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A review of open loop control strategies for shades, blinds and integrated lighting by use of real-time daylight prediction methods

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ABSTRACT

Automated shading and integrated lighting control systems are being used in buildings for electrical energy savings and improve occupant's comfort. These systems facilitate effective utilization of useful daylight in interior spaces that benefit an occupant's health, well-being, and productivity by preventing glare and overheating while maintaining the adequate illuminance levels. The pragmatic procedure to implement open loop shading and integrated lighting control comprises three parts: (i) a reliable estimation of sky conditions on real-time basis, (ii) determining indoor daylight metrics using outdoor conditions, and (iii) incorporating the metrics in the blind and integrated lighting control techniques. This paper presents a review of experimental studies done on open-loop window shade and integrated lighting control strategies. The aim of this paper is to analyse the performance and feasibility of various daylight prediction methods and their application in controlling blinds and integrated lighting system. The review mainly focuses on simulation assisted open loop control techniques that employ real-time daylight estimation methods. The review identifies the current challenges, recommends areas for improvement, and provides significant scope for future research. The paper concludes that modified and improved open loop system are more competent as an alternative compared to the conventional methods for automated blind and lighting control systems. Advanced open-loop control systems along with calibrated simulations have the capability to reduce post commissioning errors, allow easy monitoring of the system and predict daylight more extensively.

1. Introduction

Daylighting in buildings is one of the indoor environmental factors that have a substantial impact on workers' health, productivity, performance, and circadian system [1,2]. However, excessive and uncontrolled daylight admission into a building can lead to visual discomfort, and higher cooling and heating demand due to which occupants prefer to close the window blinds and use artificial lighting instead of using natural daylight hours [3]. In case of manual blinds, they remain either fully open or closed; occupants rarely operate them, and when they do, it is usually to prevent visual discomfort while facing glare [4–6]. However, shades and lighting remain in the same state even when there is no discomfort. This scenario often leads to increase in building energy demand and the inability to access outdoor views. Integration of automated window blinds with artificial lighting controls can help modulate daylight, overcome glare and heating problems [7,8]. This mechanism can be significantly beneficial to occupant's comfort, health, and productivity; and reduces the cost of energy demands for cooling, heating and artificial lighting [9,10]. It has been reported in previous studies that integrated daylighting systems can save up to 30–80% energy [11,12]. Studies show that building occupants can reduce energy consumption by more than 40% while using daylighting rather than artificial lighting [13]. For designing an effective control system, it is necessary to study an occupant's behaviour patterns, blind properties, building and room geometry to gain overall user satisfaction and energy savings [14,15].

Control strategies for blind and artificial lighting are broadly divided into open loop and closed-loop control systems. Closed loop system receives feedback whereas open loop does not. In a conventional open loop control system, the photo-sensor is positioned only to detect daylight and thus it is insensitive to the artificial light that it controls (no feedback). In the past few years, the industry of motorized shades, lighting control, and daylight harvesting system is playing a significant role in smart and intelligent buildings. The current state-of-the-art feature for modulation of daylight and artificial light employs automated window blinds with photometers either in an open loop or closed loop control system. In the open loop systems, sensors are mounted at the external surface of façade to measure sky conditions and daylight

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availability. A typical commercial closed-loop system usually has a series of indoor photosensors integrated with dimmers to maintain desk illuminance levels. Previous studies have pointed out that daylight linked control systems are not so far-flung due to the difficulty in calibration and installation of sensors [16,17]. Open loop systems offer greater flexibility in calibration than closed loop [18]. In a closed-loop system, sensor placement has to be done carefully and with calibration, unlike open loop systems. In a closed-loop system, calibration factor needs to be determined for the difference between photosensor signals (mounted on the ceiling) and work plane illuminance for both day and night time [19–21]. This process leads to inaccuracies in control decisions. As per the report by Lee et al. [22], the complicated and expensive calibration process involved in daylighting systems is among the several other challenges to make the daylighting strategies feasible. Furthermore, sensors in closed loop system are costly to install at each desk, challenging to commission, and hard to calibrate; therefore highly prone to errors. As per the study conducted by Berkeley Lab (LBNL) on New York Times Office building [23], the most significant barriers in adopting these technologies are lack of products available in the market to meet current needs, uncertainty in their performance and lack of operational understanding. The study conducted by Delvaeye et al. [24] monitors three different daylight control strategies in a school building for a year. The results show that open loop control system yields considerable energy savings when compared to the closed-loop system.

There are a lot of methods that use conventional open loop system (Fig. 1) based control for blind and lighting. With the advancement of simulation and modelling tools, simulation assisted improved open loop controls are gaining attention in previous research works [25,26]. Utilization of virtual sensors in the simulation model instead of real sensors has been evaluated and is reported to be more effective [27]. In recent times, there is more preference given to products based on personal controls and IoT based smart control system. Building performance simulation tools are widely practiced in the design process and have become mandatory for code compliance in many countries. Fig. 2 depicts the modified open loop control that utilizes the simulation model integrated with daylight prediction sensors. This system employs simulated indoor metrics for performing the blind and lighting control. In a study done by A. Mahdavi et al. [28], simulation model is updated real-time as per the changes done in blind and lighting conditions. Indoor visual comfort parameters are measured again by performing daylight simulation, and control is executed to reach the desired comfort metrics. In addition to this, few recent works demonstrate the blind control methods based on artificial neural networks [29], fuzzy logic [30], and occupant usage pattern [6,13]. It has been reported in the studies that artificial neural networks can be trained to precisely predict the daylight illuminance [31] and energy savings due to daylight harvesting systems [32].

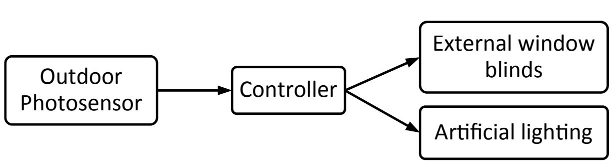

Fig. 1. Conventional open loop control system.

In recent years, there are some reviews presented in the areas of daylight harvesting and lighting control methods [15,33–35], and energy savings potential of daylight and lighting control technologies [36–39] that very well entail the current state-of-the-art in control system and corresponding energy savings. However, there is a lack of review studies done on open loop blind and lighting control strategies and very less focus is imparted towards the stages preceding the control process. These stages include accurate estimation of daylight inside a building, calibration methods incorporated for sensing and modelling the daylight and sky conditions, and integration to control strategies. The first step in formulating the open loop blind and integrated lighting control strategy requires the estimation of daylight infiltrating the building premises, especially where control needs to be implemented. Control can be performed either by directly implementing daylight data or by calculating the indoor daylight metrics.

This paper provides a comprehensive review of current practices in open loop blind and integrated lighting control strategies that include the daylight and sky condition measurement, and methods for obtaining the indoor daylight metrics. This article is divided into the following sections that discuss the processes in implementing the control strategies using open loop methods:

- Section 2 presents the methodology that explains how and from where the relevant literature is searched, and the criteria for selection and evaluation.
- Section 3 reviews various sensors used in literature for daylight estimation and their calibration methods.
- Section 4 discusses utilizing the outdoor sky and daylight information obtained for calculating indoor daylight metrics for illuminance and glare.
- Section 5 presents the review of open-loop control methods and strategies based on glare, illuminance levels, energy savings and occupants preferences for controlling blind and lighting system.
- Section 6 provides the conclusion of the paper and also presents the potential research and development work based on the review conducted.

