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A review of automatic control strategies based on simulations for adaptive facades

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ABSTRACT

Adaptive facades (AFs) are building envelopes that can control occupant's visual and thermal comfort along enhancing energy savings. However, to achieve this purpose, an appropriate control strategy is needed, in which automatic control strategies facilitate effective utilization of daylight penetration in indoor spaces. In addition, these control strategies are potentially responsible for improving an occupant's productivity and well-being by preventing discomfort risks while keeping energy in control. This paper reviews simulation-based studies which employed automatic shading control methods for balancing human comfort and energy savings. The main aim of this research is to review the existing literature and identify research gaps in controlling AFs as a pilot study for future investigations. The review basically focuses on simulation approaches towards evaluating the performance of an automatic shading control that employs either open-loop or closed-loop control algorithm. The review concludes that existing studies only investigated automatic shading controls for typical AFs such as roller shades or venetian blinds that could not deliver multi-objective control over diverse human comfort perspectives along reducing energy consumption simultaneously.

1. Introduction

A building's facade is the most visible element that defines the aesthetical appearance of a building itself. Also, it is responsible for ensuring a physical barrier and a boundary between inside and outside, and therefore exposed to uncontrollable meteorological variations throughout a year such as solar radiation, precipitation, wind and extreme temperatures that affect indoor comfort conditions of occupants and building energy consumption significantly. On the other hand, facades are responsive to different functional scenarios that may contradict each other: shading vs. artificial lighting, views vs. privacy, solar gain vs. overheating, daylight vs. glare. Particularly, in office buildings, it is important to ensure effective daylighting systems to control unwanted solar gains and discomfort glare, while offsetting electrical lighting loads [1]. To this end, building envelopes should be; (1) adaptive to short-time weather fluctuations, daily cycles or seasonal patterns, and (2) have the capability to counterbalance antagonistic performance criteria of indoor environment of occupants to achieve better performance compared to static shading systems [2]. Therefore, the most ambitious challenge for designers is an effective adaptive façade (AF) that is able to keep the balance between the daylight harvesting and view out maximization while minimizing visual discomfort and building energy load.

To achieve this purpose in early stages of design where there is no building to do experiments or occupants to conduct surveys, an alternative solution is using building simulation tools [3]. Simulation tools give the ability to analyze different design scenarios and complex modelling which cannot be performed easily in real scale through experiments. Thus, this paper reviews only simulation-based studies which employed automatic control methods for balancing human comfort and energy savings.

Furthermore, changes in contextual and environmental parameters such as outdoor sky and sun position, daylight condition and occupancy presence or comfort desires suggests an integrated control strategy to ensure a balance between antagonistic AF's aims in an appropriate timing scale. Various controlling algorithms have been proposed in literature [4,5]. From an energy efficiency point of view, previous studies found out automatic control to move shading elements dynamically, is more beneficial to control lighting and energy loads comparing to manual control [6,7], while maintaining user comfort in acceptable range. However, several studies also reported lower users' satisfactions

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Acronyms

AFs	Adaptive Facades
FOV	Field of View
ANN	Artificial Neural Network
MOO	Multi-Objective Optimization
PCM	Phase Change Material
DGP	Daylight Glare Probability
DGPs	Simplified Daylight Glare Probability
DF	Daylight Factor
E_v	Vertical Eye Illuminance
WWR	Window-to-Wall Ratio
MBC	Model-based Control
UF	Utility Function
E_{wp}	Effective Illuminance
PGSV	Predicted Glare Sensation Vote
UDI	Useful Daylight Illuminance
DGI	Daylight Glare Index

if they cannot override automatic shading controls [8,9].

Only two studies known to the authors have done a literature review over automatic shading control [10,11]. The latter study [10] explicitly covers only one of the automatic shading control typologies based on experiments, while the earlier review [11] investigated dynamic operations of shading systems in three main levels; (a) system level, (b) building level, and (c) control level, that focused only on their implications over energy and lighting loads regardless of human comfort. These observations emphasize lack of a comprehensive review of automatic shading controls for adaptive facades with respect to human comfort including visual and thermal performance along with energy savings. This paper focuses on reviewing visual comfort and its existing metrics due to the fact that higher priority was given to daylighting and glare indices as the main control inputs for shading systems among existing studies.

Consequently, this paper outlines an extensive review of current practices in automatic shading controls that is divided into the following sections:

- Section 2 outlines existing visual comfort metrics in the literature that potentially can be used as input signals for automatic shading controls,
- Section 3 explains the methodology of the review including databases, selection criterion, and keywords clustering.
- Section 4 and 5 present the review of automatic shading control principle and strategies based on daylight, glare, view out, thermal comfort and energy savings.
- Section 6 draws the conclusion of the paper and also highlights potential future challenges and investigations based on the review conducted.

2. Visual comfort indices

Designing lighting scenarios in building design stage is not necessarily limited to energy efficiency and electricity consumption; visual comfort performance is equally important. The rational aspect of visual comfort in a given work environment determines an ideal brightness for users by permitting enough light quantity. In addition, there are other factors including; glare-free view, appropriate visible spectrum to render colors, and providing a uniform indoor illuminance and luminance that influence psychological performance of the user especially in offices [12,13]. In contrary, poor visibility may cause visual discomfort and forcing the eye to adapt to brightness level quickly. Non-uniform illuminated task area is a measure of point-to-point illuminance variation that can result in disability glare or unclear visual perception. As a result, discomfort glare is a feeling of irritation caused by existing high brightness contrasts or distracting light within the field of view (FOV) [14], however its physiological mechanism is still not understood [15].

Daylight penetration in a building is a matter of collaboration between controlling methods and perimeter zones, and designers seek integrated daylighting control strategies within an energy efficient process. Therefore, it is a challenging task since it is conjoined with solar gain which means depending on the context, allowing solar gain may be an advantage, but in some cases, it must be controlled. Thus, the most ambitious question is choosing an appropriate control strategy to counterbalance daylight harvesting and mitigating discomfort risks (e.g. glare, overheating), or potentially visual and thermal comfort of the users.

Progressively, different daylighting and discomfort glare parameters have evolved to assess the desired natural light while keeping minimum visual distractions. Table 1 categorized visual comfort indices in four scopes that are proposing the main evaluation criteria of visual comfort [16]:

2.1. Light quantity

Presence of sufficient natural light enables a visible indoor environment for occupants to fulfill their tasks. Discomfort can occur either by lower or higher light intensity, in which it can be physically evaluated through a grid-based area of a work plane as illuminance. The calculation of illuminance-based metrics requires hourly weather files to obtain prompt or time-dependent results.

2.2. Direct sunlight

Allowing direct sunlight penetration into the work environment can potentially cause unwanted visual and thermal discomfort due to glare and overheating risks respectively. It involves either illuminance-based or time-dependent evaluations of horizontal surface (e.g. task plane) or vertical surface (e.g. window) that is exposed to incident sunlight beam.

2.3. Light uniformity

Light uniformity is the level of homogenous light distribution over a task plane that results in visual stress reduction due to lower rate of repeated eye adaptations between under-lit and over-lit grids. It corresponds to illuminance physically, however using illuminance-based assessments solely do not always satisfy visual perception since an average illuminance of a task area can lead to similar results under distinct occasions, but with different light uniformity [17]. Also, as stated in standard [18], there should be a well-balanced light distribution on the task area and surrounding area in the view field.

2.4. Glare

Glare is defined as "*the sensation produced by luminance within the visual field that is sufficiently greater than the luminance to which the eyes are adapted to cause annoyance, discomfort or loss in visual performance and visibility*" [19]. Glare can be classified into three classes generally [20]: (i) physiological (disability) glare; (ii) psychological (discomfort) glare; and (iii) veiling glare. Physiological glare relates to inactivating the visual system like blinking and squinting to a degree because of excessive light scattering through a very bright source [21]. Psychological glare refers to excessive contrast or non-uniform illuminated task area within FOV that results in visual performance degradation and leads to eye strain or headaches [22]. Lastly, veiling glare is regarding unwanted reflections from a light source or window on an image or screen. While physiological glare evaluation is comparatively easy to assess and identify, psychological glare is a subjective feeling of individual's overall satisfaction [23]. Therefore, most of the glare metrics are

Table 1
Visual comfort metrics and their summarized features.

Visual metric		Unit	Modified Version(s)	Light Source	Space discretization	Time aggregation	Fitness	Comfort Threshold	Recommended Threshold (s)
Quantity of light indices	Illuminance (E_p) [29]	Lux	–	Natural Artificial	Local	Static	One-tailed	Variable	Offices:500lux or 300lux
	Daylight Factor (DF) [30]	%	$DF_{average}$ [31]	Natural	Local or Zonal as ($DF_{average}$)	Static	One-tailed	Variable	2% for residences 5% for office rooms
	Daylight Autonomy (DA) [32]	%	cDA sDA DA_{max} DAv	Natural	Local	Dynamic	One-tailed	Variable	E_{limit}: 500lux
	Continuous Daylight Autonomy (cDA) [33]	%	–	Natural	Local	Dynamic	One-tailed	Variable	Not available
	Spatial Daylight Autonomy (sDA) [34]	%	–	Natural	Zonal	Dynamic	One-tailed	Variable	DA_{limit}: 300lux for at least 50% of the task area
	Maximum Daylight Autonomy (DA_{max})	%	–	Natural	Local	Dynamic	One-tailed	Variable	Not available
	Useful Daylight illuminance (UDI) [35]	%	DAv	Natural	Local	Dynamic	Two-tailed	Variable	100 lux < UDI < 2000lux
	Daylight Availability (DAv) [23]	%	–	Natural	Local	Dynamic	Two-tailed	Variable	'Fully daylit', 'Partially daylit', 'Overlit', 'Non-daylit'
	Frequency of Visual Comfort (FVC) [36]	%	–	Natural	Zonal	Dynamic	Two-tailed	Variable	FVC > 0.8 for 20% of time
	Intensity of Visual Discomfort (IVD) [36]	lux. hour	–	Natural	Zonal	Dynamic	Two-tailed	Variable	E_{over} and E_{under} no more than 30% of their value
Direct Sunlight indices	Annual Sun Exposure (ASE) [34]	%	–	Natural	Zonal	Dynamic	One-tailed	Variable	Less than 250 h over 1000 lux
	Sunlight Duration [37]	hour	–	Natural	Not applicable	Dynamic	One-tailed	C[a]	Depends on climate
	Sunlight Beam Index (SBI) [38]	m^2. hour	–	Natural	Local	Dynamic	One-tailed	C	Not available
	Annual Sunlight Beam Exposure (S_{tot}) [38]	m^2. hour	–	Natural	Local	Dynamic	One-tailed	C	Not available
Light distribution	Illuminance Uniformity (U_o) [39]	index	–	Natural Artificial	Zonal	Static	One-tailed	Variable	Between 0.4 and 0.7
Glare	Luminance [40]	Nit or Cd/m^2	–	Natural Artificial	Local	Static	One-tailed	Variable	<2000 nit: Acceptable <4000 nit: uncomfortable <6000 nit: intolerable
	Luminance Ratio [41]	index	–	Natural Artificial	Local	Static	One-tailed	Variable	Not available
	British Glare Index (BGI) [42]	index	CGI DGI	Artificial	Local	Static	One-tailed	Fixed	BGI < 7 (imperceptible) BGI > 31 (intolerable)
	Visual Comfort Probability (VCP) [43]	index	–	Artificial	Local	Static	One-tailed	Fixed	VCP > 75 (imperceptible) VCP < 12 (intolerable)
	CIE Glare Index (CGI) [44]	index	DGI	Artificial	Local	Static	One-tailed	Fixed	CGI < 10 (imperceptible) CGI > 34 (intolerable)
	Daylight Glare Index (DGI) [45]	index	DGI_N	Natural Artificial	Local	Static	One-tailed	Fixed	DGI < 18 (imperceptible) DGI > 31 (intolerable)
	New Daylight Glare Index (DGI_N) [46]	index	–	Natural Artificial	Local	Static	One-tailed	Fixed	Not available
	Unified Glare Rating (UGR) [47]	index	GGR [48] UGR_{small} [48] UGP	Artificial	Local	Static	One-tailed	Variable	UGR < 13 (imperceptible) UGR > 28 (intolerable)
	Unified Glare Probability (UGP) [49]	index	–	Natural Artificial	Local	Static	One-tailed	Variable	UGP > 0.5, comfort UGP ≤ 0.5, discomfort
	Predicted Glare Sensation Vote (PGSV) [50]	index	–	Natural Artificial	Local	Static	One-tailed	Not available	PGSV = 0 (imperceptible) PGSV = 3 (intolerable)
	Discomfort Glare Probability (DGP) [51]	index	DGPs eDGPs DGP_{mod} DGPt	Natural Artificial	Local	Static or Dynamic	One-tailed	Fixed	DGP < 0.30 (imperceptible) DGP > 0.45 (intolerable)
	Simplified Discomfort Glare Probability (DGPs) [52]	index	$Glare_{Ev}$ [53]	Natural Artificial	Local	Static or Dynamic	One-tailed	Fixed	DGPs ≤ 0.35 if Ev > 2670lux 0.35 < DGPs < 0.45 if Ev ≤ 4276 lux
	Enhanced Simplified Daylight Glare Probability (eDGPs) [54]	index	–	Natural Artificial	Local	Static or Dynamic	One-tailed	Fixed	Not available
	Modified Daylight Glare Probability (DGP_{mod}) [53]	index	–	Natural Artificial	Local	Static or Dynamic	One-tailed	Fixed	Not available

