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Control algorithm for dynamic solar shadings: A simulation study for office buildings based on ISO 52016-3

Aurora Bertini [a,*], Hervé Lamy [b,c], Alireza Norouziasas [d], Dick Van Dijk [e], Alessandro Dama [f], Shady Attia [a]

[a] Sustainable Building Design Lab, Dept. UEE, Faculty of Applied Sciences, Université de Liège, Belgium
[b] Groupement Actibaie, France
[c] Technical Committee ES-SO, Belgium
[d] Department of Civil and Environmental Engineering, Norwegian University of Science and Technology (NTNU), Trondheim, Norway
[e] EPB-research, Delft and Expert at the EPB Center, Rotterdam, the Netherlands
[f] Department of Energy, Politecnico di Milano, Italy

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ABSTRACT

In 2019, the building sector was accountable for emitting 12GtCO$_2$, equivalent to 21 % of global GHG emissions. To achieve carbon neutrality by 2050, the building sector must change its pace. One of the ways to achieve this goal is through the installation of dynamic solar shadings in buildings. This study focuses on a single office in two locations characterised by a temperate climate: Liège (Belgium) and Milan (Italy). Two control strategies are designed for Venetian and Roller blinds, one with and one without glare evaluation. They both integrate horizontal illuminance, room occupancy, indoor operative temperature and vertical irradiance according to a multi-criteria approach based on ISO 52016-3. The control strategy aims to balance visual comfort, heating, artificial lighting and cooling energy needs and considers user satisfaction by evaluating the shading activation time. The control algorithms are applied and validated on a DesignBuilder shoebox model. Regardless of location, the control strategy that includes glare control improves the user's visual comfort in terms of light quantity and discomfort glare. However, a total annual energy needs increase is registered independently of the shading. Conversely, if glare is not included in the control strategy, control of thermal loads is observed. This work contributed to developing ISO 52016-3 shading control scenarios for offices and is intended for shading producers, solar shading associations, façade engineers, facility managers and the scientific community working on solar shading simulation and analysis.

1. Introduction

In 2019, the building sector was responsible for 31 % of the global final energy demand, 18 % of global energy demand, and the emission of 12 GtCO2, corresponding to 21 % of global GHG emissions [1]. Rising temperatures caused by climate change will lead to even higher cooling energy needs [2]. Consequently, the building sector needs to accelerate its transition to achieve climate neutrality by 2050. To enable this, the European Union is guiding the building sector towards improving energy efficiency, requiring, among all the measures, the application of a smart readiness rating for non-residential buildings [3]. This scheme will evaluate the building's capability to adapt to energy systems and occupants' needs [4].

One potential solution to decreasing the environmental impact of buildings and reaching European targets is the installation of dynamic solar shadings in office buildings [5]. This technological solution can improve visual and thermal comfort for users near windows while reducing the energy consumption of office buildings [6,7]. However, the issue is finding a user-accepted control strategy that balances these latter aspects [8]. As suggested by Karlsen et al. [9], this entails ensuring users have a good view of the outside and daylight, which may conflict with the achievement of indoor visual comfort and energy-saving goals.

The scientific literature has primarily focused on developing automatic control strategies for daylight harvesting to reduce either electrical lighting or cooling/heating loads in cold climate areas [10]. Few studies have adopted a multi-criteria approach combining daylight, view, glare, and lighting/cooling/heating energy savings. This research

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* Corresponding author. Building 52. Quartier Polytech 1, Allee de la Decouverte 13A, 4000, Liege, Belgium.
E-mail address: aurora.bertini@uliege.be (A. Bertini).

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Abbreviations

BC	Base Case
CV(RMSE)	Coefficient of Variation of the Root Mean Square Error
DGI	Discomfort Glare Index
DGP	Daylight Glare Probability
$E_{h,on}$	Horizontal illuminance on the work plane
EMS	Energy Management System
$I_{sol,w}$	Vertical Irradiance on the Window
MBE	Mean Bias Error
OF	Openness Factor
RB	Roller Blinds
S1	Strategy including glare evaluation
S2	Strategy not including glare evaluation
$T_{op,in}$	Indoor Operative Temperature
VB	Venetian Blinds
VB0	Venetian Blinds with slat angle of 0°
VB45	Venetian Blinds with slat angle of 45°

addresses this knowledge gap by designing a new shading control algorithm for two shading technologies (Venetian blinds (VB) and Roller blinds (RB)), which includes all the above-listed parameters. The algorithm's effectiveness is evaluated by comparing the performance of a single office with and without dynamic solar shadings in two locations, Liège (Belgium) and Milan (Italy). The following question will be investigated: What is the optimal shading control strategy in a temperate climate to maximise office occupants' satisfaction and visual comfort while reducing the annual building energy need for heating, cooling and artificial lighting?