2. Methodology

A systematic and thorough search of scientific studies has been conducted to gather literature eligible to the review article. This section provides detailed explanation on literature search, inclusion and exclusion criteria, division of the article, and keyword classification.

2.1. Literature search

The literature search is first carried out in general web bibliographic databases such as ScienceDirect, Google Scholar, SAGE and Scopus. Then in topic specific journals and conference such as Lighting Research and Technology, Journal of Building Performance Simulation, Journal of the Illuminating Engineering Society and International Building Performance Simulation association. A search was conducted on leading publications (Windows and daylighting group at LBNL, MIT Sustainable design lab) and websites of researchers and scientists (Christopher Reinhart, Ardeshir Mahdavi, Eleanor Lee, Mehlika Inanici) to find information in the field of daylight and controls. Special issues of

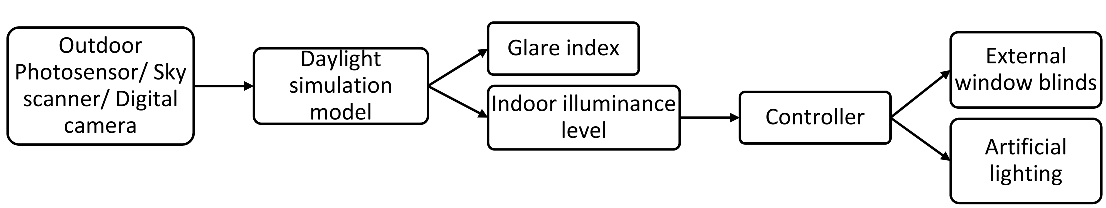

Fig. 2. Modified open loop control integrated with real-time daylight modelling.

the journal Building and Environment on "Advances in daylighting and visual comfort research" and the journal Energy and Buildings on "Energy efficient lighting strategies in buildings" were searched. Some of the searches led to review articles on lighting and blind control, daylight harvesting system, and visual comfort analysis [15,33–39,81]. The references in review articles led to further studies relevant to this review. Table 1 presents the section-wise article distribuion found on mentioned databases.

2.2. Inclusion and exclusion criteria

The search for studies that have implemented open loop blind and lighting control strategies was done and only a few papers resulted in the search [4,6,13,24–26,28,40,42,55,58–62,70,79,80]. These papers are more focused towards the control part. Since the open loop control strategies require real time daylight data therefore, it was decided to include studies that show real time daylight estimation methods and sensors, their calibration, obtaining glare and indoor lux levels using daylight data. This will provide better insights of other stages that are essential for open loop control. All the papers that met at least one of the following criteria are reviewed:

1. The paper should be either an experimental or combination of experiment and simulation study done for open loop blind or lighting or integrated control.
2. It should have at least one real-time sky or daylight measuring sensor with its calibration procedure.
3. It should demonstrate at least one method to calculate daylight glare and illuminance inside the room using daylight information.

Closed loop control strategies are excluded from the review.

2.3. Keyword analysis

The main objective of the article is to review open loop control strategies and steps prior to control. There are two major categories for defining the keywords; (1) open loop blind and lighting control and, (2) daylight estimation and indoor daylight metrics calculation. Based on the inclusion criteria, various combinations of the terms "open loop", "blind/lighting control", and "real-time sky/daylight estimation", "daylight glare control", "visual comfort" are found to be the most relevant keywords to conduct the search. In Scopus and ScienceDirect, it is possible to conduct refined search. The subject areas are kept limited to Engineering, Energy and Environmental Science in Scopus and similar publication titles are selected in ScienceDirect. In Google Scholar and SAGE there is no such filter based search, so the articles are sorted by relevance.

A text mining tool called VOSviewer that create bibliometric network has been used [82]. We used it to analyse co-occurrences of terms found in Title, Abstract, and Keywords field in the literature collected. The terms with minimum of 10 co-occurrences are filtered and mapped in VOSviewer. The terms as per their co-occurrences are then clustered and visualized. This method allows systematic analysis of keywords, research trends and frequency distribution of terms in reviewed papers. Out of all the references, 65 were downloaded from Scopus and rest of them from the sources mentioned in section 2.1. Fig. 3 is the network visualization that shows the connection and density of the terms. The

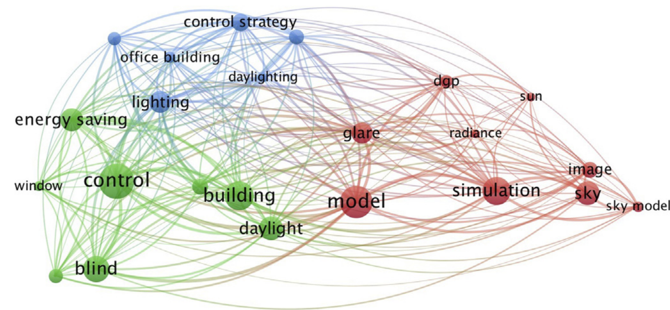

Fig. 3. Network and density visualization of most occurred terms in Abstract & Title fields of reviewed literature.

Table 1
Section-wise article distribution.

Section	Articles found	Date searched
3 Methods for estimating the sky and daylight conditions 4 Determining indoor daylight metrics using outdoor information	[4,6,9,19,24–28,40–78]	10/02/18
5 Window blind and integrated lighting control methods	[4,6,13,24–26,28,40,42,55,58–62,70,79,80]	10/02/18

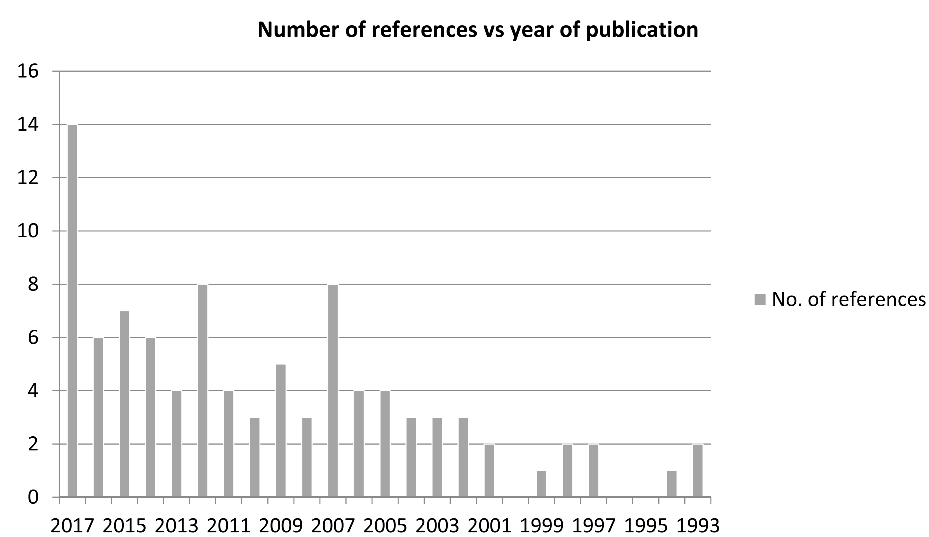

Fig. 4. Chart showing number of references to the year of publication.

size of the circle around a term is as per its co-occurrence. Higher the occurrence, greater the size. The colour is determined by the cluster they belong and lines represent links between the terms. Fig. 4 shows the number of publication in each year from 2017 to 1993. It is clear that the research on simulation assisted control system is published more in recent years.

