found to provide better daylight performance and energy saving [9, 14, 16] compared to manually operated shading devices. From the review of the recent studies on dynamically controlled shading devices, various additional conclusions can be drawn, as follows. These also point to future research needs in this area.

- *Diversity of shading devices:* Most shading device types studied include roller shades and venetian blinds. However, several studies have shown that other shading device types show promise and thus may merit further study and comparison to more conventional shading methods;
- *Thermal and visual comfort evaluation needs:* Many research efforts have focused on evaluation of visual comfort of occupants; however, there are some differences in, in particular, the parameters and assumptions used for testing among the studies, which make comparison of results across multiple studies challenging. In addition, less effort has been placed on evaluation of thermal comfort impacts from dynamic shading, which may merit further study.
- *Energy savings and consistency of baseline conditions:* Various studies have studied impacts of shading devices on energy saving, particularly the advantages in cooling dominated climates [16]. Significant energy savings have been observed in various studies; however, there is still a need of identifying proper baseline case for the comparison of energy savings. Some studies have used no shading as the baseline case [34, 37, 45], while others have used either static shading control or simpler shading control strategy [9, 12, 19]. To identify the impact of static/dynamic shading on buildings, a common or comparable baseline should be identified for each of the cases.
- *Need for better and/or faster simulation methods:* Various simulation-based studies have assessed the impact of various parameters on different climates and orientations; such studies using full-scale testing might not only be arduous but also be nearly impossible in some cases. Thus, utilizing the results from full-scale experimental testing results to improve whole building energy simulation with accurate modeling of shading devices and controls is necessary. This creates a need for accurate and faster daylight modeling as well as flexibility of control strategy implementation used for shading devices in whole building energy simulation software to assess the holistic impact of complex fenestration systems in buildings.
- *Diversity of test conditions:* Most studies reviewed are focused in commercial buildings and mostly small office buildings with fenestrations in only one orientation, most commonly south. The interaction of more than one shading device in more than one orientation is discussed rarely. The simulation for multiple orientations is performed in a few studies [16, 18, 37, 47, 56]; however, none of the experimental studies have explored dynamic shading in multiple orientations. Although simulation has been performed for multiple orientations, most studies were only focused on one orientation at a time. This points to additional research needs in this area.
- *Lack of full-scale testing validation of simulation-based findings*: In general, there is a lack of full-scale testing results to validate simulation-based findings. On the HVAC side, the impact on cooling or heating obtained from dynamic shading and lighting controls is mostly assessed in simulation studies [14, 15, 19, 20, 34–36]. There are hardly any studies that have conducted experimental testing to assess the impact of dynamic shading and lighting controls on HVAC energy savings. Hence, additional full-scale testing is needed such that the results of this could corroborate the findings from simulation studies [57].
- *Addressing full-scale testing challenges:* One of the issues associated with automated shading devices which has been reported to occur in experimental testing is shade oscillation [16], which can occur specially during turbulent sky conditions [17]. This should be avoided to prevent occupant distraction from frequent movement of the shading devices. To overcome such occurrence, a variable interval logic was introduced by Xiong and Tzempelikos [17]; however, more efforts in this area would be beneficial to further address this challenge. Guidelines could be created to determine an acceptable time interval of adjustments to shading devices, considering issues such as occupant distraction issues, and impacts on dynamic shading device lifetime.
- *Occupant interactions:* Finally, in limited studies, interfaces which enable occupants to better understand and control the shading devices have been found to increase occupant satisfaction with the ability of occupants to override automated controls [31]. Most other studies have used fully automated systems without occupant interactions. Similarly, some studies have found that current metrics used to evaluate glare which are integrated into the automated control logic of dynamic shades are not always consistent with actual conditions occupants experience [10, 33]. Given the increase in focus on more interactive solutions, these initial findings showing occupant benefits point to additional needs for research in occupant interactions and opinions and their consistency with commonly used metrics.

Compliance with Ethical Standards

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