Practically, it means to answer the questions here below:

- How do we hierarchise daylight, glare, and energy needs?
- How does the control strategy influence annual energy needs, visual comfort, and user satisfaction?

The novelty and added value of this work lie in designing a novel multi-criteria algorithm, which, concerning the choice of parameters and indicators to be included in the algorithm, complies with the new ISO 52016-3 standard (International Organization for Standardization (ISO), 2023). Moreover, the algorithm optimises visual comfort, annual lighting, cooling and heating energy needs based on all-year simulations. User satisfaction is also considered through an a-posteriori evaluation of the shading activation time that impacts view to the outside and daylight availability. The last added value is that the designed algorithm is tested for two shading technologies and locations in temperate climate areas, regions yet to be widely addressed in a scientific community mainly focused on cold climate zones [11].

The study involves and has an impact on multiple stakeholders. In the short term, the work implements a multi-criteria control algorithm that focuses on office occupants (especially the ones seated close to windows) and could be reused in further studies on more complicated adaptive façades. In the long term, the work addresses producers of shading devices, solar shading associations and façade designers, aiming to develop new, cost-efficient, intelligent and easy-to-integrate dynamic solar shading systems that could accelerate building renovation in Europe. Moreover, by guiding facility managers to adopt people-centric shading control strategies, dynamic shadings could contribute to delivering not only more efficient offices but also more comfortable and livable buildings.

The paper is organised as follows. Section 2 reviews shading control algorithms studied in the literature, identifying the knowledge gaps addressed in this work. Section 3 describes the methodology adopted, presents the case study and its location, describes the control strategies for the selected shading technologies, and describes the model validation and the postprocess of simulation results. Section 4 presents the control algorithms and their impact on annual energy needs, visual comfort, and user satisfaction. Section 5 discusses key findings, final recommendations, strengths and limitations of the work, implications on the practice for the mentioned stakeholders, and potential future research pathways. Section 6 concludes the paper.

2. Literature review

The building envelope acts as a physical barrier between the interior and exterior of a building. It is directly exposed to weather elements and their short- and long-term variations, which affect the users' comfort and the building energy consumption in a contradicting way [12]. Adaptive façades have been developed to provide user comfort and reducing energy needs [13]. According to ISO 52016-3, these building components are defined as "components with properties that vary as a function of specific situations or events" such as set points, occupant intervention or complex algorithms, and can adapt to the variations of the environmental conditions, weighing the Indoor Environmental Quality (IEQ) and energy needs of the building [14] both in Winter and Summer [15,16].

The design of dynamic solar shadings requires the selection of appropriate shading technology, material and façade position. The choice of technology and material depends on several factors such as climate, building orientation, prevailing wind conditions, building height, building character, regional preferences, building construction details, user expectations and behaviour ([17]; W. [18–20]). Venetian Blinds (VB) and Roller Blinds (RB) are the most commonly used dynamic shading technologies in office buildings. VB are made of horizontal orientable equally-spaced louvres. They are effective in providing thermal comfort, visual comfort and privacy. RB mainly controls glare and daylighting [21]. They are usually made of fabric characterised by its light and solar energy transmittance and reflection, thickness, openness factor (OF) and colour. This technology can also provide a good view of the outside if the correct combination of and colour is chosen [22].

Once the shading type is chosen, the effectiveness of dynamic shadings depends on the implementation of a proper control strategy. Automatic control systems are preferred over manual controls because they better manage lighting, energy loads, and user comfort, with different results according to the climate (if heating or cooling dominated) [23,24], the building orientation and the window size [25]. However, the control design must include occupant-façade interaction [26] and the occupant's perception of comfort [27] to be effective. Users are more satisfied and productive if automatic control systems comply with their preferences, such as the possibility of overruling them [28] or providing a view of the outside and daylight access [29–31]. On the other hand, if control algorithms are energy-efficient but do not provide occupants' comfort and satisfy their needs, users override or disable control systems [30,32], resulting in higher building energy use [33].

The field of building control systems has seen a growing interest in recent years, with researchers focusing on developing control algorithms to improve the energy efficiency and occupant comfort of buildings. Three broad categories of control algorithms can be distinguished: threshold controllers, blocking controllers, and mode and scene controllers [34]. With threshold controllers, blinds are activated according to the solar radiation level on the façade. However, this control strategy is deemed ineffective in minimising the energy demand [23], purpose that would require shading control strategies based on indoor conditions [35]. Blocking controllers move blinds according to the sun's position, allowing to control glare and keep proper illuminance levels while reducing cooling and lighting energy needs compared to fixed shadings [36–38].