3. Methods for estimating the sky and daylight conditions

The accuracy of daylight simulations is highly dependent on the luminance contours of the sky [44]. To control the window blind and lighting system so that it meets the minimum illuminance levels and prevents daylight glare requires both indoor and outdoor illuminance data. In this section, various sensors to predict the available daylight are discussed in detail. All the literature reviewed in this article has at least one sensor placed outside to record and predict daylight information.

3.1. Physical sensors

3.1.1. Sky scanner

Different models of sky scanner are designed to measure luminance, radiance, or both. The scanner divides the sky hemisphere into 145 equal solid angles (Tregenza sky model) to measure sky luminance distribution of each patch in one single scan (see Fig. 5). In few studies, Eko sky scanner measured the sky luminance and this information is used to calculate daylight illuminance [53–57]. There are other studies that used the sky scanner to compare various sky models [83–85].

For example, Li et al. [54] have compared the measured sky luminance from a sky scanner with modelled sky luminance from Perez model [86] and Kittler's model [87] for predicting the vertical outdoor illuminance. The results for all the cases show that luminance measured using sky scanner estimate the daylight illuminance more accurately followed by Kittler and Perez model. A more straightforward method using lighting simulation to predict vertical daylight factor is shown by Li et al. [53]. Another study has used a physical scale model to predict daylight illuminance, and it is validated using sky scanner data [56]. Sky luminance data from sky scanner is also applied in automated blind control as per daylight availability [55].

Although this is a very accurate and efficient instrument to model daylight by calculating luminance distribution of sky, it is rarely deployed to control window blinds. A comparison study [66] of PRC Krochmann and EKO sky scanner has reported considerable variance in case of clear skies. Moreover, sky scanner is expensive when compared to photosensor and pyranometer for daylight measurement. There are only a few manufacturers of sky scanner available in the market. Therefore, it becomes difficult to compare their performance and select a model.

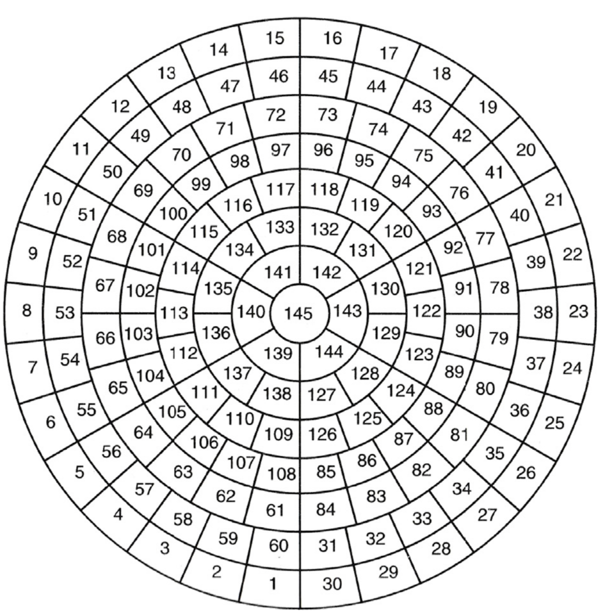

Fig. 5. The sequence of the 145 measurement points for sky scanning (Each patch shows its number) [83].

3.1.2. Sun/solar tracker and sun angle sensor

Sun Trackers are used to accurately position solar sensors towards the sun and to expose or shade a sensor from the direct sunbeam. Two modes primarily control them; sun sensor mode (closed loop) and calculation mode (open loop) [88].

A Sun angle sensor developed by LBNL in a study [58] determines the sun's altitude required to block the direct sun using automated shading device. For a similar purpose, sun tracker is used by Chaiwiwatworakul et al. [55]. The application of sun tracker is limited to block the direct sun as it is not used in literature to determine daylight illuminance and sky luminance values which are crucial for blind and lighting control strategies. Hence, it has to be used along with other sensors to predict lighting levels.

3.1.3. Pyranometer/irradiance meter

A pyranometer is designed to measure solar irradiance (solar radiation flux density in W/sqm.). They are classified into two broad categories based on the technology used; thermopile technology and silicon semiconductor technology. The type of pyranometer decides the spectral response obtained. Pyranometer is the most commonly used sensor in previous literature for open loop blind control purpose [4,6,9,19,24,26,28,40,42,55,59,60]. In few studies, pyranometer is used along with illuminance sensor, a sun tracker, and sky scanner instruments and sometimes with a personal weather station to calculate illuminance levels and sun's position [5,6,9,26,28,40,42,60]. A control algorithm considering values of illuminance, solar profile angle, sky ratio, and glare index is set to control the window blinds or slat angle. Another study has used the global and diffuse horizontal irradiance data from pyranometer to calculate sky ratio; as per the value of sky ratio slat angles set to cut off direct sunlight [55]. In a study by Gunay et al. [6] solar irradiance data on the building facade is plotted against the ratio of electric lighting switched on and blind occlusion rate to find out if daylight availability has any impact on occupant's behaviour. As per the results, it is found that change in solar irradiance values affect the blind closing behaviour of occupants. Therefore, solar irradiance data is acknowledged for the blind control algorithm which is discussed in the next section. Solar irradiance data is also utilized to validate a sun sensor which determines the position of the sun and detect the presence of direct sun at the window [9]. Again, pyranometer only gives quantitative information of solar irradiance that is used mainly for cut-off control strategy.

3.1.4. Outdoor illuminance sensor

Photometric or illuminance sensor measures the amount of light illuminating and spreading over a given surface area. Illuminance is luminous flux per unit area measured in foot-candles (lumen per square foot) or lux (lumen per square meter).

In few studies, exterior illuminance sensor is used to calibrate the sky model created from digital sky images by comparing the global horizontal illuminance from the sensors [25,26,28,40,42,43]. The calibration procedure using illuminance meter is briefed in the next section. In another study illuminance sensor is used along with a sky scanner unit to calculate daylight illuminance through the window employing various algorithms for determining daylight reflections and daylight illuminance in the interior [55]. This information is used to cut off direct sun angle by changing blind slate position. Similarly other studies have used illuminance sensor to measure outdoor illuminance for setting the slate angle and occlusion index to control glare and indoor illuminance levels [4,9,24,58,60,89,90]. A research done by Lee et al. [60] has a weather station mounted with an exterior illuminance sensor to record global and diffuse horizontal exterior illuminance, horizontal global solar radiation, and outdoor temperature.

The major shortcoming of using an illuminance meter alone to predict daylight conditions is that it may not work for all the types of sky conditions as it considers only the lux levels. It has been reported that photo controlled blinds may not always perform as expected or adjust in optimum amount especially in the case of the cloudy skies since it fails to consider the spatial dynamics of the sky [7].

