Glare-Based Control Strategies for Automated Roller Shades and Blinds in Office Buildings: A Literature Review

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Glare-Based Control Strategies for Automated Roller Shades and Blinds in Office Buildings: A Literature Review

Jiarong Xie[1], Azadeh Omidfar Sawyer[1], Ömer Tugrul Karagüzel[1]
[1]Carnegie Mellon University, Pittsburgh, PA, USA

Abstract

Automated shading systems have been used in office buildings to balance the benefits and disadvantages of daylight ingress from the window, and to create a more productive and sustainable work environment for the occupants. Previous studies have indicated that glare is the main factor driving occupants to interact with the shading devices, suggesting that glare prevention should be the primary goal for automated shading control. This paper reviews glare-based dynamic shading control methods from the literature, seeking to find or propose practical solutions that are capable of balancing control, cost, complexity and feasibility in real-world applications. Various control methods are categorized, and their advantages and shortcomings, as well as their performance and feasibility in practice, are described and discussed. The methods implemented by shading manufacturers are also summarized for a more comprehensive review. Conclusions and research gaps are summarized and suggested avenues for future research are presented. Addressing these gaps is critical for the optimal control of automated shading systems in office buildings, especially open-plan offices, to facilitate the continued progress of the sustainable building movement.

Introduction

Access to daylight has been shown to have significant benefits for office workers' health, productivity, well-being, and satisfaction (Al Horr et al., 2016; Aries, Aarts, and Van Hoof, 2015; Jamrozik et al., 2019). In typical office buildings, daylight is usually introduced to the indoor environment through windows. However, excessive and uncontrolled daylight from windows can cause glare and increase building energy demand. A balance between the benefits and drawbacks of daylight ingress is required to create a more satisfying and productive office environment. This balance can be achieved using building shading systems.

Building shading systems can be categorized as manual and automated systems. Manual systems are generally unsuccessful at optimizing glare prevention and daylight harvesting. Occupants commonly close manual shading devices to avoid glare and subsequently leave them closed for long periods of time (Gunay, O'Brien, Beausoleil-Morrison, and Gilani, 2017; Reinhart, 2004; Van Den Wymelenberg, 2012). In contrast, automated shading systems have been shown to be capable of effectively preventing glare and optimizing daylight access and energy demand. Research also suggests that interior automated blinds are more cost-effective than manual blinds over a 30-year time horizon (Nezamdoost, Van Den Wymelenberg, and Mahic, 2018).

Numerous studies have examined how to operate automated shading systems to improve occupants' thermal and visual comfort as well as building energy efficiency. Studies have specified that glare is the major factor causing occupants to interact with shading devices (Van Den Wymelenberg, 2012; Y. Zhang and Barrett, 2012), indicating that visual comfort is their primary requirement. Hence, a "glare-free" environment takes priority over other factors when designing shading control in office buildings.

Thus, this review concentrates on glare-based automatic shading control methods, with a focus on roller shades and blinds, as they are the most widely used and studied shading systems. There exist previous literature reviews on dynamic shading control, however, most focus on overall parameter design, energy savings, evaluation strategies, or specific control methods, without considering glare prevention as the main purpose of dynamic shading control (Konstantoglou and Tsangrassoulis 2016; Al-Masrani and Al-Obaidi 2019; Jain and Garg 2018; Colaco et al. 2012; Tabadkani et al. 2020). The advantages and disadvantages of various glare-based control strategies have not previously been comprehensively reviewed and compared. This review focuses on evaluation of different control strategies, accounting for glare prevention, complexity, feasibility and cost, and seeking to propose possible cost-effective solutions that can be applied in real settings, as well as providing insights for future research.

Shading/Integrated Shading and Lighting Control Methods

Blocking or redirecting direct sunlight

A typical example of this strategy is cut-off angle control, which is usually used for controlling blind tilt angle. As shown in Figure 1, cut-off angle is defined as the blind tilt angle beyond which no direct solar radiation can penetrate through the slats (Chan and Tzempelikos, 2013), and can be calculated using the solar profile angle:

$$\beta_{cut-off} = 90^{\circ} - 2\Omega \quad (1)$$

where β is the cut-off angle and Ω the solar profile angle.