Mode and scene controllers combine vertical irradiance, temperature, illuminance on the work plane and glare risk. Table 1 resumes some of the studies adopting this type of shading control. Regarding visual comfort, these studies agree that shading algorithms guarantee glare control and proper horizontal illuminance on the work plane. In terms of energy needs, they show that the use of shadings increases the heating energy needs due to the loss of solar gains in Winter, suggesting the importance of introducing in the shading control strategy the evaluation of indoor temperature to benefit from daylight and solar gains during Winter. Following the same logic, shading activation reduces cooling energy needs and overheating hours. Finally, concerning artificial lighting, energy needs are higher or lower according to the user's preferences (e.g., the level of accepted horizontal illuminance on the work plane) and the type of lighting control. In fact, non-dimmable luminaires would induce higher lighting energy needs than an ideal lighting control. Combining the results obtained for heating, cooling and lighting, the literature shows that the use of shading control algorithms allows for a reduction in building energy use, especially in locations where cooling loads are high, and hence the negative impact on lighting and heating demand does not offset the decrease in cooling energy needs.

These results highlight the importance of adopting a methodology based on a hierarchy of multiple factors to successfully designing shadings [39]. However, few studies employed a multivariable control strategy due to their design complexity. Most studies focus on daylight performance. Thermal performance analysis is limited [39], the view is neglected in 2/3 of the studies due to its difficult quantification, and none of the studies adopting a closed-loop control considered user preferences as an input. Therefore, the main control inputs are daylighting and glare, and most of the literature on automatic control is focused on daylight to reduce artificial lighting or heating and cooling energy. None of the studies investigated daylight, view, glare, lighting, and energy savings altogether [11]. Here lies the main knowledge gaps in the literature [35]: an integrated automatic control to cover human comfort objectives and energy altogether is needed [11]. This is what this study aims to do: design a new control strategy that optimises and properly hierarchises visual comfort (in terms of light quantity and glare comfort), heating, cooling and artificial lighting energy needs, considering user satisfaction related to the view to the outside through the evaluation of shading activation time.

The control algorithm is designed following the new ISO 52016-3 (2023) (ISO, 2023), which provides a methodology for calculating energy needs for heating and cooling, considering the integration of adaptive building envelope elements. ISO 52016-3 suggests parameters to be included in shading control scenarios and their relative thresholds, according to the most used indicators in literature and the available sensor technologies (to measure them in real applications). Moreover, it provides reference control scenarios for different shading technologies (VB, RB and electrochromic glazings) and building uses (residential and non-residential). They are obtained by combining the considered parameters and selecting, among the 144 combinations that can be obtained, the 20 most relevant that are finally associated with a different extension of the shading and into a different slat angle.

3. Methodology

This work applies the so-called modelling approach, a methodology based on creating a numerical model of the building under study to test the control algorithm. The research has been conducted in accordance with the framework depicted in Fig. 1.

After conducting a literature review, the focus shifted to data collection about the site, building, and solar shadings. Based on the collected data, it was possible to make the building model using DesignBuilder and define the control strategy to adopt. The control strategy was divided into two parts: during working hours, where the primary aim was to provide visual comfort to the users while maximising their satisfaction, and outside working hours, where the focus was on minimising energy needs.

The algorithm, written in the Energy Management System (EMS) language on DesignBuilder and was tested on the office model. The results were post-processed in Excel to analyse the shading behaviour and the impacts of the control algorithm on visual comfort, energy needs and view to the outside.

To conduct this research, boundary conditions and hypotheses were established. Firstly, the study focuses on a single office built in a temperate climate and oriented towards the South. The office's orientation is fixed, so the impact of the room orientation on the shading performance is not analysed. The office is occupied by a single user, who can assume two orientations: obliquus (45°) and perpendicular to the plane of the window. The variation in the activity type or the number of occupants is beyond the scope of this study.

Regarding building systems, the office is equipped with heating, cooling, and mechanical ventilation. Since the study focuses on the control algorithm's design and its impact on the visual and energy performance of the office, the HVAC system is auto-sized by the software, and its type remains constant across different simulations. Therefore, the impact of varying heating, cooling, and lighting system types is not analysed. Natural ventilation is only possible during the day, as is the case in the reality of the case study. Hence, the evaluation of the nocturnal passive cooling effect provided by natural ventilation is out of the scope.

Concerning the envelope, considering the building type and climate, a solar control double glass unit was adopted for all the window configurations, with and without shading. Two shading technologies were selected and tested: external VB (with a fixed slat angle of 0° and 45°) and external RB. The choice to keep VB's slat angle fixed is related to the cost of sun azimuth and elevation sensor, which led us to exclude the sun's position from the control strategy. Finally, due to a software limitation, the shading can only have two states: fully up and fully down. It is not possible to partially shade the window.