3.1.5. Digital camera/image sensor

Deploying digital cameras to predict indoor daylight availability for controlling blinds and electric lighting is relatively emerging technology. Previous studies have shown that digital sky images can produce accurate sky luminance distribution that can be used as sky model for daylight simulations [27,41,43,44,46–48,50,63]. The methodology followed by few studies have used a digital camera with fisheye lens and an illuminance meter in a sky monitoring device [25,26,28,40–43]. Illuminance measurements taken from the sensors are used to calibrate the digital images for which images are divided into a different number of patches. Sky luminance maps are created using these calibrated images which are further used in the simulation model to predict daylight. Calibration procedures followed here are compared with photometric measurements; then the method with the best correlation is preferred. Various control algorithms based on daylight illuminance levels, indoor lighting levels, and user preferences are employed to control window blinds. Some studies have used a personal weather station to measure external illuminance and solar irradiance data for calibrating sky images captured from a digital camera to create a sky model [26,28,40,42].

The experiment performed by Borowczyński et al. [49] has shown that a digital camera alone as a single sensor can be used for open loop window blind control without taking any photometric measurements. The workflow includes achieving sky luminance distribution maps by high dynamic range imaging and blind slat control decision based on sky types. The control algorithm is valid only for the window visual range of sky as a limited part of sky is seen by the window. Their application is extended further to assess glare [47] and predict indoor lux levels [27] for blind [49] and lighting control [40]. As evident from previous studies, it is feasible to have reliable predictions of daylight level by simulating image based sky models. However, they are labour intensive, require proper calibration and validation against measured values [45]. Nonetheless, digital cameras are more affordable when compared to highly expensive sky scanners. Digital cameras have capability to replace sensors such as photosensor, pyranometer and luminance meter to control blind and lighting [61].

3.2. Calibration techniques used for various sensors

Calibration is needed for all type of sensors to ensure accurate and reliable prediction of daylight availability. Only few of the previous studies have mentioned about the calibration techniques used for the sensors. A brief of these techniques are provided below.

3.2.1. Digital image calibration

HDR image based sky model presents an alternative to mathematical sky model used in simulation tools [50–52]. It has been reported previously that mathematical models of the sky are incapable of considering the actual sky luminance distribution [44]. HDR image based sky model can be added to lighting simulation using Image-based lighting (IBL) technique to model the sky dome over a simulated space [46,91]. To implement this method a backward raytracing engine RADIANCE [92] is used for lighting simulation purpose though, accurate post-processing and calibration of images are required before using them for lighting simulation to obtain point-in-time daylight metrics. The first step is to create an HDR image by fusing the multiple exposure sequence images. Some studies have used a tool called Photosphere [93] for this task that calculates camera response curve by in-built calibration algorithms [46,51,52,59]. Most of the studies have performed scale correction, lens vignette correction, geometric correction and few of them also included a neutral density filter in mapping the luminance of sun [27,46–48,50,94]. In few cases HDR images of the sky are used as an environment map (vertical fisheye image taken outside the window) to obtain more accurate predictions of luminance and interior illuminance levels [27,44,46,47].

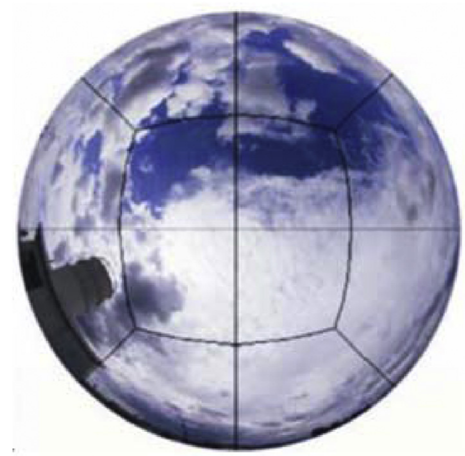

Fig. 6. Fisheye sky image with 12 projected sky patches taken using sky monitoring device [43].

Some of the studies have followed a slightly different calibration procedure that has been described by Mahdavi et al. [43] [25,40,42]. The method considers a pattern of 256 patches on the sky image and for each patch, sky luminance is calculated as per the algorithm [95]. It takes the values of the image pixel and camera metadata as input; calculates the luminance value at each given pixel for creating sky luminance distribution map. These maps are calibrated using three alternate calibration methods that vary in sky area divisions. The calibration methods are compared using three different experimental cases to measure the sky illuminance: a sky monitoring device, a scale model, and measurements taken in real space as the base case. The sky monitoring device used by Mahdavi et al. [43] consists of 12 illuminance sensors to measure 12 sky patches and a digital camera with fish eye lens to capture the sky as shown in Fig. 6. All three methods are compared with measured photometric illuminance values. It is reported that digital image based sky presents reliable daylight simulations when compared to measured value. However, the calibration method requires a lot of sensors to set up the sky monitoring device and a very lengthy workflow as compared to other methods.

A research conducted by Borowczyński et al. [49] has followed radiometric, photometric, and spatial calibration methods as described by Jacobs et al. [51] that make use of high dynamic range (HDR) images. Another method to calibrate the HDR images for glare evaluation is by using a Minolta luminance meter and performing calibration in the tool Photosphere [59].

3.2.2. Non-imaging sensors calibration

Some of the studies that have performed calibration for the sensors; pyranometer and photosensor are discussed under this section. Others have mentioned using industry manufactured calibrated sensors within some reported errors for daylight calculation and control [55,56]. In a study conducted by Yun et al. [59], normal and diffuse solar irradiance is measured using a Pyranometer with shadow ring, and a correction factor is applied as per Muneer and Zhang correction model [96].

Muneer's method [96] is based on anisotropic sky-diffuse distribution theory to correct diffuse solar irradiance measured using shadow ring. It takes zenith radiance and view angle subtended by shadow band at the sensor as input. This method provides a correction factor which is multiplied by the measured diffuse irradiance to get corrected diffuse solar irradiance. The standard calibration of pyranometer is done against pyrheliometer by taking readings in clear sky scenario with shaded and un-shaded pyranometer and comparing it with pyrheliometer [97]. It requires first calibrating the pyrheliometer itself. The calibration technique used by Tzempelikos et al. [64] for Li-cor photometric sensors uses a standard lamp of known luminous efficacy (683 lumens per watt) to calibrate the sensor against the lamp. The sky scanner is calibrated by adding a correction factor that fluctuates around 1 and the factor correlates with clearness of the sky [56].

3.3. Summary

Most frequently used sensor is outdoor photosensor mounted on the window façade and pyranometer to get global horizontal illuminance and irradiance values. Though photometric devices such as irradiance sensor and photosensor yield the correct daylight information; they do not provide any luminance distribution of real-time sky condition. For predicting reliable daylight information, it is recommended to have accurate sky models [53–57]. This can be achieved using sky scanners and digital camera. Most of the sensors employed in open loop controls require calibration that could be a labour intensive and error prone procedure to perform. There are very few sensors that can be used independently for control applications. Table 2 presents a comparative analysis of the sensors discussed in previous sections with reference to studies.

4. Determining indoor daylight metrics using outdoor information

This section describes the methods exercised in literature to calculate daylight illuminance levels, window luminance, and daylight glare index in interior spaces utilizing the data from outdoor sensors. The contribution of daylighting in indoors is predicted to analyse the area qualitatively and quantitatively for deploying blind and lighting controls. Glare and illuminance levels can be obtained by performing virtual simulation and also by numeric algorithms employing solar angles, envelope properties, and outdoor environment information. Some techniques are the combination of both simulation and calculation. A combination of experimental and simulation methods for determining illuminance levels and daylight glare index are analysed and discussed in the following sections.