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Table 1 (*continued*)

Visual metric	Unit	Modified Version(s)	Light Source	Space discretization	Time aggregation	Fitness	Comfort Threshold	Recommended Threshold (s)
Time-dependent DGP (DGPt) [55]	index	–	Natural Artificial	Local	Dynamic	One-tailed	Fixed	DGPt < 5%
Annual Visual Discomfort Frequency [56]	%	–	Natural Artificial	Local	Dynamic	Two-tailed	Fixed	$E_{v,beam} < 2000lux$ $E_{v,total} < 2670lux$
Glare Sensation Vote (GSV) [57]	index	–	Natural Artificial	Local	Dynamic	One-tailed	Fixed	Ls-%2000-C < 1.9% Ls mean/Lt mean < 1:15

[a] C: Climate-dependent.

evolved within numerical equations to evaluate discomfort glare that tie in with luminance intensity, or distributions in an observer's FOV [24].

As a comprehensive selection criterion, reviewed indices are classified by six features as shown in Table 1 that are adapted partially from Ref. [16]:

1 Light source – the numerical equations of indices have been developed to limit their application within an illuminated environment if they are affected only by natural light, or artificial light or a combination of these two sources.
2 Space discretization – A local index refers to a single value of a single test point of the task area that is often presented by grid-based maps to show the index intensity over an entire space. A zonal index gives an average value illustrating the whole space analysis outcome.
3 Time aggregation – there are number of terms used to describe time-varying visual comfort indices; static *vs.* dynamic [25] or short-term *vs.* long-term [26]. Static or short-term indices refer to illuminance-based evaluation of a given lit environment such as Daylight Factor [27]. Whereas, dynamic or long-term approach like Climate-based Daylighting Metrics (CBDM) [28] use illuminance-based assessment and interior day-lit condition (ex. automatic shading) to yield a comprehensive result by taking into account dynamic changes of sky and climate conditions over an extended duration of time.
4 Fitness – several indices assess visual performance by reconciling single or multiple physical quantities and thresholds. The fitness can be one-tailed or two-tailed referring the level of accepting of one reference value (a > x, a < x) or within a defined range (x < a < x + n) respectively.
5 Comfort threshold – some indices are specified by specific boundaries for evaluating the level of visual comfort of a given space, however due to deeply rooted visual experience of occupants, defining boundaries depend on the conducted experiments and lighting techniques. In general, illuminance-based comfort thresholds are mostly variable (can change based on designer decisions), while glare-dependent metrics are more restricted by fixed boundaries since they are physiological outcomes of occupants. Additionally, in Table 1, the term 'C' shows the third possible comfort criteria, when the index is entirely depended on 'Climate' to define an acceptable range.
6 Modified versions – during last decades, there are many individual research introduced new metrics based on previous field studies as modified metrics to fulfill existing missing gaps as a stronger correlation between occupant's sensation of comfort and numerically-calculated visual performance.

3. Methodology

A systematic review with a specific selection criterion and keywords have been conducted to collect eligible research studies across the literature. This section provides detailed explanation on inclusion and exclusion of criteria, keywords and their clusters.

3.1. Inclusion and exclusion of criteria

Initially, the literature review is carried out in five web bibliographic databases of academic publications: Scopus, Web of Science (WoS), Environment Complete (EC), Green File (GF), and Engineering Village (EV). In all databases, there was a possibility to conduct advanced searching based on clustering major categories for defining the terms, therefore a searching criteria through keywords has been used as shown in Table 2. As a result, all the papers must meet the following criteria:

- Findings should focus on evaluating automatic or occupant-based shading control method(s) in office buildings. The control method should propose a solution for at least one of the main objectives, including: (1) visual comfort (daylight, glare and view out), (2) thermal comfort, and (3) energy and/or lighting savings.
- User interactions over the shading system are excluded at this stage and will be the main focus of a future paper.
- As mentioned previously, the main focus of this review is based on simulation tools, each study should use either simulation-based evaluation solely or along with field measurements. Researches that are conducted through experiments only are not included.
- Advanced methods such as artificial neural network (ANN) or fuzzy logic are excluded since they predict user preferences based on complicated mathematical multi-objective optimization (MOO) and analyzing past data collections [58,59] that are not the focus of this review.
- They should demonstrate at least one method to calculate visual comfort metrics highlighted in Table 1.
- And finally, shading systems integrated with smart materials, Phase Change Materials (PCMs), any kind of switchable glazing systems (electro-chromic, thermos-chromic, or photo-chromic), and BIPV systems are out of the scope of this review.

3.2. Keywords and clustering

The main objective of this paper is to present a comprehensive review of automatic shading control strategies and their implications on human comfort and energy efficiency. Therefore, keywords have been clustered into three groups (Table 1): (1) shading systems, (2) control types, and (3) human comfort, and various combinations of the terms are found relevant to conduct the search. Consequently, 417 references are collected (Scopus (312), WoS (71), EC + GF (29), EV (5)), and 351 non-duplicate studies remained for criteria matching process. Among them, only 26 studies could meet the selection criteria properly that are published between 2007 and 2019. Additional 4 references are found through a forward and backward citations of key author's publication lists.

Alternatively, a text-based tool called VOSviewer is used to visualize bibliometric network [60] as shown in Fig. 1. It helps to analyze co-occurrences of terms found in Title, Abstract, and Keywords in the collected literature. A minimum of 20 co-occurrences is chosen in VOSviewer to illustrate a systematic analysis of terms, research aims and frequency distribution of keywords. The higher the size of the circle, the more frequent occurrence of the term. The lines represent the

Table 3
Summary of the critical review of automatic shading controls.

Reference* (Climate, Location)	**Shading System**	**Automatic Control**				**Evaluation Method**	**Control Outputs**							
		Office Type	Control Protocol	Input Signal(s)	Visual Comfort Metrics		Measurement	Feedback	Thermal Comfort	Daylight	View Out	Glare	Lighting/ Energy	HVAC control
[72] Tropical Climate (Singapore)	Interior venetian blinds	Shared	Open loop	Sky condition, Task illuminance, DGP	DGP, Illuminance	Radiance, HDR camera, EnergyPlus	✓	×	×	✓	×	✓	✓	×
[80] Subtropical Climate (Italy)	Interior roller shade	Shared	Open loop	Task illuminance, Sun position	DA, eDGPs	EnergyPlus, Ladybug, Matlab	×	×	✓	✓	×	✓	✓	×
[85] Cold Climate (Germany)	Exterior venetian blinds	Shared	Open loop (MBC)	Solar radiation	UDI, DGPs	TRNSYS, Radiance	×	×	✓	✓	×	✓	✓	×
[73] Multi-climate (Canada, USA, Chile)	Exterior venetian blinds/Exterior perforated louvers	Shared	Open loop	Global irradiance	sDA, ASE	EnergyPlus, Radiance, mkSchedule	×	×	×	✓	×	×	✓	×
[86] Cold Climate (Germany)	Interior venetian blinds	Private	Open loop (MBC)	Global irradiance, Task illuminance, E_v	DA, DGPs	Fener	✓	×	×	✓	✓	✓	✓	×
[79] Hot Climate (Italy)	Interior venetian blinds, Exterior roller shade, Solar control film	Shared	Open loop	Global irradiance, Indoor temperature	Illuminance, Uniformity	EnergyPlus	×	×	✓	✓	×	×	✓	×
[69] Multi-climate (Singapore, USA, Germany, South Korea)	Exterior venetian blinds	Private	Open loop	Global irradiance	DGI	EnergyPlus	×	×	×	×	×	✓	✓	×
[5] Subtropical Climate (Japan)	Interior venetian blinds	Shared	Closed-loop	Sun position and angle	PGSV	Numerical calculations	✓	✓	×	×	✓	✓	✓	×
[76] Hot Climate (Egypt)	Exterior/Interior venetian blinds	Private	Open loop (MBC)	Sun position	Daylight hours	Ladybug, Honeybee	×	×	×	✓	×	×	×	×
[90] Subtropical Climate (India)	Interior roller shade	Private	Closed-loop	DGP	DGP	DIVA	×	✓	×	✓	×	×	✓	×
[102] Hot Climate (Qatar)	Exterior venetian blinds	Shared	Open loop	Solar radiation	DGI	EnergyPlus	✓	×	×	×	×	✓	✓	×
[82] Temperate and Hot Climates (USA)	Interior roller shade	Shared	Open loop	DGP, DGI	Glare frequency	Radiance, EnergyPlus, EMS	×	×	×	×	×	✓	✓	×
[67] Cold Climate (Denmark and Norway)	Exterior/Interior venetian blinds	Private	Open loop	Global irradiance, Vertical illuminance, Temperature	Operative Temperature, sDA, E_v	IDA ICE	✓	×	✓	✓	×	✓	✓	✓
[89] based on [88] Humid Climate (USA)	Interior roller shade	Shared	Open loop (MBC)	Global irradiance, Transmitted illuminance	Illuminance, E_v, DGP	Window, Hybrid Ray-tracing and Radiosity	✓	×	×	✓	✓	✓	✓	×
[75] Cold Climate (Denmark)	Exterior/Interior venetian blind	Private	Open loop	Global irradiance, E_v	Illuminance, E_v	VELUX, Survey	✓	×	×	✓	✓	×	×	×
		Private		Task illuminance	DGP, DGPs, E_v		×	×	×	×	×	✓	✓	×

(continued on next page)

Table 3 (*continued*)