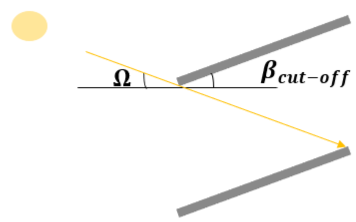

Figure 1. Cut-off angle of slat (adapted from Choi, Lee and Jo, 2017)

This shading control strategy is simple and easy to implement, which is why it is commonly used in commercial automated shading systems for open-plan office buildings (Iwata, Taniguchi, and Sakuma, 2017). However, it can fail to prevent glare when applied to slats with specular properties (Chan and Tzempelikos, 2013). For instance, the second reflection from the bottom surfaces of the slats to the indoor environment may still have high illuminance intensities as illustrated in Figure 2. It is also possible that reflected sunlight can be directed towards occupants when the cut-off angle is negative. It has been reported that blind manufacturers usually add an additional slats angle to the initial cut-off angle to meet occupants' requirements (Iwata, Taniguchi, and Sakuma 2017). Several studies have concluded that this strategy is insufficient to avoid glare (Chan and Tzempelikos, 2013; S. Zhang and Birru, 2012; Y. Zhang and Barrett, 2012).

To overcome the shortcomings of using cut-off angle control, Chan and Tzempelikos (2013) proposed a daylight redirection strategy based on cut-off control. Essentially, the slats are set perpendicular to the profile angle if a second reflection occurs. Meanwhile, the redirection angle is set to 30º, which would eliminate daylight reflection to the occupants in most cases. The slat tilt angle is calculated based on the blind geometry and occupant's position to the window. The maximum calculated control angle and the cut-off angle is selected as the final tilt angle of the slats. Simulation indicates that this strategy offers better glare performance than the cut-off control in winter. However, setting the slats perpendicular to the profile angle also blocks most of the useful diffuse light that could have been introduced into the indoor space. Similar to the cut-off control, it fails to prevent glare when the tilt angle is lower in summer. Another problem common to these methods is that they do not account for sky conditions. Under overcast skies, the tilted blinds will block useful diffuse light.

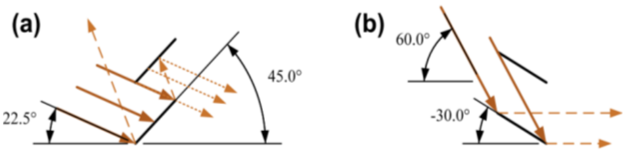

Figure 2. Scenarios when a cut-off angle approach fails to prevent glare: (a) second reflection from bottom surface, low profile angle/cut-off slat angle; (b) avoids second reflection, but transmitted light direction will cause glare, high profile angle/cut-off slat angle (Chan and Tzempelikos, 2013)

The original cut-off strategy was developed to adjust the slat angle of blinds. Zhang and Barrett (2012) developed a closed-form cut-off angle calculation method that can also adjust the height of blinds for glare control. The control logic takes an analytical solar angle model and window geometry as inputs. Illuminance on the exterior window is measured and the blinds kept fully open when the illuminance is below a threshold to allow diffuse light from overcast sky to enter. Experiments illustrated that the proposed method can successfully block direct sunlight while enhancing daylight harvesting. However, it should be noted that the introduction of sensors makes the control strategy much more complex than the simple cut-off angle strategy, especially in open-plan offices where multiple sensors would be required due to multiple windows. In addition, successful blocking of direct sunlight does not necessarily mean the system can effectively prevent glare, as glare can arise from other factors, such as a high contrast ratio between the window and the wall.

Sensor/meter-based glare control

1) Preventing glare based on direct sensor readings

A number of dynamic shading systems based on direct sensor readings have been developed over the years (Karlsen, Heiselberg, Bryn, and Johra, 2016; Lee and Selkowitz, 2006; Tzempelikos and Shen, 2013). This method is one of the most common strategies applied in commercial shading systems (Katsifaraki 2019). It commonly controls the state of shading devices based on direct measurements obtained by sensors, such as horizontal illuminance on the work plane (Lee et al., 1996), vertical illuminance at occupants' eye level (Karlsen et al. 2016) and solar radiation on the exterior window (Inoue et al., 1988; Tzempelikos and Shen 2013). A threshold value or range will be assumed to determine what actions should be taken in response to real-time daylight conditions. For instance, the slat angle of venetian blinds in a private office was adjusted based on the average measured illuminance on the work plane, to maintain the average lighting level within 540–700 lux (Lee et al., 1996). Inoue et al. (1988) developed an automated control method that operates blind occlusion according to the direct solar radiation on the window, with a threshold of 50 W/m^2. Karlsen et al. (2016) applied measured vertical eye illuminance on the sidewall and used a threshold of 1700 lux as the activation criterion to tilt the blind slats. This control strategy was found unable to consistently keep vertical eye illuminance below 1700 lux, which suggests challenges related to sensor placement, since there is no perfect correlation of vertical illuminance at two positions.