3.1. Climatic analysis

Two cities were selected in this work: Liège and Milan (Fig. 2). Liège corresponds to the location of the real case study building and was chosen to represent the temperate climatic conditions of Northern Europe. Milan, instead, is characterised by hotter and more humid Summer conditions and, hence, by higher cooling loads. Moreover, it is the city with the most significant office stock volume in Southern Europe's temperate regions [43].

The climatic analysis of Liège was conducted utilising the.epw file of Beek, which represents the climatic conditions associated with Bierset-Liège Airport in DesignBuilder. For Milan, the.epw file of Milan available in DesignBuilder was used. Data analysis was conducted using Climate Consultant (Ligget et al., s.d.).

3.1.1. Climatic analysis of liège

According to the Koeppen-Geiger climate classification [44], Liège is characterised by a Cfb climate, i.e., a temperate oceanic climate with cool summers and mild winters for its latitude. The warmest months are July and August. In July, the highest average temperature is recorded, while in August, the maximum temperature reaches 36 °C. Temperatures exceed the comfort range of 20–24 °C from May through September. Additionally, the highest solar radiation is registered in the hottest months of the year, leading to an increase in heat gains in the office.

Concerning global horizontal illuminance, the monthly average illuminance exceeds 1000 lux throughout the year, with a peak of 3700 lux in July. The maximum absolute value registered is 96000 lux, which could cause a severe visual discomfort inside the office.

Based on the Givoni diagram, when the external air temperature passes 20 °C, the installation of a shading system is the most effective solution to improve thermal comfort in the office.

Table 1
Summary of the studies on the design of control strategies for dynamic shading, with the independent variables introduced in the algorithms and the outcomes analysed.

Ref.	Year	Control algorithm independent variables									Study objective	Results
		Indoor temperature	Solar irradiance	Occupancy	Glare risk	Horizontal illuminance on the work plane	Vertical illuminance	Desktop illuminance	Sun position	Shading fraction		
[23]	2015	X	X	X				X	X		Energy needs, glare discomfort, overheating	Reduction in primary energy use, especially in locations with high cooling loads
[35]	2007	X	X								Energy needs, thermal comfort, visual comfort	Increase in heating demand, reduction in overheating hours
[36]	2001								X		Cooling and lighting energy needs, illuminance level	Reduction in cooling and lighting energy use, glare control, proper illuminance levels
[37]	1998								X		Illuminance level, cooling and lighting energy needs	Cooling and lighting reduction, increased daylight availability compared to static blinds
[38]	2021		X	X					X		Lighting energy needs, visual comfort	Reduction in lighting energy use, better glare control and view to the outside compared to cut-off strategy
[40]	2002		X		X	X					Energy needs, visual comfort, daylight distribution, shading movement	Increase in lighting energy use, improved visual comfort (glare and horizontal illuminance on the work plane)
[41]	2017				X	X				X	Energy needs, visual comfort, view to the outside	Reduction in total energy needs, uniform indoor illuminance when shading activated
[30]	2023		X		X	X					Thermal comfort, visual comfort, view to the outside, user satisfaction	No impact on thermal conditions, multi-objective control with intermediate shading position provides sufficient daylighting conditions and view-out maximization while avoiding glare
[9]	2016	X	X	X		X					Energy needs, visual comfort,	Compromise between energy needs, visual

(continued on next page)

Table 1 (*continued*)

Ref.	Year	Control algorithm independent variables									Study objective	Results
		Indoor temperature	Solar irradiance	Occupancy	Glare risk	Horizontal illuminance on the work plane	Vertical illuminance	Desktop illuminance	Sun position	Shading fraction		
											shading activation time	comfort and shading activation time depends on the chosen control algorithm
[42]	2019				X	X	X				Lighting energy needs, visual comfort, shading movement	Annual lighting energy use varies according to user's preference profiles
[27]	2019		X			X			X		User satisfaction (daylight)	The higher the daylight availability and the closer the user to the window, the higher is the user satisfaction