Reference* (Climate, Location)	Shading System	Automatic Control				Evaluation Method	Control Outputs							
		Office Type	Control Protocol	Input Signal(s)	Visual Comfort Metrics		Measurement	Feedback	Thermal Comfort	Daylight	View Out	Glare	Lighting/ Energy	HVAC control
[7] Subtropical Climate (South Korea)	Exterior venetian blinds		Open loop (MBC)			HDR camera, EnergyPlus, DIVA								
[68] Hot and Humid Climates (Dubai, UK, USA)	Exterior/Interior venetian blinds	Shared	Open loop Closed-loop	Task illuminance, Sun position and angle, Vertical illuminance	DGI	EnergyPlus, BCVTB, Matlab	×	✓	×	✓	×	✓	✓	×
[4] Cold Climate (Norway)	In-between venetian blinds	Private/ Shared	Open loop	Indoor/outdoor temperature, Cooling load, Glare Index	Illuminance, DGI	Comfen, EnergyPlus	×	×	✓	✓	✓	×	✓	×
[97] n/a	Exterior venetian blinds	Private	Open loop	Task illuminance	DGI, View Factor	EnergyPlus, Daysim	×	×	×	×	✓	✓	✓	×
[66] n/a	Interior venetian blinds	Private	Open loop Closed-loop	Direct reflection, Task illuminance	DGP, cDA	Hybrid Ray-tracing and Radiosity	×	✓	×	✓	×	✓	×	×
[78] Subtropical Climate (Italy)	Exterior venetian blinds and roller shade	Shared	Open loop	Glare index, Global irradiance	DGI	EnergyPlus	×	×	✓	✓	×	✓	✓	×
[92] Temperate Climate (South Korea)	Exterior venetian blinds	Shared	Open loop	Global irradiance, HVAC mode	DGI	EnergyPlus	×	×	×	×	×	✓	✓	✓
[94] Hot Climate (USA)	Interior venetian blinds	Shared	Closed-loop	Task illuminance	UDI	EnergyPlus	✓	✓	×	✓	×	✓	✓	×
[83,84] Cold Climate (Austria)	Interior venetian blinds	Shared	Open loop (MBC)	Sky condition, Global horizontal illuminance	Illuminance	Radiance, Digital Camera	✓	×	×	✓	×	×	✓	×
[81] Cold Climate (Denmark)	Exterior venetian blind	Shared	Open loop	Indoor temperature, Glare index	DF	iDbuild	×	×	×	✓	×	×	✓	×
[64] Tropical Climate (Thailand)	In-between venetian blinds	Private	Open loop Closed-loop	Sky condition, Global irradiance, Task illuminance	DGI, Illuminance, Transmittance	Numerical calculations	✓	✓	×	✓	✓	×	✓	×
[93] Cold Climate (Sweden)	Interior/in-between venetian blinds	Private	Closed-loop	Solar radiation, Outside temperature	Illuminance	Parasol, Radiance	✓	✓	×	✓	×	×	✓	✓
[52] Temperate Climate (Belgium)	Exterior venetian blinds	Private	Open loop (MBC)	Global irradiance, Direct sun on Task plane	DGP, DA	Radiance, Daysim	×	×	×	✓	✓	✓	✓	×
[91] Cold Climate (Canada)	Exterior roller shade	Private	Open loop	Global irradiance	DAv ratio	TRNSYS, Radiosity	×	×	×	✓	×	×	✓	×
[77] Temperate Climate (Belgium)	External mobile screen	Shared	Open loop	Global irradiance, Indoor/outdoor temperature	_	TRNSYS	×	×	✓	×	✓	×	✓	×
	Overall contribution of each objective out of 30 studies						11	7	8	24	9	19	28	3

* Studies are sorted based on year of publication.

Table 2
Systematic searching summary of automatic shading control.

Database	Date of search	Inclusion/exclusion searching criteria in Title, Abstract and Keywords	Number of articles
Scopus	May 11, 2019	(TITLE-ABS-KEY (*"shading control*"* OR *"shading system*"* OR *"window shad*"* OR *"shading device*"*) AND TITLE-ABS-KEY (*"Thermal Comfort"* OR *"Visual comfort"*) AND NOT TITLE-ABS-KEY (*"personalized"* OR *"user feedback*"*) AND TITLE-ABS-KEY (*"Control strateg*"* OR *"glare control*"* OR *"lighting control*"* OR *"daylight control*"*))	312
Web of Science	14/05/2019		71
Environment Complete	16/05/2019		22
Green File	16/05/2019		7
Engineering Village	17/05/2019		5

interrelation among terms and colors are the clusters they belong. Regarding AF's control, Fig. 1 also confirms three main clusters of this research, including; (1) thermal comfort (green color), (2) visual comfort (red color) that include daylighting, glare, view, and their impacts on building energy performance, and (3) user cluster (blue color) that adds an extra complexity in driving control algorithms, although is not the aim of this review.

4. Automatic shading control

Particularly, two main strategies are defined in the literature for automatic control of AFs with respect to environmental conditions; intrinsic and extrinsic control strategies [2]. Both terms indicate that an adaptive mechanism is triggered by environmental stimulus like surface temperature or solar irradiance as inputs from sensors. Intrinsic control is based on internal self-adjustment like smart materials and its actuation is activated by fluctuations in internal energy through material sensors. This kind of control requires low initial costs, and does not allow direct user interactions or any external inputs, therefore a feedback loop is absent in its logic and is also known as 'direct', 'passive' or 'open-loop' control. In contrary, extrinsic control uses an external decision-making system as a feedback signal that increases the initial costs and complexity level, while allowing user intervention in its algorithm. This is so-called 'active' or 'closed-loop' control. Thus, in order to not use different terms interchangeably, open-loop and closed-loop are used as the main types of automatic control in this paper.

In practice, both control loops are prone to unpredictable disturbances according to Ref. [61]. Disturbances enters the loop in two main forms: (1) real information such as noise and loads, and (2) virtual information from different resources like changing in desired set-points or environmental conditions by users. Therefore, dealing with existing disturbances is the main notion towards adopting feedback loops to correct errors constantly at three levels: identifying the feedback, evaluate the feedback, and decide based on the feedback within controllers as shown in Fig. 2.

In the open-loop control, the indoor environment does not change the system performance as the controller is actuated by outdoor environmental information solely through mounted exterior sensors with predefined thresholds [62]. This control is insensitive to indoor environmental changes or user demands (no feedback), but can employ a network of local sensors to share information [10]. As a conventional open-loop algorithm (Fig.3, a), a photo-sensor has been widely used on exterior to capture sky or daylight-linked values without considering indoor artificial lighting. However, utilization of virtual sensors (Fig. 3, b) through advancements of modelling and simulation tools or namely, model-based instead of real sensors were reported more effective in Ref. [63]. Model-based sensors read external real-time information and process them in a simulation software to change the shading settings. Therefore, indoor comfort parameters such as glare index are measured again by simulation modeling to reach the acceptable range without any feedback loop. Consequently, artificial lighting control is not optimized in open-loop method as it delivers spatial distribution as an average of comfort metrics unlike the closed-loop method, where individual values can determine the control inputs within a feedback loop.

In the literature, the most common type of open-loop control strategy

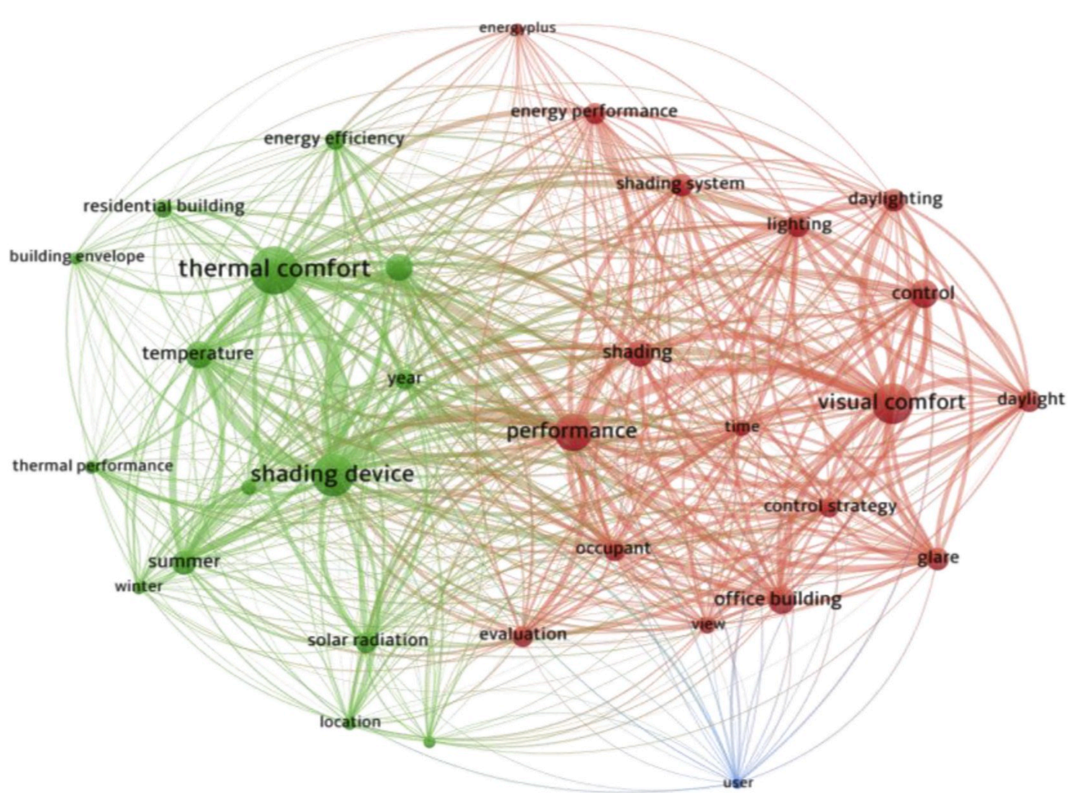

Fig. 1. Density and network visualization of most observed terms in Title, Abstract, and Keywords of collected literature of automatic control.

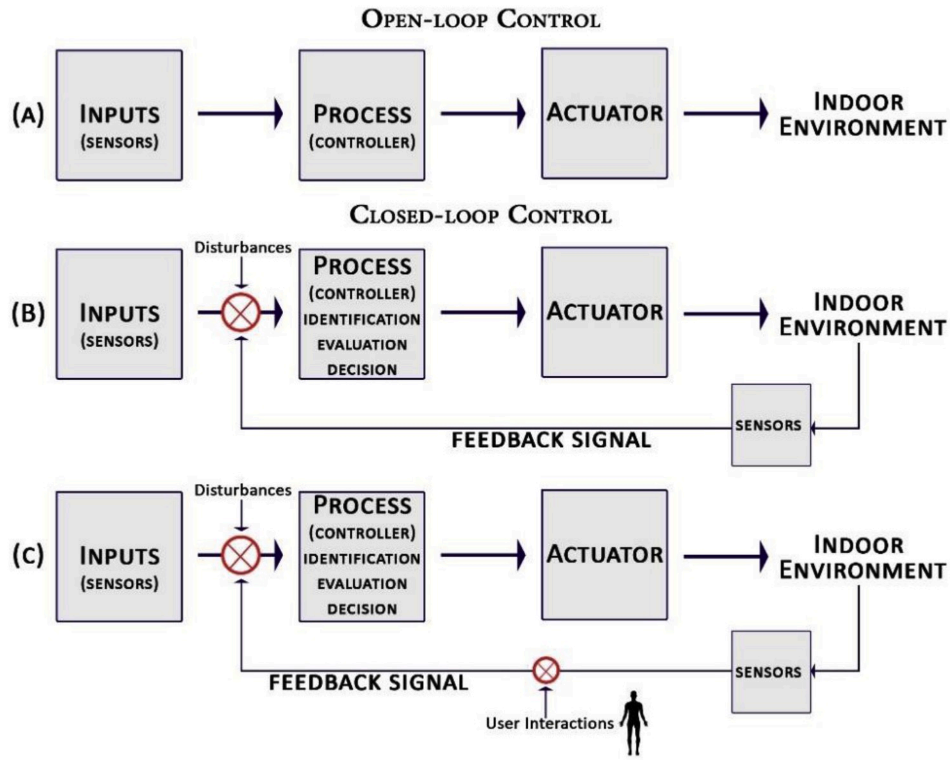

Fig. 2. Open-loop and Closed-loop control algorithms.