Compared with shading control that is based on sun positions, the application of sensors provide more accurate inputs and most often achieve better performance. However, this method has its own limitations. One of the main challenges is the placement of sensors. For instance, it is usually not practical to place illuminance sensors on the work plane because they could disturb or interfere with office workers. Additionally, the readings of some sensors (like illuminance sensors) might be influenced by occupants' activities, leading to irregular values and inappropriate shading system operation. Another shortcoming is that there is a wide disparity among the threshold values applied. For instance, the solar radiance used in shading control in the literature ranges approximately 100–450 W/m^2 (Van Den Wymelenberg 2012). It would be difficult to determine a threshold that can ensure elimination of glare. Moreover, this method could entail excessive cost and labor for the installation, calibration, maintenance and replacement of sensors, especially in open-plan offices. Additionally, the use of multiple sensors would also be limited by considerations of aesthetics and functionality in open-plan offices.

2) Preventing glare based on images captured by cameras

As excess brightness is not the only factor that can cause glare, researchers have proposed glare metrics that account for other factors, including indexes such as the Daylight Glare Index (DGI) (Nazzal 2001) and Daylight Glare Probability (DGP) (Jan Wienold and Christoffersen, 2006). The calculation of these glare metrics accounts for the brightness of the light source and the contrast between the light source and the background, as well as observers' position and view direction relative to the light source. Of the proposed metrics, DGP has been shown to predict glare from daylight most accurately in a cross-validation study (J. Wienold et al. 2019). It is also the most widely used indicator for glare evaluation (Chan and Tzempelikos, 2013; Xiong and Tzempelikos, 2016). According to Wienold and Christoffersen (2006), DGP is a function of the vertical eye illuminance as well as of glare source luminance:

$$DGP = 5.87 \times 10^{-5} \times E_v + 9.18 \times 10^{-2} \log\left(1 + \sum_{i=1}^{n} \frac{L_i^2 \times \omega_i}{E_v^{1.87} \times P_i^2}\right) + 0.16 \quad (2)$$

where E_v is eye-level vertical illuminance (lux), ω_i the solid angle of the glare source (sr); L_i the luminance level of the glare source (cd/m^2); and P_i the Guth position index expressing the occupants' sensitivity within their field of view.

Most other glare metrics include variables similar to DGP. As indicated above, the estimation of these glare metrics requires the distribution of luminance, which can be obtained using image sensors like high dynamic range (HDR) sensors. The captured images can be processed using computer graphic technology, the luminance distribution of the workstation visually rendered, and the glare index calculated, as shown in Figure 3.

An advanced glare control approach to operate automatic shading systems use these metrics or relevant parameters as the activation criteria. Several studies have investigated the performance of these shading control strategies (Goovaerts, Descamps, and Jacobs, 2017; Newsham and Arsenault, 2009). Notably, Newsham and Arsenault (2009) proposed a proof-of-concept prototype camera-based system to replace multiple sensors required for shading and electric lighting system control and first demonstrated its application in an private office. The roller blind is set to one of three positions: fully open, fully closed, or mid position based on sky-upper luminance. They found that the proposed control method was successful at maintaining the desired illuminance level on the work plane (mean ± standard error: 448 ± 28 lux). Overall energy consumption decreased by 10.7% compared to a lighting system with a fixed output of 450 lux and manually closed blinds. However, no glare metrics were reported in that study. Later, Goovaerts, Descamps, and Jacobs (2017) developed a shading control strategy to eliminate glare while optimizing daylight availability using a low-cost camera. DGP was used to evaluate glare, which was extracted from HDR images taken by the camera. The slats of the venetian blinds were rotated with a 10º interval at each time step according to the value of estimated DGP. The control algorithm was tested in a mock office and a real open-plan office with a single venetian blind. These experiments showed that the proposed control logic is able to provide sufficient daylight while maintaining the glare within an acceptable range. A subjective visual comfort evaluation from one participant indicated that DGP underestimates the impact of direct sun in some cases. Validation in the real office suggested that the proposed control strategy can satisfy occupants' visual comfort requirements well, with only one override instance of closing the blind out of a total of 252 system actions.