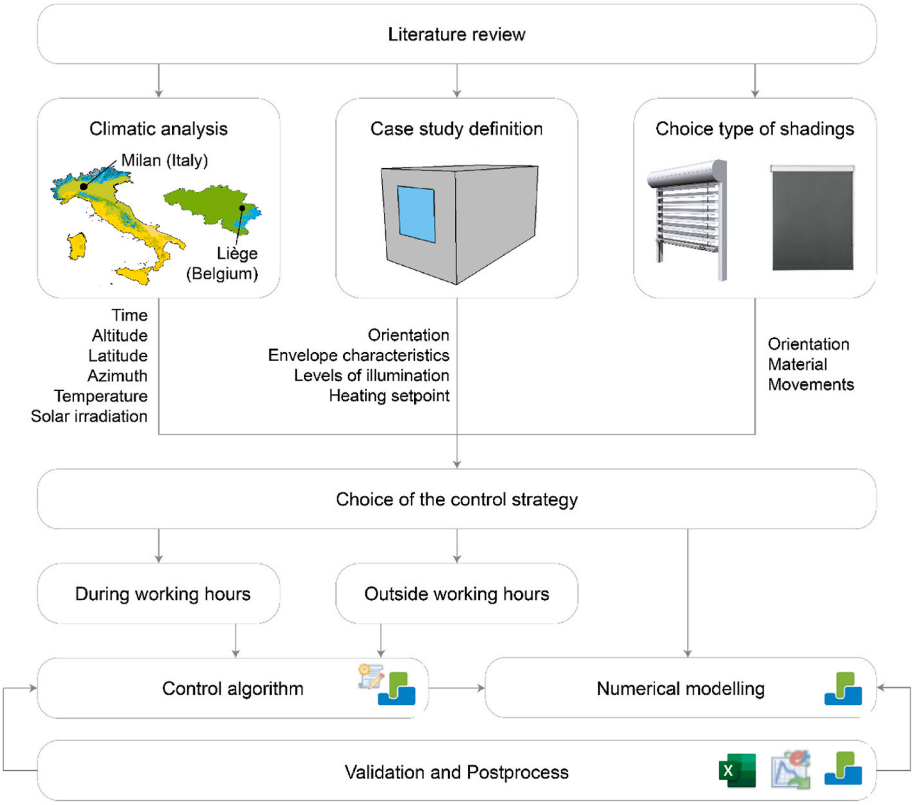

Fig. 1. Study conceptual framework.

Considering that the climatic analysis is done on a typical meteorological year (that does not consider the effects of climate change), installing solar shadings is supposed to be even more relevant to limiting overheating and cooling load in summer. Ultimately, this solution could improve worker visual comfort as well.

3.1.2. *Climatic analysis of milan*

Milan falls under the Cfa climate category, as per the Koeppen-Geiger climate classification [44]. This climatic zone is characterised by a humid subtropical climate with hot and humid summers and cool to mild winters. The warmest month is July, with a maximum average temperature of 33 °C and the highest solar radiation. During the months of May to September, temperatures exceed the comfort range of

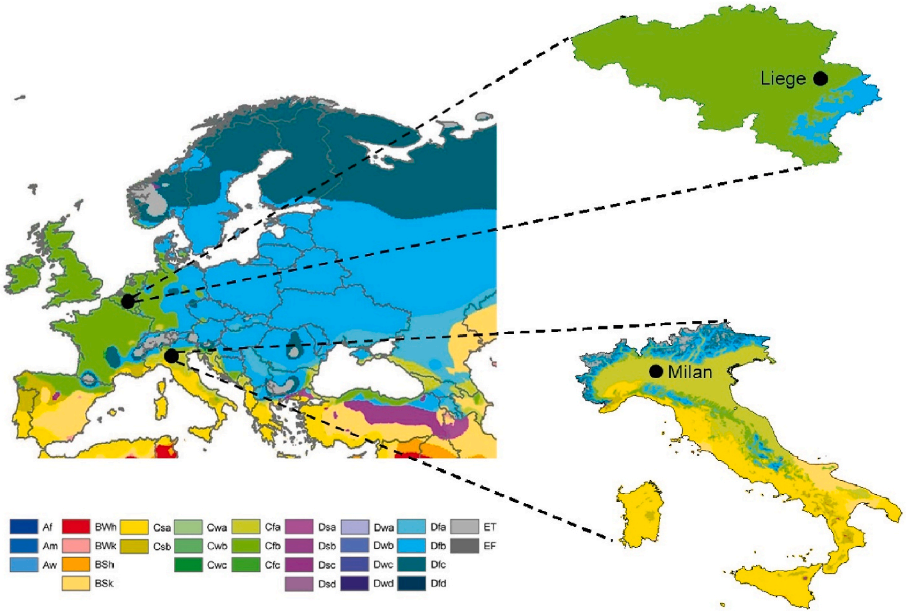

Fig. 2. Koeppen-Geiger classification for Liège, Belgium (50°38′1.43’’N, 5°34′2.96’’E) and Milan, Italy (45°27′51.37’’N, 9°11′22.24’’E). Modified after from Ref. [44] (H. E. [45]).

20–26 °C. Particularly, from June to August, temperatures can remain above 27 °C for the entirety of working hours.