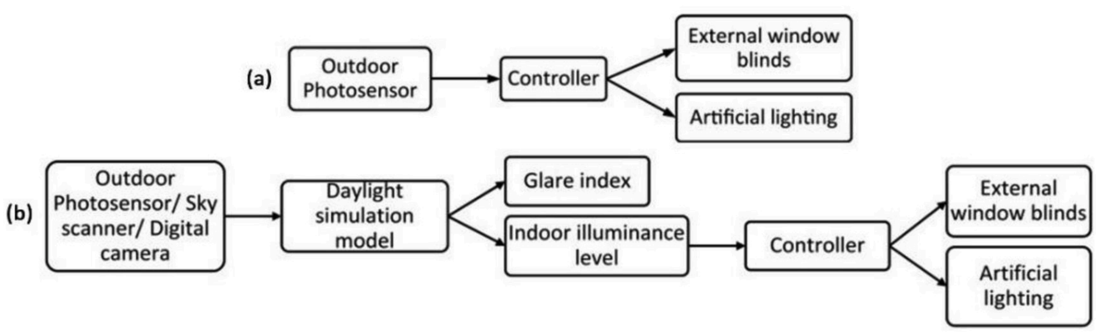

Fig. 3. Conventional (a) and Model-based (b) open-loop algorithms [10].

is cut-off angle for blinds [64–66], that considers sun position to determine the blind angle based on cutting direct sunlight all the time, however, in several studies it is reported a cut-off angle strategy is not sufficient to control glare since indirect daylight and sky condition are neglected [52,66]. Therefore, several studies integrated other strategies like glare control or occupant's information into open-loop control algorithm [66–69].

Closed-loop control accepts a feedback loop whereas open-loop does not. A typical closed-loop control includes a series of indoor sensors that control artificial lighting control to maintain specific illuminance level on task plane for energy savings [10]. Different lighting control methods are introduced based on occupancy-detection, On/Off control, dimming control, time-schedule control, pattern control, group control, and blackout control [70,71]. Among them, dimming control has the most efficiency by providing acceptable amount of brightness based on indoor illuminance or occupant inputs. Therefore, the control input receives two signals; one from the reference sensor that collects the boundary conditions information and one from feedback loop as a measured signal from actual output (Fig. 2, b). This feedback loop allows closed-loop algorithm control to respond to possible user interactions (Fig. 2, c). As the most striking feature of these systems, they deliver a double mission, that is, regulating outdoor/indoor environmental changes beside accommodating different user decisions to sustain adaptive behavior in real-time signal processing.

5. Systematic analysis

Following the systematic review and the selection criterion, the documented studies are analyzed from seven identified common aspects among studies: (1) open-loop control, (2) multi-objective control, (3) occupancy-scheduled patterns, (4) model-based control, (5) closed-loop control, (6) other improvements, and (7) sources of input signals.

5.1. *Open-loop control*

As a recent study of open-loop control, Babu [72] investigated seven combinations of lighting controls (no dimming, dimming) and shading controls (close, retracted, automatic) for interior venetian blinds in test cell under three different sky conditions as overcast, intermediate and clear. The control strategies were triggered based on sky condition, task

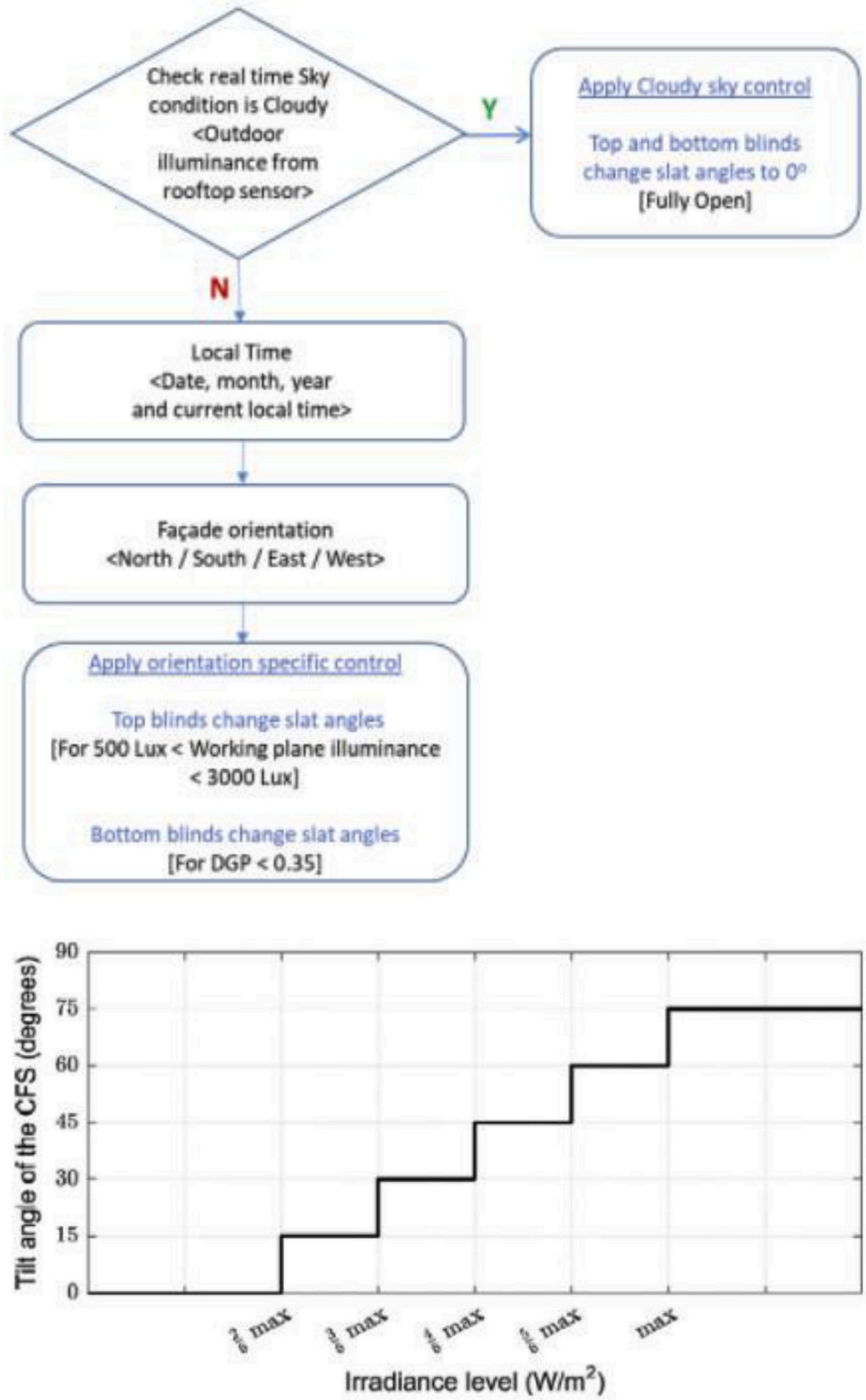

Fig. 4. (Top) Adapted control algorithm in Ref. [72], (Bottom) Slat angle control strategy [73].

illuminance sensors and DGP value for a standing occupant towards window as shown in (Fig. 4, Top). Results showed automatic blinds with auto-dimming lighting control could save lighting energy up to 75% and 67% based on experimental setups and simulation respectively, while maintaining acceptable visual comfort. However, the experimental results were recorded only during three days' measurement that cannot represent an entire year energy savings. A different open-loop control was tested over external venetian blinds and perforated louvers by Ref. [73], in which the slat angle was a function of maximum solar irradiance on window surface (Fig. 4, Bottom). According to the results, perforated louvers could save more energy since it could permit more solar gain and indoor illuminance through perforations, although the maximum solar irradiance was calculated based on both optimum daylight level and least energy consumption. Thus, the control strategy could not ensure the user's visual comfort due to discomfort glare.

As mentioned earlier, the most common type of open-loop control that is applied in literature is cut-off strategy to obtain the optimum blind angle to block direct solar radiation regardless of sky condition. To this end, Al Touma [74] employed three scenarios: no control, cut-off control, combination of cut-off control and daylighting control

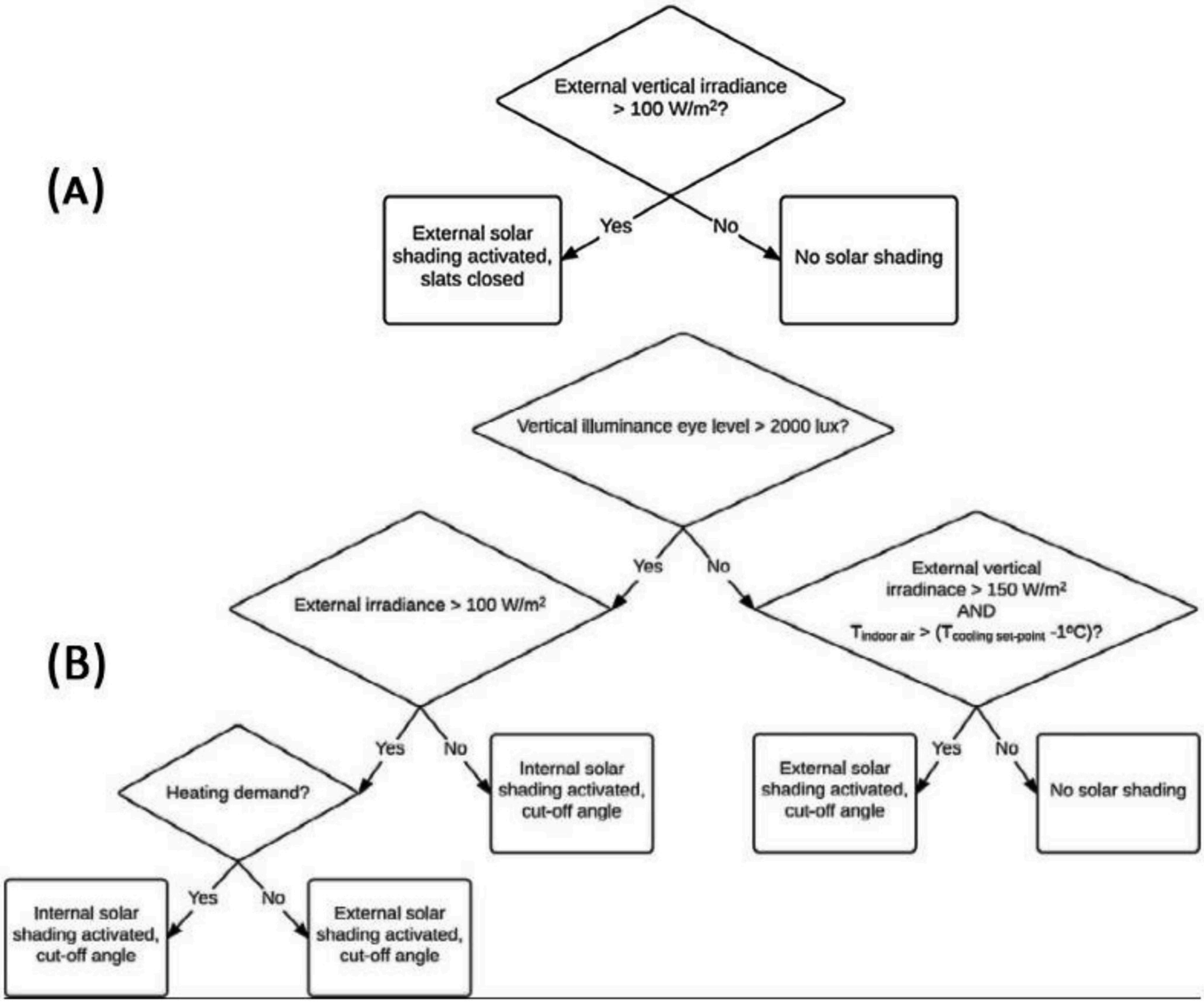

Fig. 5. Typical simple (A) and detailed (B) control algorithms adopted in Ref. [75].