4.1. Illuminance levels

4.1.1. Numerical methods

There are various numerical methods used in literature that employ mathematical equations to calculate illuminance. In an experimental study conducted by J. Hu [56], interior illuminance levels are recorded in a scaled physical building model in the presence of a scanning sky simulator. The method is validated by calculating illuminance in the physical model under real sky conditions using daylight coefficient approach that employs sky luminance data from a sky scanner [98]. The result shows a difference of 10% between predicted illuminance values using scanning sky simulator and real sky. Another study [55] calculates daylight illuminance through the window using methods adapted from Engineering reference of EnergyPlus [68]. Daylight illuminance is calculated by the input of slat geometry, slat transmittance, and reflectance, solar profile angle, normal beam illuminance, sky and ground luminance. Various physical sensors are used to provide the input values. Optical properties of slat and window are measured using a spectrophotometer. Normal beam illuminance is recorded at a 5 min interval, utilizing a sun tracker. Sky luminance is measured using a sky scanner.

Table 2
Classification of methods by outdoor environment information used via sensors placed outside.

S. No.	Outdoor Sensors	Purpose	References	Calibration	Strengths	Weakness
1	Digital camera	HDR sky imaging for generating sky model	[25–28,40–52,63]	Corrections such as scale correction, geometric correction, lens and vignette correction are required along with post processing of images.	Can be used to simulate virtual sensors accurately, hence possibility of replacing indoor lux/ luminance sensors. Can be used independently. Provides qualitative information for sky modelling.	Computer-intensive approach and requires proper calibration
2	Sky scanner	To measure sky illuminance, irradiance, and luminance	[53–57]	Industry manufactured, pre-calibrated sensors with some reported errors in clear and sunny skies. Sometimes a correction factor is added for clear skies.	Pre-calibrated scientific instrument that measures sky luminance precisely, less prone to errors.	Expensive instrument and very few models available
3	Sun tracker and Sun angle sensor	To determine sun's altitude and measure beam normal illuminance and irradiance	[55] [58]	Industry manufactured, pre-calibrated sensors with some reported problems of stability loss pointing at the Sun near the Zenith.	High end research instrument, also useful in case of integrated PV applications	Expensive instrument, involves monitoring, can't be used individually, needs calibration
4	Pyranometer/Irradiance meter with or without shadow ring	To measure direct and diffuse solar irradiance	[4,6,9,19,24,26,28,40,42,55,59,60]	Calibration is required to correct diffuse solar irradiance when used with shadow ring.	Easily available, and most commonly used. Can be used independently for cut off control strategies.	Requires calibration and only applicable for cut off strategy
5	Exterior illuminance sensor	To measure global and diffuse horizontal illuminance	[4,55,60–62]	Photosensor and lux sensors are calibrated against a lamp of known efficacy using an integrating sphere. Indoor photosensor are calibrated against an outdoor sensor.	Easily available option with many manufacturers to compare.	Requires calibration and expensive to install over each window pane
6	Outdoor Photosensor	To measure outdoor vertical illuminance	[7,9,24,58,64,89]		Easily available, and most commonly used. Can be used independently for cut off control strategies.	Requires calibration and needs to be installed on each window/façade

Table 3
Daylight Simulation software and methods used in literature.

S. No.	Simulation method used	Simulation tools used	References
1	Backward ray tracing	Radiance, Diva for Rhino, Daysim	[6,26,27,40,42,44,47,48,59,62–64]
2	Radiosity	Dialux	[24,64]

To obtain the final daylight illuminance at any patch in the interior of the room, proportionate contribution of reflected daylight from slats as a direct light flux at that patch is calculated. The method for this calculation is adapted from the report on Daylighting coefficient of utilization tables [99]. All the algorithms used to calculate daylight illuminance in the room interior are coded in Visual Basic 6 and compared with measured values.

A study done by Tzempelikos et al. [64] has calculated blind slat illuminance instead of task illuminance to control the artificial lighting. First, it calculates the window transmittance by using two pre-calibrated photometric sensors positioned on the exterior and interior of façade. The window with venetian blind is simulated in a radiosity model with measured beam and diffused transmittance values using CIE and Perez sky model to predict luminous emittance of blind. The interior illuminance of blind is estimated through the simulation model using the method described by Murdoch et al. [100]. Measured and modelled transmittance and lux values are compared for different blind angles by conducting full-scale experiments. The difference between measured and modelled values lies within a 10% limit. Based on the blind slat illuminance, a dimmable luminary is controlled for lighting energy savings.

Similarly, another study done by T. Iwata [62] calculated the daylight reflected on the ceiling from windows that can potentially save lighting consumption rather than desk level illuminance by using a method described by Taniguchi et al. [65].

Blind slats luminance are calculated using outdoor illuminance, irradiance values, slat geometry and optical properties. All the methods discussed do not require any indoor sensor to determine daylight on the ceiling, which is otherwise prone to errors due to the reflectance of objects below them.

4.1.2. Simulation methods

There are mainly two methods used for lighting simulation: raytracing, and radiosity. In backward raytracing, rays are traced from an observer's eyes to the light source and vice-versa in forward raytracing method. Radiosity is scene dependent algorithms that are adapted from heat transfer techniques to lighting simulations [101].

In a study done by Li et al. [53], daylight on façade is calculated considering light from sky and reflected light from ground and surroundings. Sky scanner is used to measure sky luminance and values are compared with CIE sky standards. CIE sky with least root mean square error is simulated in Radiance along with building model for calculating vertical illuminance on façade. The mean bias error between measured and simulated illuminance is 6.2% that indicates overestimation. The method is applicable only for overcast skies because in case of clear skies, sky scanner is reported to be less reliable [66]. The study conducted by Yun et al. [59] uses DIVA-for-Rhino, a Radiance based tool for simulating vertical eye illuminance (E_v) for glare calculations. It takes DHI and DNI values from Pyranometer as inputs for weather file. Simulated illuminance is compared with measured values, and it is found that simulated values are over predicted by 12%.

Some experimental studies have used calibrated digital sky images in Radiance model to simulate task illuminance levels [25,26,28,40,42]. A validation study of calibrated sky images by the same group shows the comparison of three different calibration methods (discussed in section 3.2) in accurately determining the simulated indoor illuminance levels [41,43]. In this method, dynamic raytracing model of test room employs the real-time calibrated sky model in Radiance. The model takes the room geometry, materials, and sky as input for scene description and calculates horizontal daylight illuminance at defined sensor points in the room. Radiance model is then integrated with the control application to change blind position and artificial lighting levels based on daylight availability. In some studies, the HDR image based sky model is added to Radiance scene of the room using Image-based lighting (IBL) technique to define the diffuse component of the sky [27,44,47,48]. For the direct component, solar irradiance or illuminance data is used in Radiance to describe the sky. Radiance simulated illuminance levels are compared with the actual measurements. It is found that virtual sensor's lux values are accurate with a correlation of 0.98 with measured values [27].