The monthly average for global horizontal illuminance is constantly above 800 lux, with a peak of 3600 lux in July. The maximum absolute value recorded is 74000 lux. Hence, the installation of a shading system is crucial also in this location to enhance the visual and thermal comfort of the worker.

3.2. Case study definition and choice of the type of shadings

The research is centred on a single office in building B52 of the University of Liège. The building comprises two parallel blocks at the North and South of the building connected by a central block characterised by a vast circulation space. The first two blocks have their main axis in the direction North-South and are occupied by offices and laboratories. They are built on five levels ranging from −2 to +2, with level −1 located at the street level at an altitude of −3.24 m. Building plans and elevations are provided in the Appendix for reference.

The office under consideration is situated at level 0 of the Southeast block. The office has a dimension of 3.10 × 5.90 m, with its primary axis oriented in the North-South direction (Fig. 3). The office is adjacent to offices on the West, East, top and bottom, with a corridor on the North and the outside on the South. The office’s window is 160 × 160cm and can only be opened when the room is occupied, as per security reasons. The office is occupied by one user, who works at 1.3 m from the window and can assume two positions, one facing the window (with an orientation of 180°) and the other obliquus to the window (with an orientation of 135°) (Fig. 4).

In the present case, the type of window opening influenced the selection of shadings in terms of technology and fixing mechanism. Specifically, the horizontal pivot opening of the window prevented the installation of a shading system fixed on the extrados of the window. Consequently, external VB and RB fixed on the window frame were adopted, which can turn solidly with the window.

The selection of grey-coloured screens was made to preserve the building’s character given by its stainless-steel finishing. Furthermore, a glass fibre and PVC tissue was chosen for the RB, as it allows users to have a good view of the outside while being fully opaque from the outside when the screen is rolled down. The main properties of the chosen VB and RB technologies are summarized in Table 2.

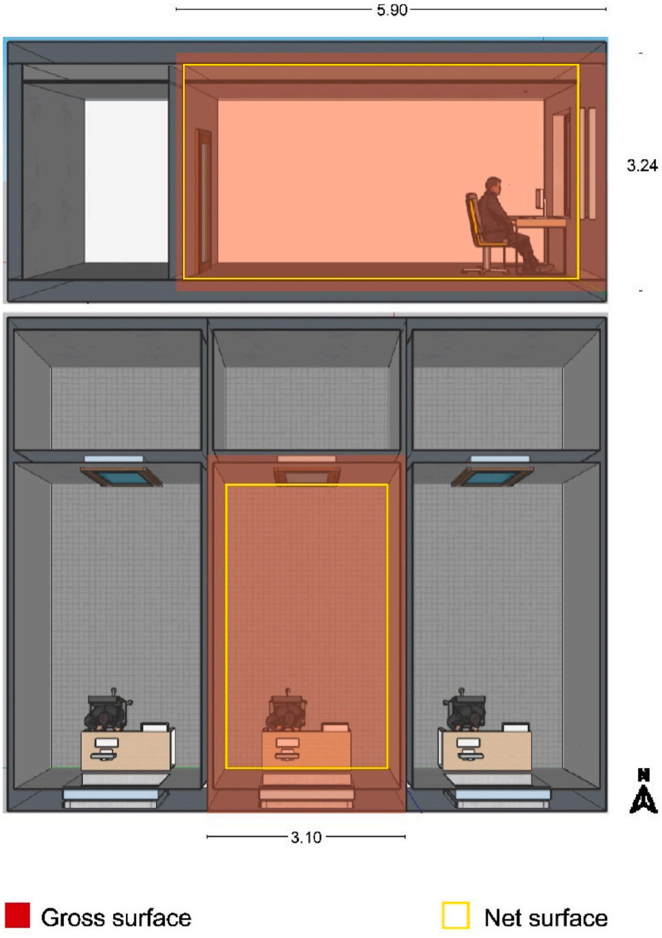

Fig. 3. Office plan and section.

Fig. 4. User's orientation in the office. Perpendicular to the window (180°) on the left, obliquus (135°) on the right.

Table 2

Main properties of the selected VB and RB technology.

VB	
Property	Value
Distance glass-shading	35 mm
Slat depth	25 mm
Slat distance	18.75 m
Slat thickness	0.22 mm
Thermal conductivity	221 W/(m · K)
Slat angle	0/45°
Slat reflectance	90 %
RB	
Property	Value
Thickness	55 mm
Light transmittance	11.6 %
Openness factor	5 %
Solar energy transmittance	12.4 %
Solar energy reflection	59.8 %

3.3. *Choice of the control strategy*

The control strategy employed for the two types of shading is the same and is designed to maximise the visual comfort of the worker while minimising the impact on the office's energy needs. To satisfy those requirements, the control strategy is separated into two blocks, one for working hours and one for non-working hours. During working hours, the primary objective is maximising visual comfort, which requires providing the correct illuminance on the desk and avoiding glare. During summertime, this requirement must be combined with the limitation of solar gains and the impact on the view to the outside. Outside working hours, the aim is minimising energy needs. During Winter, this means taking advantage of solar gains, which, on the contrary, must be limited during Summer.