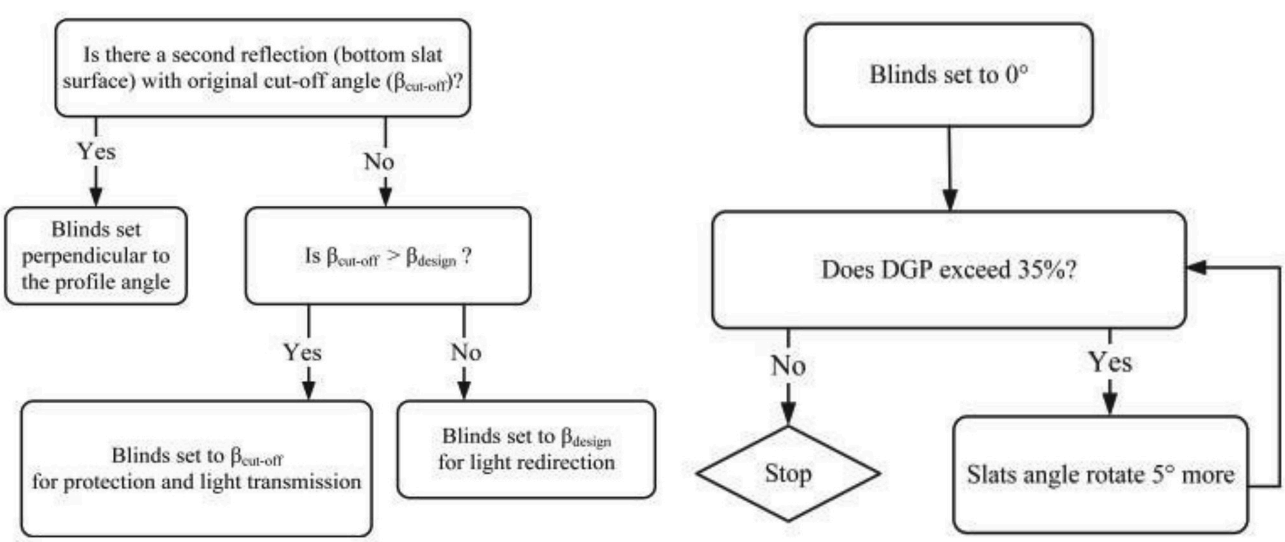

Fig. 6. Daylight redirection (left) and glare control (right) control algorithms adopted in Ref. [66].

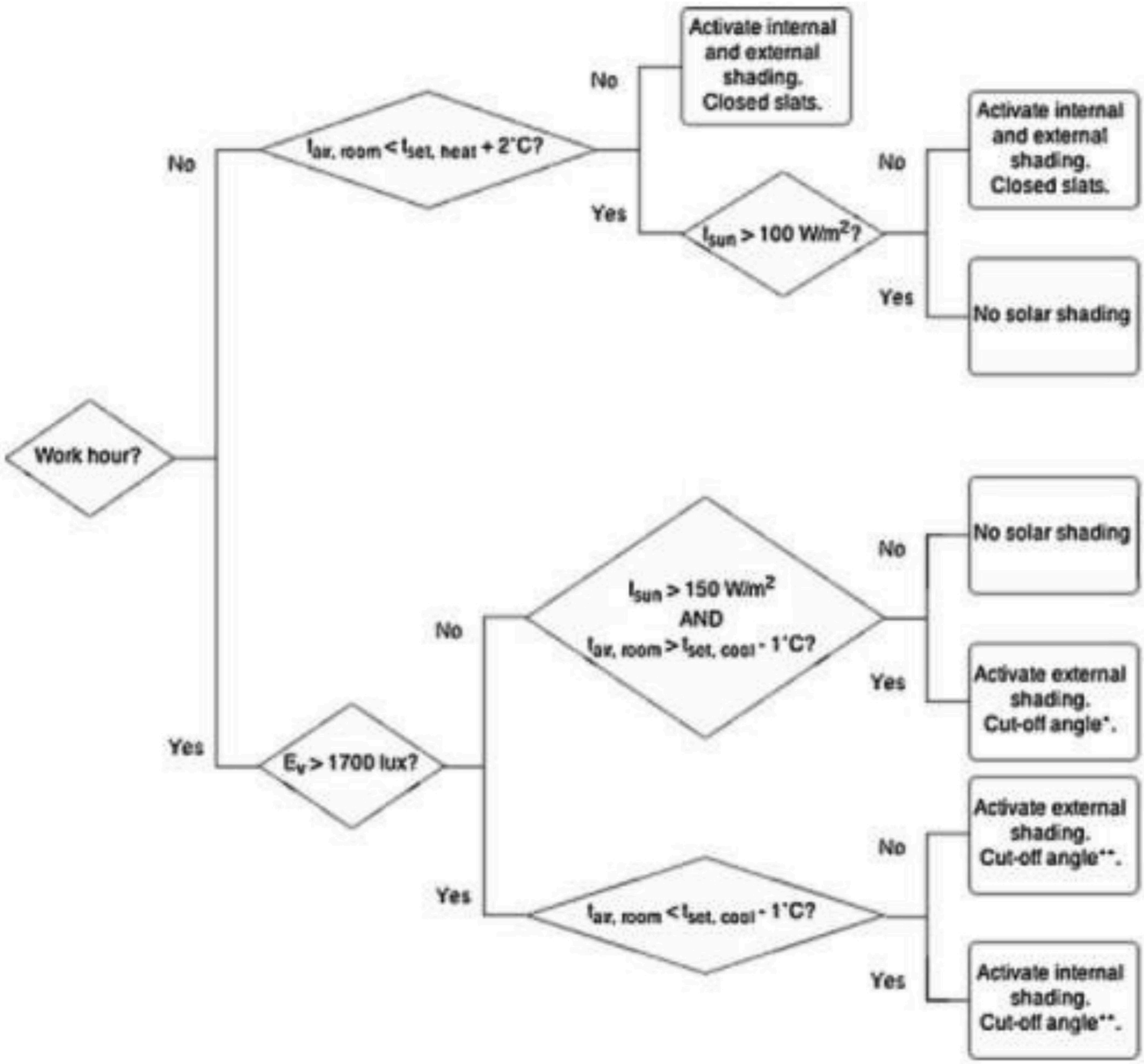

Fig. 7. Open-loop control based on occupancy activity [67].

together, for a single office test room throughout a year. Comparing the results with the reference case (no control), adopting independent open-loops (third strategy) reduced lighting and cooling loads by 37.8% and 26.1% respectively, while keeping glare index below uncomfortable threshold for entire time. Another study by Ref. [52] evaluated three manual and one automatic control (cut-off) strategies based on slat angle and height to control glare, uniformity, contrast and view out towards DGPs validation. The results showed that manual controls were rarely used in summer and satisfying several aspects could lead to opposing shading positions, where cut-off strategy seems to be a good equalizer between solar loads and visual comfort in summer, however, it cannot prevent glare completely. To investigate the occupant's satisfaction, two studies [4,75] tested venetian blinds in different positions (internal, external and in-between-panes) based on two blind controls; simple fully-closed and cut-off as detailed control (Fig. 5). In latter study [75], results showed higher energy savings in a shared office than a single occupant space. Such cut-off approaches, however, found more suitable to satisfy occupants since it allows view out, but have failed to prevent all glare risks in all previous studies.

Progressively, several studies used glare controls or modified cut-off strategy to provide higher visual performance. Chan [66] utilized a hybrid method of ray-tracing and radiosity to compare cut-off angle, daylight redirection and two glare control strategies either using real-time DGP values or pre-calculated correlations between DGP and transmitted illuminance (Fig. 6). Glare controls performed the best to deliver high daylight autonomy without having glare risk in all case studies as opposed other two controls. Eltaweel [76] focused on improving the cut-off control through a parametric-based algorithm to reflect daylight onto the ceiling to ensure only the daylight level while preventing direct sunlight to reach deep area of the workstation. Thus, no attempt was made to quantify other comfort indices. These studies used glare protection controls mostly to reduce summer solar gains, while users generally prefer to have view access to outdoors that is not the aim of cut-off and glare control strategies. Therefore, an alternative

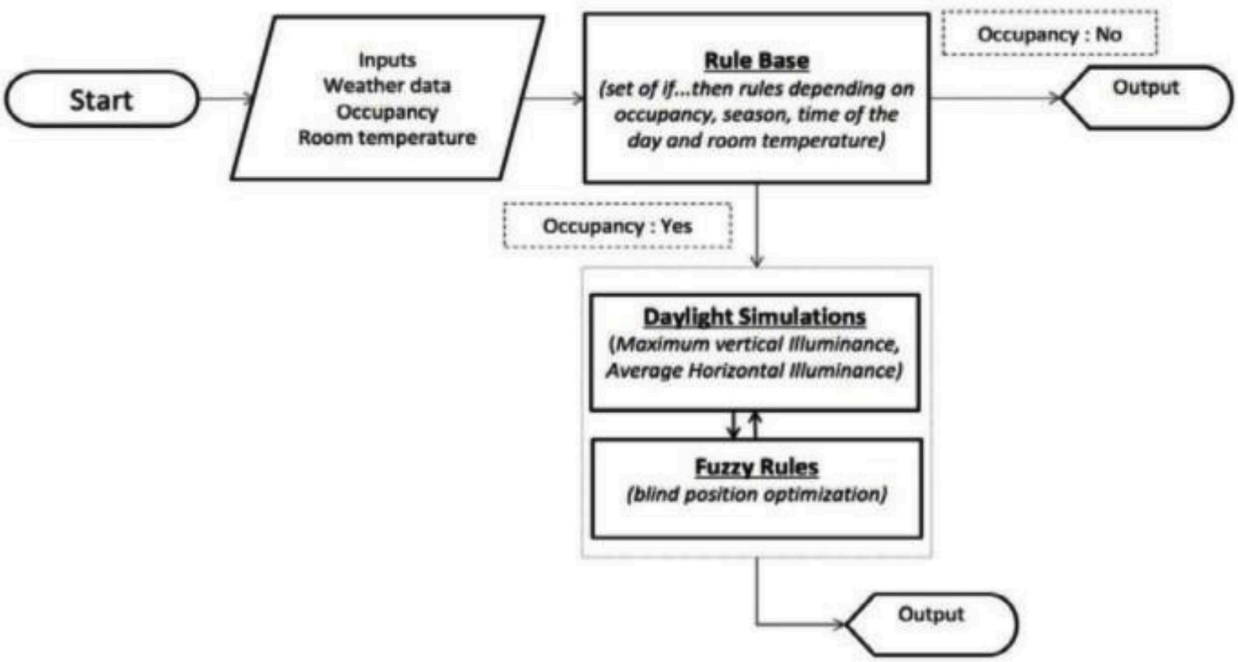

Fig. 8. Implemented occupancy-based control strategy in Ref. [86].

control could be using window luminance within FOV or taking individual preferences of seated users (in case of office spaces).