4.1.3. Summary

Simulation methods are used more than numerical methods in previous literature. Radiance is the most commonly used tool for daylight simulation as shown in Table 3. Major inputs given to any method include outdoor environment information, blind and room geometry, material properties. A limited number of studies have integrated real-time sky and daylight conditions in the building simulation model to predict daylight metrics and use it for lighting and shading controls. However, with advancements in simulation tools, simulation assisted open loop methods demonstrate high potential for accurately determining the indoor illuminance levels as relevant from the results.

4.2. Glare index

Glare is a subjective phenomenon sensed when visual discomfort or disability or annoyance is felt due to higher luminance in field of view of human eye [102]. Glare may be divided into three types: disability glare, discomfort glare and veiling glare [47]. Disability glare affects visual performance whereas discomfort glare causes discomfort when background luminance is higher than source luminance in the field of view [102]. Veiling glare is due to the indirect reflection of a bright light source on the field of view [75]. There are various metrics that quantify glare, such as Daylight Glare Index (DGI) [69], Predicted Glare Sensation Vote (PGSV) [103] and Daylight Glare Probability (DGP) [73]. In general terms, glare is expressed as the ratio of luminance of source, its size, and location to the scene luminance [104].

Glare indices calculated in previous studies is either by numerical calculations or by using the simulation tools. In the reviewed literature, glare metrics used for blind control are Daylight glare index [55,67], Daylight Glare Probability [59], and Predicted Glare Sensation Vote [62,70]. This section discusses methods used for determining daylight glare metrics in reviewed experimental studies for open loop blind control.

4.2.1. Daylight glare index (DGI)

DGI is mathematically similar to general glare expression except that it also considers window luminance. It is the ratio of source luminance to background and window luminance. DGI value greater than 31 represents intolerable glare and less than 18 stands for barely perceptible glare index [105]. There are various lighting simulation tools available to calculate DGI such as IES-VE, DiaLux, Radiance and other Radiance based tools. In a study conducted by Touma et al. [67], the Split-flux daylighting method in EnergyPlus is used to calculate the DGI values in office spaces containing brise soleil and venetian blinds installed on the facade. In a validated EnergyPlus simulation model, two DGI sensors are placed, and values are calculated on an hourly basis for annual simulation. Spilt-flux method takes into account the solar radiation intensity, direction, façade geometry and its optical properties and glare sensor location [68]. Since for an office space, maximum allowable DGI values is 22 [69], therefore, in the results it is shown that south façade with the Venetian blind is most effective with 10.9% of the hours exceeding DGI limit.

Another study employs DGI for evaluating two test rooms, one with automated blinds and another without it [55]. In this case, numerical algorithms adapted from EnergyPlus Engineering reference [68] are coded in Visual Basic 6 to calculate the DGI values. The value of window luminance is determined using an outdoor illuminance sensor by measuring the exitance from the window. To obtain the source and background luminance inside the room, a proportionate contribution of reflected daylight from slats as a direct light flux at that patch is calculated. The method used by authors for this calculation is adapted from the report on Daylighting coefficient of utilization tables.

4.2.2. Predicted Glare Sensation Vote (PGSV)

PGSV is a result of a subjective experiment that predicts the glare sensation vote proposed by Iwata et al. [103]. The values of PGSV are 0: just perceptible, 1: just acceptable, 2: just uncomfortable, 3: just intolerable [103]. PGSV can be calculated by the source-fixed method where the entire window is treated as a glare source [62]. Consequently, to calculate PGSV, window luminance should be calculated first. The experimental study done by Taniguchi et al. [70] has considered the contribution of surroundings in window luminance calculation. Slat luminance is calculated from the outdoor illuminance sensor.

Similarly, Iwata et al. [62] have shown the equations for calculating sky luminance and surrounding luminance that compose the total window luminance. The study proves that slat angle based on PGSV values can approximately reduce 30% of the lighting consumption while simultaneously providing view satisfaction for 46%–50% of working hours. A subjective evaluation performed to validate the PGSV calculation method has proved that glare sensation is significantly reduced when surroundings are taken into consideration [70]. An alternate way to calculate blind luminance has been demonstrated by using hybrid raytracing and radiosity model of blinds [71].

4.2.3. Daylight Glare Probability (DGP)

Daylight Glare Probability introduced by Wienold et al. [73] shows the strong correlation with the probability of persons getting disturbed and glare index when compared to other commonly used glare metrics. A significant difference between DGP and other metrics is that DGP considers vertical eye illuminance E_v rather than background or window luminance to evaluate the degree of visual discomfort. A DGP value less than or equal to 0.35 is recommended to avoid discomfort. A simplified expression to calculate DGP termed as simplified DGP (DGPs) is proposed by Wienold [106]:

$$DGPs = 6.22 \times 10^{-5} \times E_v + 0.184$$

A Radiance tool, evalglare is used to calculate DGP value [73]. It takes the luminance distribution map of the scene as input where the glare needs to be evaluated in the form of high dynamic range images of either simulated model or actual scene photographs. Evalglare renders DGP value, along with other glare metrics values (DGI, UGR, CGI, and VCP) as output. Evalglare includes task-area method in which the luminance of area higher than x-times the average luminance of whole task area is considered as glare source.

A study done by Yun et al. [59] has calculated DGP and E_v in Evalglare tool using three different input methods: i) by capturing high dynamic range images of a mock-up room, ii) hdr images of the scale model of same mock-up room and iii) simulated hdr images of room scene in a tool DIVA-for-Rhino that uses Radiance. Then, comparison and validation of the simulation model against the physical space are done. It is concluded that E_v is a better measure of glare than DGP.

A validation study done by Jones et al. [47] has compared the glare measurements from HDR images of a particular scene created using four different methods where a photograph of the scene serves as the reference case. Other three cases are the scene renderings of the digital model built in Radiance using three different sky models; Perez sky model, HDR image based sky and environment luminance map respectively. The comparison is made using global glare metrics such as DGP, E_v and local glare metrics as the contrast ratios CR_v (veiling glare on the monitor) and CR_d (discomfort glare due to work surface contrast). The results conclude that the Perez model provides a better estimation of glare than the other two sky models.

Table 4
Glare metrics and their threshold values used in literature.

S.No.	Glare Metric	Tools used for calculation	Glare threshold values used	References
1.	DGI	IES-VE, DiaLux, Radiance	DGI ≤ 18: imperceptible, DGI ≤ 24: perceptible, DGI ≤ 30: disturbing, DGI > 30: intolerable	[55,67]
2.	PGSV	Evalglare (Radiance)	PGSV = 0: just perceptible, PGSV = 1: just acceptable, PGSV = 2: just uncomfortable, PGSV = 3: just intolerable	[62,70,71]
3.	DGP	Evalglare (Radiance)	DGP ≤ 0.35: imperceptible, DGP ≤ 0.40: perceptible, DGP ≤ 0.45: disturbing	[47,59,73–75]

Other than metrics mentioned above, a study by Colaco et al. [61] has used sky ratio as an input parameter to control glare. Sky ratio is obtained by dividing diffuse horizontal irradiance to direct horizontal irradiance; and a value higher than 0.8 suggests cloudy sky [55].