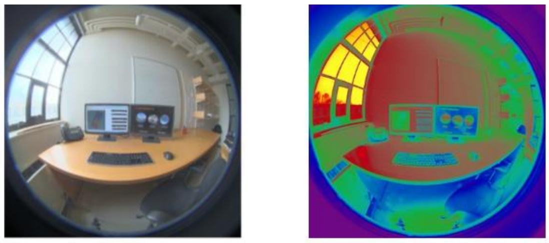

Figure 3 Original HDR photos (left) and processed glare images (right) (http://web.mit.edu/sustainabledesignlab/projects/VisualComfort/index.html)

Camera-based shading control demonstrates great potential in avoiding glare while enhancing daylight utilization. A single camera can replace several sensors required in a conventional shading control system. However, it should be noted that when applied in open-plan offices, a camera-based approach can also cause problems. Similar to the method based on direct sensor readings, multiple cameras would be required to employ this strategy in open-plan offices. All of the problems associated with using sensors apply to this method as well. More importantly, it may cause privacy concerns, making it impractical or infeasible in real office settings. Another drawback of this method is that the estimation of glare index depends on occupants' position and view direction. More cameras would be required to account for a greater number of possible sitting positions or view directions. Hence, researchers have usually assumed a fixed position with a fixed view direction. This assumption might not appropriately represent the real conditions experienced by occupants. Additionally, very few studies have examined its performance in real office settings. Evidently, more research with extensive measurements are required to test the validity of such approaches for glare prevention.

Model predictive control using real-time daylight simulation

With the advancement of simulation and modelling tools, simulation assisted control is gaining more attention (Chaiwiwatworakul et al., 2009; Chan and Tzempelikos, 2012; Katsifaraki, 2019; Xiong and Tzempelikos, 2016). The significant advantage of this method is its elimination of the need for multiple sensors while obtaining sufficient information for automated shading control. Typically, a pyranometer is used to measure direct and diffuse solar radiation, which provides sufficient data to allow for real-time daylight simulation. This method estimates real-time daylight glare metrics and sets a threshold to control the shading system. An example of typical blind control logic is illustrated in Figure 4 (Chan and Tzempelikos, 2013).

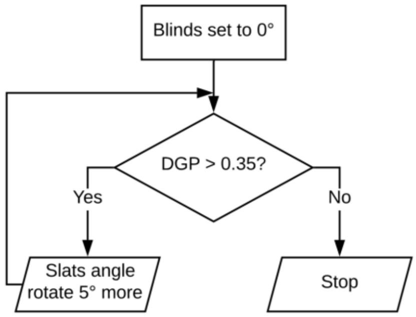

Figure 4 Flowchart of a typical approach to glare-based blind control (Chan and Tzempelikos, 2013)

Jain and Garg (2018) reviewed existing experimental studies on open loop control strategies for shades, blinds and integrated lighting that make use of real-time daylight estimations. Their review summarized the sensors used for daylight estimation and their calibration methods, the use of the daylight information obtained to estimate glare, and the various control methods and their performance regarding daylight access, glare, energy savings, and occupants' preference, concluding that real-time daylight simulation-assisted control strategies offer more benefits than conventional methods. Specifically, Xiong and Tzempelikos (2016) proposed a model-based shading and lighting control algorithm to minimize lighting energy use while avoiding glare from daylight. They implemented and compared three control strategies: glare-based, vertical eye level illuminance-based, and work plan illuminance-based, with respective thresholds of 0.35, 2500 lux, and 2000 lux. Eleven predefined discrete shading positions were selected based on the simulated illuminance or DGP value. They found that DGP-based and vertical illuminance-based control most often maintained DGP under 0.35 with sufficient provision of daylight, while work plan illuminance-based control led to glare risks, with occasional DGP above 0.4. During the summer, all three controls resulted in disturbing or intolerable glare, with DGP greater than 0.35, mainly due to direct sunlight penetrating the fabric. However, DGP-based control resulted in the smallest percentage of time with DGP above 0.35 (2.3%) and the fewest shade movements. This approach shows great potential in reducing shading operation and electric lighting use while maintaining the visual comfort of occupants. A more recent study developed a simulation-based shading control strategy, using maximum vertical illuminance at eye level to adjust the slat angle of blinds (Katsifaraki 2019). This method does not require detailed knowledge on occupant position. A fuzzy logic-based method was developed to assess the indoor visual conditions and determine the trade-off between the vertical and horizontal illuminance. This strategy performed well in preventing glare and providing access to daylight, as well as reducing the lighting energy use associated with normal blinds. However, the author indicated that the effectiveness of this method would be compromised with perforated and specular blinds by the resulting direct or reflected sunlight entering the field of view.