5.2. Multi-objective control

Alongside the visual comfort, controlling the thermal environment usually occur based on global irradiance and temperature. Van Moeseke [77] used two simulation sets to minimize shade deployment time (maximize view out), energy demand and overheating hours based on six different shading and natural ventilation control modes. For shading purpose, a combination of internal temperature and solar irradiation performed the best to balance energy savings and comfort, however, day cooling strategy could not be effective enough to reduce energy demand. Another example is integrating typical blind glare control (simple fully-closed) with indoor operative temperature [78,79], to compare exterior venetian blinds and roller shade performance. In case of an air-conditioned space [78], researchers concluded that external shading application only reduced the thermal comfort fluctuations since the temperature is controlled with mechanical system. However, in a naturally-ventilated office space [79], external roller shade and solar film could reduce the indoor temperature significantly when they were lowered by solar irradiance and indoor temperature above 200 w/m^2 and 26 °C respectively, in which authors suggested internal venetian blinds should be avoided.

Additionally, simple fully-closed strategy results in compromising the cooling loads reduction with lighting and heating loads increment. Thus, a new method based on parametric simulation developed an advanced shading control to perform intermediate positions for roller shades to guarantee a comfortable indoor environment while keeping energy consumption low [80].

5.3. Occupancy-scheduled patterns

Integrating occupancy schedule into open-loop controls was the basis of some studies. Nielsen [81] focused on comparing the performance of adaptive venetian blinds through cut-off control strategy with fixed or no shading by considering different window heights and orientations, while during unoccupied hours, shading control remain only based on indoor temperature. In terms of energy demand and DF, adaptive and fixed shading performed the best and the worst respectively, in which the energy demand difference did not exceed 16% while DF was improved by 150% for a given orientation. Similar results are outlined in another research by Ref. [82].

As a comprehensive study by Ref. [67], authors divided the control mode into occupied and unoccupied hours (Fig. 7). In occupied hours, user comfort was prioritised by avoiding glare through vertical eye illuminance (E_V) calculation, while in unoccupied hours, energy saving was the main goal. Consequently, optimized solar shading control based on outdoor and indoor environmental conditions had higher efficiency to balance thermal/visual comfort and energy savings. However, in few hours, vertical illuminance exceeded the defined threshold and manual override was necessary.

A different automatic scenario based on predefined coefficients was employed by Ref. [69]. Researchers proposed an open-loop control activation method for venetian blinds based on a weighting factor scheme as user preference (no direct interactions) between visual comfort and lighting energy consumption. Therefore, to control venetian blinds, if visual comfort was desired, slat angle should be larger, while if energy saving was more important, higher activation threshold of global irradiance was required. Nevertheless, the strategy did not explain how to measure the weighting factor and the method itself depends on WWR and climate significantly.

5.4. Model-based control (MBC)

Alternatively, a distinct real-time controlling is 'model-based control' (MBC) which was proposed initially by Ref. [63]. It is based on real-time virtual sensing in software and lighting simulations simultaneously. In similar studies [83,84], 64 scenarios among 700 possible options were simulated at each time step (every 15 min), to maximize utility function (UF) that balances mean indoor illuminance, lighting, cooling loads by multiplying with fixed weighting factors (defined by simplified preference functions) as user preference. As a result, MBC strategy delivered indoor illuminance within acceptable range during experimented days. Then, all 700 options were objectively ranked based on UF to set proper control state and results showed more than 80% of

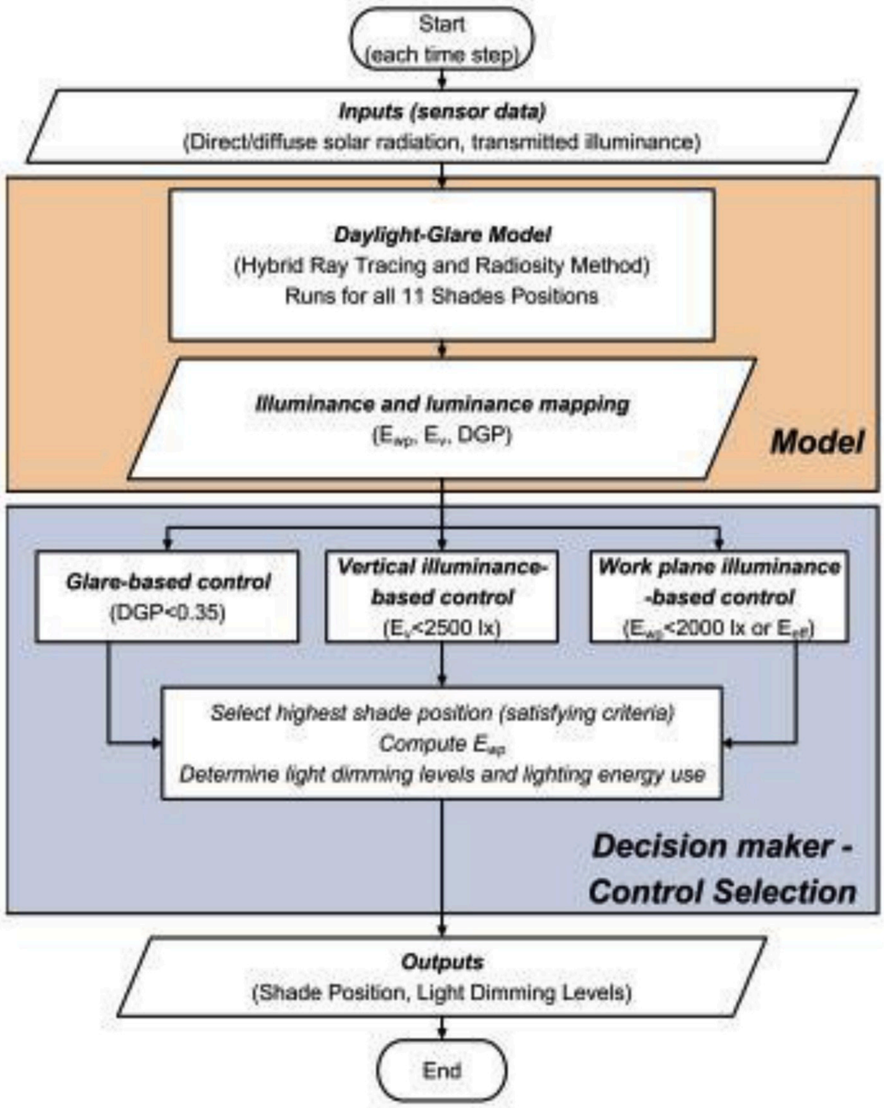

Fig. 9. Implemented model-based controls in Ref. [89].

MBC recommendations were among top 10% of UF. Similarly, another study by Ref. [85] simulated predefined slat angles and obtained the proper states through a ranking procedure. Then, a comparison was conducted between three open-loop strategies and two MBC strategies depending on penalty functions with fixed weighting coefficients as individual priorities, in which MBCs improved energy efficiency along with thermal/visual comfort significantly. However, these methodologies represented static and highly simplified example of individual preferences that is far from real use situations (e.g. preferred indoor illuminance was assumed fixed). But, using MBC approach and virtual sensors had several advantages: (1) reduces the need for physical sensors for various performance monitoring, (2) virtual sensors can obtain wider range of information comparing with physical sensors, and (3) makes the integration of multiple systems (heating, lighting, ventilation, or glare) explicit.

Furthermore, a research study validated the accuracy of MBC to deliver a balance between daylight, glare and view out and compared its overall performance with two common existing blind strategies; cut-off and radiation control [86]. Based on simulation results, model-based controller balanced daylight admission and glare protection better than the other two strategies due to the proposed optimization process (Fig. 8), however, in terms of window occlusion height no improvements were reported. Also, the new method reduced the energy demand substantially up to 10%, while view to outside remained a very complex metric to satisfy occupants.

Yun [7] used DGP to evaluate visual comfort and energy loads by implementing 10 different MBCs for venetian blinds, and first stated that E_v is a better metric compared to DGP to evaluate glare that confirmed by other researchers [87]. The results showed that the control strategy highly depend on the control priority, or the season, but dynamic shading control proved better performance in most cases. Obtaining DGP data in real-time is challenging, therefore several studies used DGPs and vertical eye illuminance specifically, since they can be simulated in real-time. Based on previous studies [88], Xiong presented the implementation of three integrated MBCs of a roller shade (Fig. 9) [89], including: DGP-based, E_v-based, and effective illuminance (E_{wp})-based controls. The control logic attempted to select the highest shade position among pre-calculated possibilities of 11 shading positions at each minute. Particularly, DGP-based control showed lower frequency of shade movements and a better glare controller compared to E_v-based, and (E_{wp})-based resulted in higher glare discomfort over the year, but higher view accessibility to outdoors. In terms of lighting energy loads, only (E_{wp})-based performed slightly better. In addition, the study proposed a variable control interval for DGP-based method that could reduce the

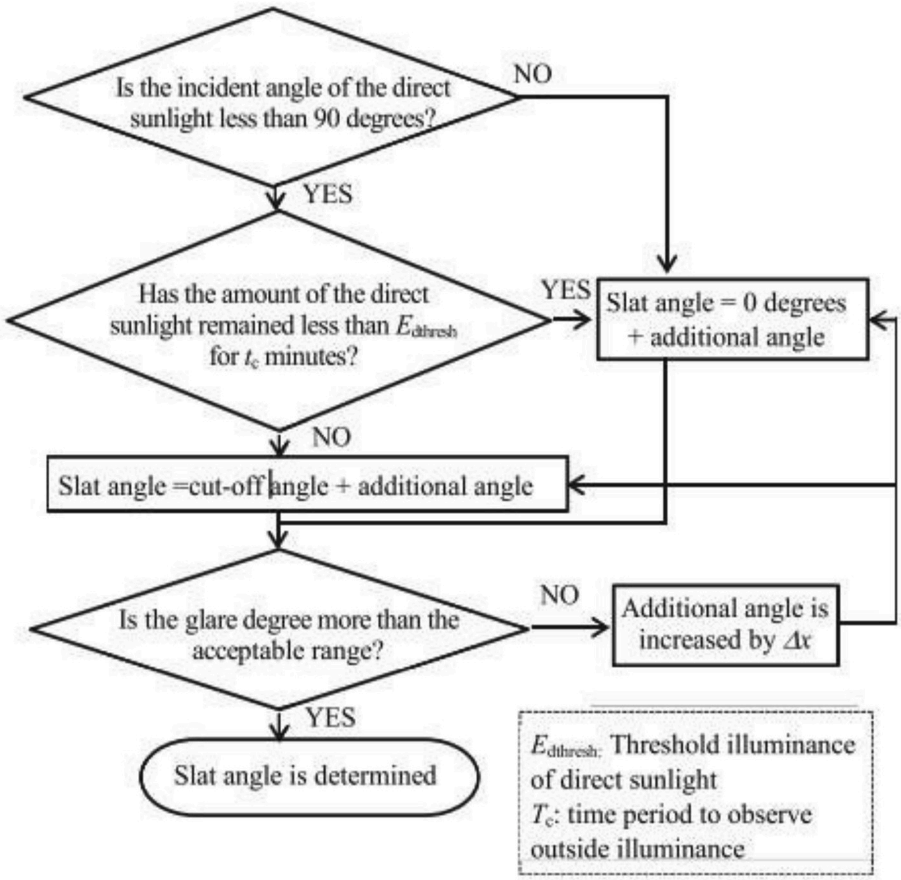

Fig. 10. An example of closed-loop control for venetian blinds [5].

number of shading movements by 25% with the same discomfort glare rate.