4.2.4. Summary

Many of the previous studies have considered cutting off direct solar radiation to reduce glare rather than using glare metric to evaluate visual discomfort [49,58,64,89]. However, it has been shown that the cut-off strategy may not be sufficient enough to avoid the glare [72]. Therefore, studies that have employed various glare metrics to assess the discomfort, and devise the glare control blind algorithms are discussed. To conclude about glare metrics, DGI is used for large glare sources, therefore it is less suitable for interiors [69]. DGP is calculated for daylight glare from windows and validated by researchers [73–75]. However, DGP is reported to be less reliable in case of direct sunlight entering the rooms [76]. PGSV as well is for glare from windows, but its use in scientific studies is limited as compared to DGP. DGP also has the advantage of using high dynamic range imaging for assessment of daylight glare. It is now commonly used metrics in research as well in practice to assess the glare [62,78]. Table 4 summarises the glare metrics, their threshold values, and tools used to calculate metrics. A comparison study of glare indices shows that different index may provide different results while evaluating visual comfort [77]. Therefore, it is necessary to identify reliable metrics as per the light sources and parameters pertaining visual discomfort.

5. Window blind and integrated lighting control methods

This section discusses open loop blind and integrated lighting control methods. Lighting controls alone are not discussed here since artificial lights are primarily controlled for energy savings and requires spot lux measurement with higher accuracy. Open loop methods provide a spatial distribution of lux unlike the closed loop, where point values are measured. Therefore, lighting controls are not much practiced in open loop. However, for glare control, the open loop method is preferred where comfort is primary than energy saving. Integrated controls are also possible by using simulation assisted open loop control methods. Following subsections discuss these methods in detail.

5.1. Open loop blind control strategies

Window blinds may be controlled for different purposes including daylight glare reduction, lighting energy savings, thermal comfort, accessing outdoor views and privacy. Some methods can quantify first three objectives and therefore provides control parameters for blind control algorithms. These methods are discussed in this section. The control objectives for the window blind in various studies include glare, overheating, and illuminance levels. There are different categories of window blinds; the most common are roller shades and venetian blinds. In case of venetian blinds, blind control is referred to both blind height and slate angle control. As reported by previous studies, the slat angle control is more frequent than height control due to reasons related to avoiding motor noise by occupants [55]. Following are the methods used in literature for open loop blind control.

5.1.1. Cut-off control strategy

The most widely used open loop control algorithm is cut off angle control strategy [4,9,49,55,58,64,89] that considers solar profile to cut direct sunlight all the time by orienting blind slats. In Cut off angle control algorithm, blind slats are rotated such that it always cuts the direct radiation. It takes solar profile angle as input and returns blind tilt angle as output. Following is the standard equation to calculate cut-off blind angle [72]:

$$\beta_{cut-off} = 90^\circ - 2\Omega$$

where Ω is solar profile angle. There are two cut-off angles that exist for one solar profile angle, one towards the sky and another towards the ground [89].

Some studies have done various modifications in cut off strategy which do not require solar profile angle. The experiment conducted by Borowczyński et al. [49] has used sky models based on digital sky images for louver control. The sky models are classified into three types: clear, partly cloudy, and overcast. Blind slats are either closed or semi-open depending on the sky type and the presence of direct sun in window visual range. Though the method presents a very simplified approach and avoids any sensor usage; it is unreliable in case of the partly cloudy sky. A closed form solution for open loop blind height and angle control based on solar positions, outdoor vertical window illuminance sensor and blind geometry is developed by Ref. [89]. Blind slats are rotated to horizontal if illuminance sensor is below the set point to maximize the view. MATLAB is used to simulate the test room and blind geometry with blind height and angle control algorithms and automated by a C++ program. Blind height is calculated and changed only if the difference is greater than or equal to 10% of the window height. The control objectives in a study conducted by Tzempelikos et al. [64] consider maximizing the window transmittance illuminance along with cut off strategy to reduce glare and increase daylight penetration, thereby saving 67% lighting energy.

Though cut-off angle is the most commonly used method; it is reported to be not sufficient to control the glare as it only considers the presence of direct sun and does not consider sky conditions [72]. The experiment conducted by Chaiwiwatworakul et al. [55] has shown that motorized blinds with cut off angle control can shade the direct sunlight but glare index reaches beyond the allowable limit for visual comfort conditions. Therefore, glare control strategies are preferred due to their ability to detect glare sources.

5.1.2. Control based on glare metric and illuminance levels

In many studies, window shading devices are controlled to prevent glare by first quantifying the glare and then setting threshold glare index for the control device [55,59,62,67,70]. A typical glare control algorithm can be depicted by a flowchart shown in Fig. 7. As discussed

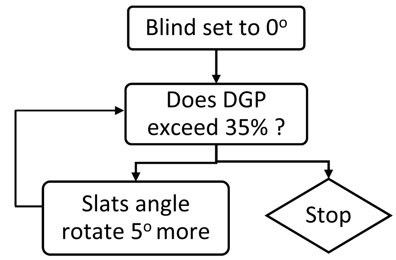

Fig. 7. Typical glare blind control flowchart [107].

in section 4.2, various glare metrics are utilized to assess the glare. Glare control algorithm followed in a study [55], first calculates the sky ratio; if the value is greater than 0.8, slats are set to horizontal (fully open), and DGI is calculated. Otherwise, slats are rotated to cut off angle and DGI is calculated. If DGI is greater than 22 (discomfort zone), slat angle is increased, and the step is repeated till DGI becomes less than 22. If DGI lies in comfort zone, interior illuminance levels are checked and if they are greater than 500 lux, slat angle is increased. The annual simulations have reported the DGI under 22 for 100% of the time. A similar kind of control algorithm is followed by Touma et al. [67] (study conducted in Qatar) in which after rotating the blind angle to reach the DGI value 22, the *BlockbeamSolar* method in EnergyPlus is used to increase the angle to achieve thermal comfort.

In another study by G. Yun [59], Energy plus and Diva for Rhino performed the dynamic simulation three orientation, four angles of blind and lighting levels as on/off or 4 levels of dimming based on vertical eye illuminance (E_v) values calculated using Evalglare tool. Value of E_v as 3000 lx is set as the threshold for glare control. Control strategies are optimized for preventing glare and maximum energy saving. In some studies, the PGSV index, solar profile, and outdoor illuminance are considered to change the blind angle, height and artificial lighting levels [32,62,70]. Electric lightings are dimmed based on glare prevention algorithm to keep the average window luminance constant. Subjective assessments are done as well to find view satisfaction. It is reported that this method can save upto 30% of lighting energy annually and provide view satisfaction for 46%–60% of the time [32].

5.1.3. Control based on Occupant's usage pattern

There are some methods that set the control logic based on occupants preference survey conducted [4,6,13,80]. Algorithm demonstrated by Gunay et al. [6] develops discrete-time Markov logistic regression models based on blind and lighting usage behaviour of occupants. The method determines the photosensor set points based on blind usage data collected for the control of blind and artificial lighting. Field implementation results show that the algorithm can reduce lighting energy consumption by nearly 25% in perimeter zones. Bourgeois et al. [13] have proposed to add advanced behavioural models in the simulation algorithm of daylight control to improve the accuracy. The experiments and blind usage survey conducted by Kim et al. [4] have evaluated the environmental performance of manual/motorized blinds and automated blinds. Performance evaluation is done by measuring work plane illuminance and taking predictive mean vote (PMV) measurement for overall satisfaction. Automation of blinds is performed considering outdoor vertical illuminance level. It is found that automated blinds performed better that manual blinds under the criteria regarding energy savings and comfort, but there is a need for more efficient control algorithms to automate the blinds.