This simulation-based glare control strategy seems to be promising, even in open-plan offices. It can replace multiple sensors-one irradiance sensor on the roof top is sufficient to provide model inputs for the control of multiple shading devices. Simulation also allows for consideration of multiple sitting positions and/or view directions for more accurate glare prediction. However, there is currently a lack of advanced daylight simulation tools that enable incorporating parallel computing for fast simulation (Jain and Garg, 2018). More importantly, simultaneous real-time glare simulation for multiple workstation directions would require intensive computation, which could be problematic for the local controller. More accurate consideration of glare by accounting for various sitting positions and/or view directions would make the problem more computation intensive. Thus, a new method is required that would reduce the amount of simulation. To that end, Santos and Caldas (2018) proposed a heuristic approach that relies on spatial and time sampling to estimate glare. By correlating DGP and vertical illuminance, they found that the critical time and view direction pair can be identified and used to represent the glare condition at different locations, thus reducing the number of simulations required to evaluate glare. However, the performance of this method has not been assessed with experimental analyses.

Adaptive occupant-centric shading and lighting control

Several researchers argue that since there is large variability in occupants' visual preferences in indoor lighting conditions, automated shading control should include occupants in the control loop (Gunay et al. 2017). This type of control strategy is semi-automated. In contrast to fully automated control, it is capable of continuously learning occupants' preference through their interaction with the shading devices and lighting system to better satisfy their personal visual comfort requirements.

Recent research studies examining such control methods can be found in the literature (Gunay et al. 2017; Cheng et al. 2016). For instance, Cheng et al. (2016) proposed a satisfaction-based Q-learning strategy for integrated blind and lighting control. In the field of machine learning, Q-learning is a reinforcement learning algorithm that seeks to find the best action to take given a current state. In Cheng et al.'s study, the proposed control logic aimed to find the best blind position given occupants' current satisfaction of the visual environment. In particular, occupants' feedback (e.g., complaints about glare or a dim environment) are collected and sent to the controller via an interface. Together with measured work plane illuminance, the subjective information collected is used to build a visual comfort model to determine occupants' comfort level. Accordingly, the Q-learning controller will determine the control policy to adjust the tilt angle of the slats and the number of lights that are turned on. The proposed control logic was implemented in a private office with the participation of 12 subjects. The result showed the approach offered high occupant acceptance, with most participants (about 92%) assigning a relatively high score ($\geq$ 4)). The approach also resulted in lower energy consumption than manual control and higher energy savings than traditional integrated automated control. However, the test period was short (10 days) and the number of participants small (12 subjects, 7 of whom participated for only one day). Future research with more participants and a longer study period will be required to confirm the efficacy of this method. It should be noted that this method requires occupants to constantly report their feedback before the control logic converges, which can be quite disturbing to them. Hence, it is not practical in real-world settings.