5.5. Closed-loop control

Following the closed-loop control, Iwata [5] used PGSV metric and calculated window luminance towards blind control based on glare prevention and focused on ceiling illuminance to reduce the electric lighting demand (Fig. 10). Results showed 30% reduction of lighting load, while keeping view satisfaction up to 50% during working hours, however, the control strategy was only suitable for open spaces with interior partitions that could block the direct sunlight and view out evaluation found to be extremely complicated and required further investigations. A new scenario for roller shade deployment with five positions from fully-closed to fully-opened was conducted by Ref. [90], in which implementing a feedback loop could achieve DGP less than 0.4 and save lighting energy up to 91% comparing with the worst scenario (fully-closed) for the entire year.

Several studies investigated both open-loop and closed-loop controls together [64,66,68]. Shen [68] quantified four independent and two integrated strategies and improve their performance by pairing HVAC and occupancy information (Figs. 11 and 12). Compared to the base case with no blinds and blinds with no control, the fully integrated strategy without blind height control performed the best in both visual comfort and energy saving modes, while independent control strategies increased energy load and visual discomfort. However, the study simplified the glare control strategy and HVAC system due to the limitation of simulation settings compared to real-world controls.

With a similar approach [64], two open-loop strategies (cut-off) and a closed-loop glare control (Fig. 13) have been assessed numerically. Experimental results showed that automatic blind control based on external inputs (sky condition and global irradiance) delivered more daylight into the space, while employing glare control caused in lower indoor illuminance, but ensured a glare-free environment. However, both control strategies improved lighting savings up to 85% throughout the year.

5.6. Other controlling improvements

Several studies outlined the importance of building orientation, glazing portions, shading properties and their effect on automatic shading control [4,78,81,91]. These studies attempted to solve part of the objectives through implementing open-loop protocols without adopting a feedback loop as confirmed in Table 3. The majority of them integrated a closed-loop lighting control into open-loop shading control, but only three of them allowed a HVAC control for shading strategy which is a complex design challenge [67,92,93].

More design improvements have been carried out regarding venetian blinds like adjusting different reflectance on back and front slat surfaces [92], that could eliminate glare (less than 0.1% in entire year) and save energy by 29.2%, or proposing a closed-loop split-controlled venetian blinds [93,94]. In this study [94], a control method based on daylighting and view modes was used to change blinds angle proportionally (split blinds) according to their position on the window (Fig. 14). The control method could improve energy savings up to 37% and indoor illuminance compared to conventionally-controlled blinds. However, glare was evaluated only based on UDI metric.

5.7. Sources of input signals

As discussed earlier, the initial stage of any automatic control strategies relies on their incoming information from sensors that read

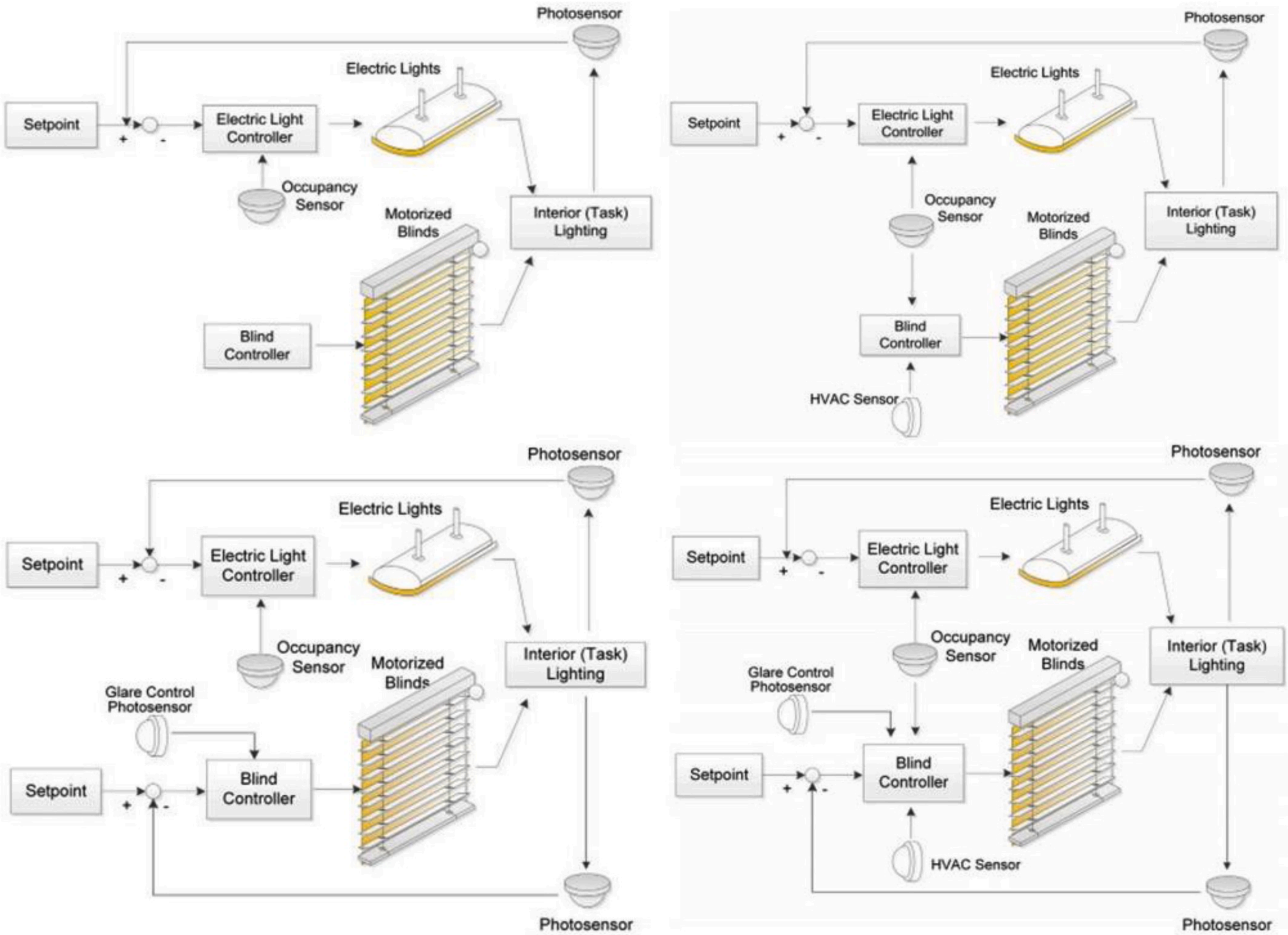

Fig. 11. Examples of independent control loops [68].

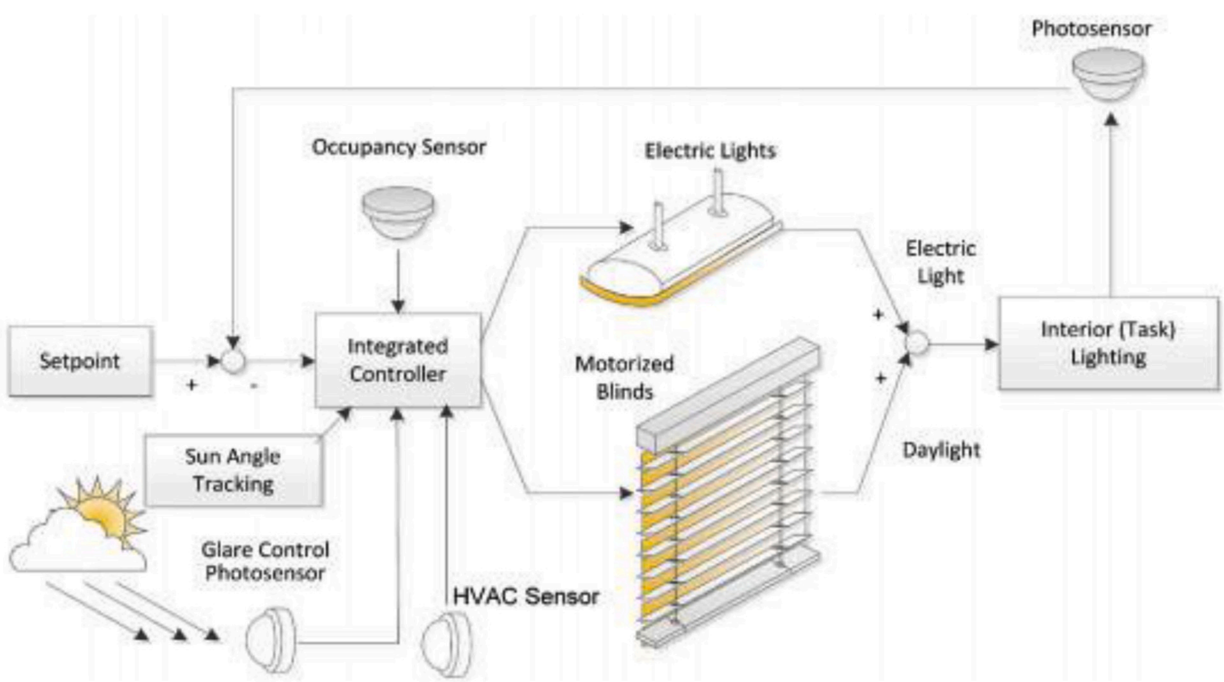

Fig. 12. Example of an integrated control loop [68].

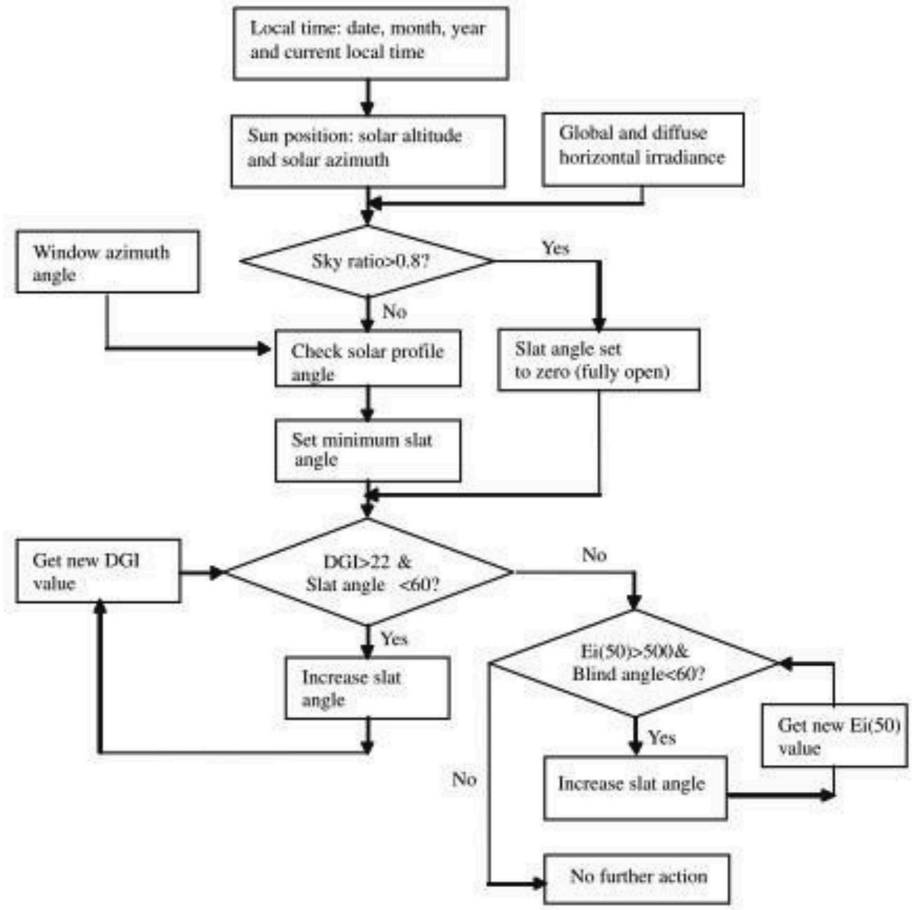

Fig. 13. A closed-loop control to control glare [64].

indoor/outdoor environmental conditions. With respect to simulation-based methodologies within reviewed studies (Table 2), weather file information was the main source of several outdoor environmental conditions including global irradiance, solar radiation or temperature to adjust the shading systems [73,85]. In addition, glare index was also evaluated mostly for a seated occupant towards workstation or window [4,82], although only two studies used DGP as a sensor using Radiance [82] and DIVA [90] interfaces. Moreover, the number of indoor sensors for reading illuminance or temperature values were limited to two reference points due to the incapability of the simulation interfaces such as EnergyPlus [79] or an average value of a number reference points regarding indoor illuminance was used for energy calculations [72].