Meeting these requirements brings us to make contrasting choices regarding shading control. For instance, shadings need to be rolled down to prevent glare, but this limits natural daylight availability and vision to the outside during working hours. Conversely, to maximise heat gains during Winter and reduce the heating needs, shadings must be deactivated, resulting in high glare discomfort for the worker.

Satisfying all requirements necessitates introducing, defining hierarchies and finding an optimum trade-off among the following parameters (Table 3): occupancy, indoor operative temperature, vertical irradiance on the window, horizontal illuminance on the work plane (i.e., 0.80 m) and discomfort glare index (DGI) at the head level (i.e., 1.20 m).

Occupancy is used to differentiate between the control strategies for occupied and unoccupied hours. Indoor operative temperature ($T_{op,in}$) is introduced to characterise the thermal conditions of the office, according to ISO 52016-3. Vertical irradiance on the window ($I_{sol,w}$), as per ISO 52016-3, helps distinguish between day and night. Horizontal illuminance on the work plane ($E_{h,on}$) identifies the low daylight conditions and events, according to ISO 52016-3. It is the only index that considers the contribution of both natural and artificial light. For this reason, it is used in EN 12464-1 to define the minimum illuminance threshold in workplaces (500 lux for offices where the main activity is writing, typing, reading, and data processing) [46].

DGI at the head level identifies the conditions and events for glare occurrence. While ISO 52016-3 suggests using Daylight Glare Probability (*DGP*), DesignBuilder's only available index to evaluate discomfort glare is DGI [47]. DGI is calculated for two user orientations: one with the occupant's view direction of 180° (i.e., the occupant looking towards South, according to DesignBuilder convention), and one at 135° (i.e., South-East). This double evaluation allows to consider in the model a certain degree of freedom in occupant's adaptation and response to eventual visual discomfort during working hours.

Table 3 displays the selected setpoints for the considered parameters. Specifically, the $E_{h,on}$ setpoint was chosen to be 600 lux instead of the 500 lux suggested in EN 12464-1. The rationale behind this decision was that users tend to request a higher illuminance level on the work plane in the case of natural lighting.

As for $T_{op,in}$, the setpoint was selected to achieve optimal control of shadings in the early morning. The cooling setpoint of 25 °C allows for activating the shadings in the early morning when solar gains are

Table 3

Independent variables considered in the study, with correspondent sub-variables, indicators, units of measure and thresholds adopted.

Variable	Sub-variable	Indicator	Unit	Value	Reference
Indoor conditions	Room occupancy	Desk presence	–	0 = occupied 1 = unoccupied	/
	Light quantity	Horizontal illuminance on the work plane – Shading on ($E_{h,on}$)	Lux	600lux at 0.80 m	/
	Temperature	Indoor operative temperature ($T_{op,in}$)	°C	25 °C	/
	Glare	Discomfort Glare Index (DGI)	–	22 at 1.20 m	Hopkinson's scale
	User's orientation	Occupant view direction	°	180°/135°	/
External conditions	Solar irradiance	Vertical irradiance on the window ($I_{sol,w}$)	W/m^2	150W/m^2	[9]

already present and the office is still unoccupied. This action helps to limit overheating during the day since the effect of solar gains takes some hours to be perceptible due to the building's inertia.

In the calculation of the number of hours with discomfort glare, a DGI limit of 22 at 1.20 m was considered since the maximum recommended value for DGI in offices is 22, according to Hopkinson's scale [10,48]. Finally, the setpoint for $I_{sol,w}$ was chosen based on literature [9,49] and considering the type of building and the fenestration size.

To isolate the impact of visual comfort evaluation on energy needs, two different control algorithms were designed: one including the glare evaluation (S1) to maximise the user's visual comfort, and one without glare evaluation (S2), focusing on controlling thermal loads.

3.4. *Numerical modelling*

The model and the algorithm have been designed in DesignBuilder V.7.0.1.6 [50]. The model includes only the analysed office and not the overall building because, to analyse the effect of shadings on the office performance, the office envelope neighbouring the other offices and the corridor is assumed adiabatic. The office is modelled as a single thermal zone, whose gross and net areas are defined according to the Cened handbook [51] (Fig. 3).