In addition to strategies mentioned above, J. Hu et al. [29] utilize artificial neural networks for the control of blind slats to achieve desirable illuminance inside the room. An EnergyPlus model is used to train the artificial neural networks by obtaining the illuminance levels at pre-defined sensor points. The results show that ANNs can predict the illuminance with an error less than 10% and can set the optimum blind angle with an error less than 5%.

5.2. Integrated blind and artificial lighting control strategies

There are some methods that use real-time simulation assisted controls for integrated blind and artificial lighting control [25,26,28,40,42]. For simulation supported controls, the input simulation parameter includes building models and blind and lighting control strategies. The output parameters are related to energy and daylight metrics.

A study conducted by Mahdavi et al. [42] considers a test room with two blinds and two dimmable luminaries and a self-updating dynamic simulation model of same room integrated with occupancy sensor and location sensing system. The alternatives of blind positions and luminaries are simulated with a control objective to minimize lighting use, cooling load and maintain constant desk illuminance levels. Simulation done every 15 min are compared and ranked as per occupants preferences, and final control state is either automated or adjusted by users. The system uses Radiance integrated control applications. Related studies are done that integrates window blind and lighting control with the incorporation of simulation assisted controls [26,28,40]. A different approach used by Chang et al. [79] presents pilot control system for daylight responsive lighting control based on hybrid simulations and neural networks method. The system predicts indoor illuminance applying machine learning to the simulated model; glare and lux levels act as the performance indicator for the control system.

DiBartolomeo et al. [58] have developed a working prototype of integrated dynamic envelope and lighting system that attempts to maximize visual comfort while minimizing energy usage. Blind control is done by using cut off strategy, and blind is adjusted to meet required workplane illuminance [9,58]. As per the available daylight, lighting levels are dimmed. Authors have reported that the system may not be reliable in case of cloudy sky.

5.3. Summary

In comparison to studies that shows open loop blind control methods, there are very few studies that incorporate open loop methods for integrated lighting and shading control. As mentioned earlier, closed loop strategies are practised more in case of artificial lighting for energy savings. If illuminance estimation can be improved in open loop strategy, there is an opportunity to implement it for lighting control. This will reduce the errors that occur with sensor calibration in closed loop system and will also reduce the number of sensors. Table 5 summarises the open loop control methods and tools used in previous research.

6. Conclusion

The article reviewed the current state of the art in open loop blind and lighting control strategies that allowed to elucidate some issues and highlight potentials concerning utilization of sensors and their calibration, accurate estimation of daylight inside the building, assessing visual comfort, and finally discuss the control strategies being practiced for blinds and lighting.

The focus of the review was estimating the daylight inside the building to perform open loop control of windows blinds. One of the major challenges in accurate estimation of sky conditions is the correct calibration of the system. It should be ideally one-time calibration to avoid post commissioning errors in the system. The estimation has to be done real-time considering the rapidly changing dynamics of clouds. The sky luminance estimation is usually reported to be less reliable when direct sun is present as it is difficult to map such high luminance. Most of the methods recommended to completely close the blinds in case direct sun was present in the window visual range. Maintaining the response of control towards real-time daylight conditions is a far more

Table 5
Control strategies/algorithms used in literature for blind control, integrated blind and electric lighting control.

S. No.	Control method	Control objective	Input variables	Control implementation tools and methods	References	Control parameters	
						Blinds	Blind + Electric lighting
1	Cut-off angle Control to block direct sunlight	Achieving visual comfort	Solar altitude angle, solar profile angle, sky model, blind occlusion index	MATLAB simulation, Radiosity method, LabView Controller, C++ algorithm	[4,9,49,55,58,64,89]	✓	
2	Control decision based on outdoor illuminance levels	Maintaining adequate daylight illuminance inside the room	Outdoor Photosensor signals, Sky model, window azimuth angle	MATLAB, RADIANCE based sky model, Somfy Animeo IB, Radiosity method to model sky	[4,24,42,55,58,60–62]	✓	
3	Control as per the glare index	Achieving visual comfort by minimizing glare	DGP/ DGI/ PGSV/ E_v	RADIANCE simulation using Evalglare and Findglare, Diva-for-Rhino	[55,59,62,70,79]	✓	
4	Control decision as a function of illuminance level, electric energy consumption and cooling load	Electrical energy savings	Solar irradiance, Indoor Photosensor signals, data logger signals, lighting state, temperature	EnergyPlus Simulations, VIOLAS, Somfy Animeo IB, DOE-2 Energy simulations	[4,24–26,28,40,42,79]		✓
5	Control based on occupant's preferences and ranking through subjective assessment	Occupant's satisfaction	User preferences (view satisfaction and glare prevention)	Subjective user assessment, Simulation based ranking of preferences	[4,6,13,80]	✓	

challenging task in case of cloudy skies. Most frequently used sensors in open loop control methods are pyranometer and photosensor. However, it has been reported that sensors are less reliable for cloudy skies since they do not have the capability of analysing the cloud patterns and their directionality. Employing sensors during cloudy skies results in either delay of the control or exceeding the control when it is not required; thereby disturbing the occupants. In such scenarios, inaccurate prediction of visual comfort parameters is difficult to avoid.

One significant outcome that the article presents is that advanced simulation assisted control introduces an innovative solution for integrated blind and lighting control, considering their benefits in obtaining energy savings and visual comfort with cost reduction by minimizing the sensor usage. Moreover, many studies published the accuracy of simulated indoor daylight metrics. On the contrary, very few studies have reported the integration of simulated daylight metrics with control systems. Also, there are very few studies that consider the real-time sky modelling to assess the impact of daylighting on blind control. The challenges identified in this regard are the slow response of control system when performing real-time daylight simulation that may take a lot of time; and lack of daylight simulation tools that are fast and friendly enough to integrate into controls process. Though in recent studies, tools like Accelerade based on GPU has been validated to speed up the lighting simulation process [47,108], there is a need to integrate them with control application.

When considering commercial solutions, there is a tremendous gap between currently available technologies and the techniques recommended as research results. Daylight modelling itself is a lengthy process when modelling the complex and large building envelopes of commercial buildings. This may be counted as a significant limitation and obstacle for simulation assisted controls to become an industrial application. Machine learning can play a vital role here by replacing the daylight building model and reducing the time to milliseconds. This approach is explored by fewer researchers and presents a better alternative to modelling practices in control applications.

Based on the literature review, various challenges and gaps are identified that suggest research and development in the following sections:

- Reliable daylight and sky model prediction and calibration techniques.
- Incorporation of learning algorithms modelling and control process.
- Easy integration of real-time daylight information into the simulation model.
- Advanced daylight simulation tools incorporating parallel computing for fast simulation.
- Simulation integrated controls that learn the control pattern and ability to work independently.
- Monitoring the control system during cloudy skies.
- Algorithm for speeding up the control process and timely reaction of the control system.
- Commercially deployable and scalable working prototype of the system.

The review concludes that compared to conventional methods, modified and improved open loop system compete as a more beneficial alternative for integrated blind and lighting control and automation systems; however further research in this system is required.

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