Among studies that were conducted real measurements to verify the performance of a control strategy (Table 3), different input signals and locations were used for shading adjustments including; (1) sky condition that was basically triggered by one sensor on rooftop using pyranometer [72] or converting to global and diffuse horizontal illuminance through digital camera [84], (2) global irradiance on window surface or façade [67,75,89], (3) indoor horizontal illuminance sensors that were elevated between 0.7 and 0.8 m from the floor to measure the incoming natural light on individual task planes [72,86], (4) indoor vertical illuminance to capture the possibility of discomfort glare that were placed at eye level (seated position ~ 1.2 m) either for individual users [86], or a single position towards window [67,75], or (5) DGP value using HDR camera at eye level for a standing user (1.7 m) [72].

6. Conclusion

The article reviewed existing state of the art in automatic shading controls for adaptive facades that allowed counterbalancing human comfort (visual and/or thermal comfort) and building energy performance. The aim of the review was exploring potential approaches to control shading systems at early stages of design through simulation tools. Following the individual critical review of each study and the summarized analyses shown in Table 2, there are several significant research findings and gaps towards automatic shading control as outlined below:

- Most of the literature on automatic control is oriented to manipulate shading systems for daylight harvesting to reduce electrical lighting, or cooling/heating loads. A compromise between human comfort and energy consumption is an appropriate solution, but few of the studies focused on thermal comfort and none of them investigated all five main objectives altogether (thermal comfort, daylight, view, glare, lighting/energy saving). Each research study employed its own control method to evaluate the shading efficiency. This means there are still no reliable standards and building designers have to customize their control decision making. In other words, high-technology and different control protocol exist and seem to be efficient, but '*are we able to define an optimal control for a shading system?*'
- Venetian blinds and roller shades in different positions were the main focus as adaptive facades with different automatic controls, and the number of studies that used complex shading devices (e.g. origami-based facades) is none at the time of this review, that may prove their limitations in utilization currently.
- Task illuminance, global irradiance and indoor/outdoor temperature have been the most cited driving signals for automatic control. However, global irradiance is expressed in different terms like solar radiation or beam/direct sunlight. With respect to glare and thermal comfort metrics as outputs of the studies, E_v, DGI, DGP or its

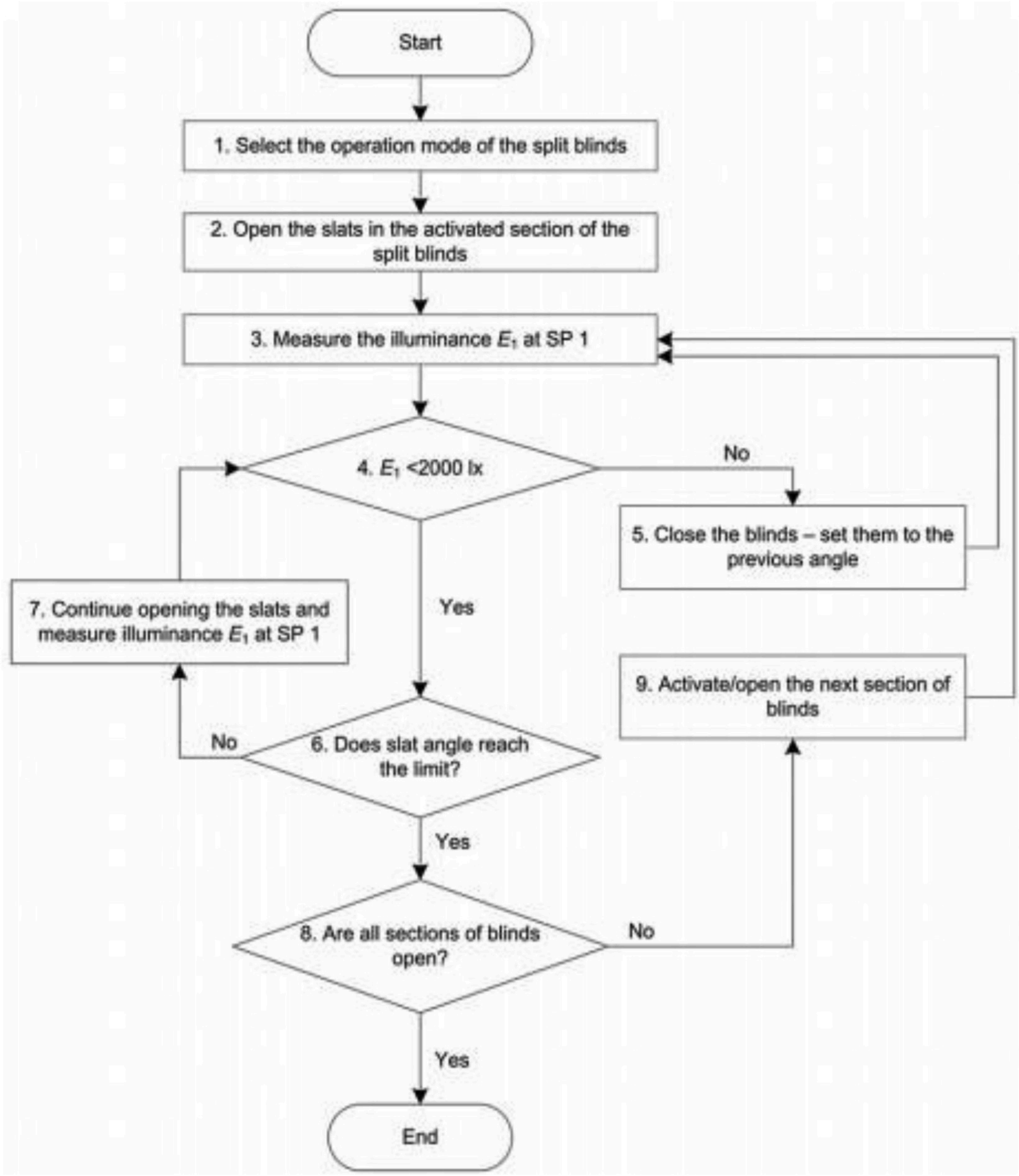

Fig. 14. Closed-loop split-controlled venetian blinds [94].

modified versions, and PMV-PPD model are evaluated mostly. Each one has their own limitations in human comfort evaluation, however several studies suggested E_v is a better indication of discomfort glare.

- It is very difficult to generalize and assess the compatibility of each visual comfort index with the proposed control strategy, since each of them was evaluated in different climatic conditions and under specific circumstances such as the location of illuminance or glare sensors within the space or user's distance to façade. Also, with respect to the spatial dimensions, there is no standard room for conducting simulation-based methodologies to control an adaptive facade.
- With respect to the frequency of shading adjustments due to the automatic control strategies, only one study [89] proposed a model-based control methodology to reduce the number of shading movements throughout a year when a glare control strategy was in charge (DGP-based).
- With respect to environmental conditions, there is no clear correlation between climate types and automatic control efficiency, however, cold climate has been mostly investigated.
- Among 30 reviewed studies, the most comprehensive research study is conducted by Ref. [67] in Nordic countries (covered four of the main objectives), although, it is based on no-feedback control loop (open-loop).
- None of the studies evaluated the impact of automatic shading control on user comfort individually in a shared work environment such as open-plan offices. Only one study [4] compared the energy implications of predefined control strategies between a single and two occupant office space.
- According to selection criteria of Table 2, it can be concluded most of the studies used EnergyPlus simulation tool [96] for shading control assessment. Almost one third of the studies (36%) verified the proposed control strategy with real measurements, but very few studies have reported the integration of model-based control (MBC) with control loops which can deliver a great potential of replacing indoor/outdoor real sensors with virtual signals to make a closed-loop control more cost effective.
- Among 23% of studies that investigated closed-loop control and were expected to involve user preferences in their feedback loop, none of

them considered it as an input for an automatic approach. However, two studies proved the potential of adding simplified user preference factor into open-loop control [69,83]. As such, examples of entailing occupant demands in automatic control are relatively limited.

- Occupant's preference has shown to be the most important factor to determine the level of automatic control efficiency, in which glare and view access to outdoors were the dominant factors of user satisfaction in offices [97]. Several studies confirmed that occupants can endure short periods of glare discomfort if view is available [98, 99]. Thus, it is necessary to do glare analysis in combination with indoor illuminance and view to avoid control methods that entirely block view connection to exterior, although, view is often neglected in two third of studies due to its quantification difficulties. Also, due to simulation limitations, glare evaluation is done either in one or at most two reference points in a space, where in case of multi-occupant spaces glare can happen any time in different locations.
- Among human comfort evaluation, daylight and glare have the highest contribution in literature (80% and 64% respectively), where thermal comfort is assessed only through open-loop control in 23% of studies. Alternatively, only in three studies, energy or lighting load were not the focus of studies, while the same portion focused on the correlation between automatic shading control and HVAC system.

Based on the literature review, several recommendations are outlined that require further investigations:

- Designing an integrated automatic control for adaptive facades is needed to cover human comfort objectives and energy altogether.
- Only typical AFs are used within studies like venetian blinds and roller shades that could not deliver multi-objective control over diverse human comfort perspectives along reducing energy consumption simultaneously. This can be mostly due to available control technologies and the design features of these types of facades that are limited to certain number possibilities like slat angles or opening/closing. Therefore, future investigations need to develop different design layouts for adaptive systems such as origami-based facades [100] with higher flexibility that can respond to immediate indoor and outdoor environmental changes through a wide range of configuration possibilities.
- Despite the diversity of preferences of each individual, the main social constraint of occupants in shading control is presence of others. However, current studies did not deliver an automatic shading control strategy for individual users in a shared working environment.

Finally, there are many studies that outlined the possible limitations of automatic shading controls in two main principles [101]: (a) they are more accepted if users can overrule them, and (b) users are highly satisfied if automatic controls meet their preferences, otherwise they are a source of discomfort. Therefore, there is a need for shading controls based on user demands and preferences that opens a new challenge and will be reviewed by authors in a future study.

Acknowledgment

The aim of this research is to contribute to the body of knowledge of the International Energy Agency (IEA) Energy in Building and Communities (EBC) Annex 79; Occupant-Centric Building Design and Operation.

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