In a similar approach, Gunay et al. (2017) developed a different adaptive system to integrated blinds and lighting control based on occupant behavior (Gunay et al. 2017). In particular, the strategy was based upon analysis of occupants' lighting and blind use behaviors in ten private offices with concurrent collection of solar irradiation, ceiling illuminance and occupancy data. A recursive learning algorithm was applied to predict the light switch-on and the blind closing behaviors of the occupants. Specifically, the algorithm aimed to identify the lowest illuminance level that would cause the occupant to close the blinds-closing action and the highest illuminance level that would cause the light switch-on action. This method allowed occupants to manually control the blinds and lights. The system's main task was to open blinds and switch off lights without increasing or decreasing the illuminance level to the upper or lower bounds. The control logic was implemented in a laboratory shared office space for over a year. Compared with the default manual control schema, the blind occlusion rate decreased from 18% to 12% and electric lighting use reduced by 22%. The system was generally accepted by occupants, with only 14% of automated blinds opening actions and 6% of instances of automated switching off of lights rejected. Annual simulation also revealed that the approach could reduce electric lighting use by about 25% without adversely affecting occupants' visual comfort. This type of method relies on collected occupant behavior data, which could be costly and intrusive. In addition, whether the model developed in one office can be generalized to a different office is unknown. Furthermore, similar to Cheng et al.'s (2016) study, this approach seeks to provide personalized visual comfort to the occupants, an approach that is difficult to apply in offices with multiple occupants present.

Glare control approaches that combine different strategies

As discussed above, none of the reviewed shading control strategies are always effective. Several researchers have come up with control methods that combine two or more of the aforementioned strategies (Karlsen et al., 2016; Shen and Tzempelikos, 2017). Karlsen et al. (2016) measured vertical eye level illuminance and exterior solar radiation and used them as the activation criteria for blinds. If the logic determines that the blinds should be open, a cut-off angle strategy is applied to adjust the slat tilt angle. The researchers reported that the proposed control strategy could balance energy use and indoor visual comfort. Another study by Shen and Tzempelikos (2017) proposed a simplified model-based roller shades control strategy. A new concept, "effective transmitted illuminance," was developed and defined as:

$$E_{eff} = \frac{E_g \cdot A_g + E_{sh} \cdot A_{sh}}{A_g + A_{sh}} \quad (3)$$

where E_{eff} is the effective transmitted illuminance, in lux; E_{g} and E_{sh} the illuminance transmitted through the unshaded and shaded parts of the window, respectively, in lux; and A_{g} and A_{g} are the areas of the unshaded and shaded portions of the window, in m^2.

The roller shades' position is determined in two steps. First, a preliminary position is determined based on solar profile angle and occupants' distance to the window to prevent direct sunlight from reaching the work plane. Second, the effective transmitted illuminance is correlated to the work plan illuminance using simulated or measured data. A threshold of 2000 lux is used to limit the work plan illuminance to prevent glare, thus limiting the upper bound of the effective transmitted and further determining the highest position of the roller shade. The final selected position of the roller shades is the minimum of the heights calculated in the two steps. The control strategy was implemented in a mock office for several months. Testing showed that this method could maintain the work plane illuminance between 500 and 2000 lux most of the time, with energy savings of 50–70% compared to no lighting control. This control logic can be applied to spaces with multiple shading devices. However, further laboratory and field tests are needed to support the study's conclusions. A shortcoming of this method is that it cannot prevent glare caused by sunlight penetrating the fabrics, a common drawback of roller shades.

Shading control accounting for visual and thermal performance

Aside from visual comfort and lighting energy use, the operation of dynamic shading systems also has a significant impact on occupants' thermal comfort and the heating and cooling energy consumption. However, most of the studies reviewed did not consider these aspects in parallel. Few studies have included monitored indoor temperature in the shading control loop (Karlsen et al. 2016; Katsifaraki 2019). Indoor air temperature is more usually compared to a threshold, such as a heating or cooling setpoint, and used as one of the activation criteria to adjust the states of shading devices. One recent study presented a unique method that applies radiance daylight simulation to estimate the solar radiation that enters from the facade and falls on the occupant's body to evaluate the impact of shortwave radiation on occupants' thermal comfort (Zani et al., 2018). The incorporation of such a method into automated shading control is both promising and necessary to account for both visual and thermal comfort.

Very few studies have incorporated heating or cooling demand or energy use information into the shading control loop. Yun, Yoon, and Kim (2014) integrated annual visual comfort and energy demand analysis to evaluate several shading control strategies using simulation tools including Diva-for-Rhino and EnergyPlus. Four static blinds positions and different light dimming levels were tested based on the simulated vertical eye level illuminance. However, this coupled simulation method can be extremely difficult to apply to real-time dynamic shading control due to its computation-intensive nature.

The Fener simulation platform was developed at Fraunhofer ISE to enable coupled thermal and daylight simulation for shading system in a computationally efficient manner (Bueno, Wienold, Katsifaraki, and Kuhn, 2015). The platform integrates thermal and daylight simulation on a time-step basis, so shading control methods that rely on thermal variables, such as indoor temperature and cooling load, can be simulated. However, this software assumes a shoe box geometry, and limits the application to one thermal zone. To the authors' knowledge, no other studies have used the coupled simulation functionality of this platform for dynamic shading control.

Shading control methods implemented by manufacturers

Various commercial shading control systems with the goal of achieving visual comfort, thermal comfort, and energy efficiency have been developed. In his PhD thesis, Katsifaraki (2019) conducted a market review of the available commercial systems with a focus on leading manufacturers in the field. The automated horizontal blinds and roller shades currently on the market are summarized in Table 1. Unsurprisingly, most existing commercial shading systems implement relatively simple control strategies, which could compromise their effectiveness. Novel methods that can balance the complexity and effectiveness will be required to improve the performance of automated shading systems in real-life application.

Table 1: Shading control methods implemented in commercial systems (Katsifaraki, 2019)

Shading control methods	Horizontal blinds	Roller shades
Programmed events - time-based, season based, occupancy-based	√	√
On-off depending on sensor measurements - photo-sensors, irradiance, temperature etc	√	√
Controlled daylight penetration depth - based on variable shade height	√	√
Sun-tracking system - according to the solar profile angle	√	×
Building surroundings information - taking into account major obstructions around the building	√ (Combined with the sun-tracking system)	×

Conclusion

This paper reviewed the current state of the art in glare-based shading control strategies, with a focus on venetian blinds and roller shades. The advantages and shortcomings of various control methods, as well as their effectiveness and feasibility, are described and discussed.

Methods for blocking or redirecting direct sunlight, such as cut-off angle control, are widely adopted in commercial systems due to their simplicity. However, these strategies are not sufficient to prevent glare. Control strategies that depend on readings or images captured by sensors are typically more effective than simply blocking or redirecting sunlight. As the number and type of sensors increase, the control accuracy and effectiveness can also improve. However, this is not an optimal solution, especially when contemplating scale implementation or application in open-plan offices with multiple shading devices. Additionally, image sensors can be difficult to apply in real office settings due to associated privacy concerns. An improved approach is to minimize the use of sensors with the assistance of the simple strategies like the cut-off angle control method. Model predictive control based on daylight simulations can prevent glare without excessive use of sensors. However, the lack of tools integrating real-time daylight simulation into the control logic and the intensive computation are major challenges. Less complex model-based control methods or simplified real-time daylight simulations are required. Adaptive shading control can provide personalized control based on occupants' preference. It is more suitable for shading control in private offices where the occupants have high requirements of the visual environment. However, this approach can be costly and quite challenging regarding data collection, which makes it infeasible in real office settings.

Methods that combine two or more of the above strategies may be the most promising and cost-effective solutions. However, more laboratory and field tests are required to test these methods' capability to eliminate glare, user acceptance, and energy performance. Return on investment analysis and life cycle assessment analysis may also be needed to evaluate their lifetime performance. Overall, most current shading control methods are integrated with electric lighting control for energy saving purposes. A few of them incorporate thermal variables in the control loop. The main obstacle is the lack of tools that allow for coupled daylight and thermal simulation.

This review of the literature has identified multiple gaps and areas for future study:

- Control strategies that are more effective in preventing glare without being too complex for application in real settings;
- Studies that focus on shading control in open-plan offices;
- More comprehensive methods for glare estimation that allow for consideration of multiple occupant positions and view directions;
- Field studies that test the performance and user acceptance of different control strategies;
- Studies coupling visual- and thermal-based shading control;
- ROI analysis and LCA analysis of various control methods;
- Methods that can simplify or reduce the simulations required for model predictive control.

In conclusion, mixed methods that combine multiple simple shading control strategies could be an attractive alternative to current solutions. It is possible to optimize the operation of automated blinds and shades in a manner that accounts for both visual and thermal comfort, as well as energy efficiency. However, future research is required to develop and optimize these methods for real-world applications.

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