Table 4 resumes the main model inputs for building envelope, heat gains, activities, and systems As for the envelope, we can highlight that the properties of the combination glazing/shading were obtained from simulation using the Window software [52].

Concerning heat gains, activities and systems, the operating schedule for building systems was assumed to be the same as the occupancy schedule (Monday through Friday, from 08.00 to 18.00). Mechanical ventilation is employed to regulate humidity and air quality, with natural ventilation as an option in warm outdoor conditions (when the temperature is between 15 and 25 °C) or when the cooling system is not activated and the indoor temperature rises above 27 °C. These temperature constraints for natural ventilation are imposed to minimise heat losses during Winter and heat gains during Summer.

Finally, lighting control was activated to evaluate the impact of control strategies on artificial lighting needs. A 1-step lighting control was modelled, where lights can be in one of three states: on, off, and half power. Two control points were considered, one at 1.30 m from the façade and the other at 1.30 from the opposite wall (Fig. 5). The first one triggers artificial lighting activation when the horizontal illuminance on the work plane is lower than 500 lux. The second control point is positioned in the unoccupied office space, where, since no working tasks are performed, lights can be turned on at a lower threshold, here fixed at 300 lux.

3.5. *Validation and postprocess*

The office's wing of the case study building was audited between 2015 and 2018 [55]. The model was validated using the average data for monthly delivered heating and lighting electricity energy over the three years. For this scope, the whole office's wing of the building was modelled on DesignBuilder. The monitored data and simulation results obtained are compared in Fig. 6. Lighting simulation results correspond to the monitored values, with a maximum error of ± 0.2 kWh/m^2. Instead, simulated heating overestimates the real delivered energy, except for January and February. This discrepancy can be due to the weather file used in the model, the occupancy schedule and the holiday calendar.

According to ASHRAE Guideline 14-2002 [56], two indicators are used to evaluate the reliability of a building energy simulation model: the Mean Bias Error (MBE) and the Coefficient of Variation of the Root Mean Square Error (CV(RMSE)). They are calculated according to the following equations:

Table 4
Model inputs for office envelope, activity, systems and heat gains.

BUILDING ENVELOPE		
Opaque elements		
Parameter	Value	Reference
U-value external wall	0.416 W/(m$^2\cdot$ K)	ULiege technical office
U-value internal wall adjacent to office	2.869 W/(m$^2\cdot$ K)	ULiege technical office
U-value internal wall adjacent to corridor	2.288 W/(m$^2\cdot$ K)	ULiege technical office
U-value floor	1.873 W/(m$^2\cdot$ K)	ULiege technical office
Window frame		
Material	Wood	ULiege technical office
Glazing		
Stratigraphy	6-12 (air)-4 with solar control	ULiege technical office
Light transmittance	71 %	ULiege technical office
Solar energy transmittance	36 %	ULiege technical office
Shading coefficient	0.41	ULiege technical office
U-value	1.50 W/(m$^2\cdot$ K)	ULiege technical office
Glazing + VB45		
Light transmittance	20 %	Window
Solar energy transmittance	10 %	Window
Shading coefficient	0.10	Window
U-value	1.27 W/(m$^2\cdot$ K)	Window
Glazing + VB0		Window
Light transmittance	70 %	Window
Solar energy transmittance	36 %	Window
Shading coefficient	0.41	Window
U-value	1.27 W/(m$^2\cdot$ K)	Window
Glazing + RB		Window
Light transmittance	7 %	Window
Solar energy transmittance	4 %	Window
Shading coefficient	0.05	Window
U-value	1.30 W/(m$^2\cdot$ K)	Window
ACTIVITY, SYSTEMS AND HEAT GAINS		
Parameter	**Value**	**Reference**
Occupancy schedule	Mon-Fri, 08:00–18.00	/
Heating setpoint	20 °C	ISO 17772-1 [53]
Cooling setpoint	26 °C	ISO 17772-1 [53]
Heating system COP	3.9	/
Cooling system COP	2.9	/
Natural ventilation – Indoor maximum temperature	27 °C	/
Natural ventilation – Outdoor minimum temperature	15 °C	/
Natural ventilation – Outdoor maximum temperature	25 °C	/
Illuminance level for artificial lighting activation	500/300 lux at 0.80 m	EN 12464-1 European Committee for Standardization [46]
Discomfort Glare Index	22 at 1.20 m	Hopkinson's scale
Equipment gain	11.77 W/m^2	"Generic working area" DB occupancy template
Lighting gain	11 W/m^2	/
People gain	123 W/person	"Generic working area" DB occupancy template
Ventilation + Infiltration gain	0.85 vol/h	EN 16798-1 [54]

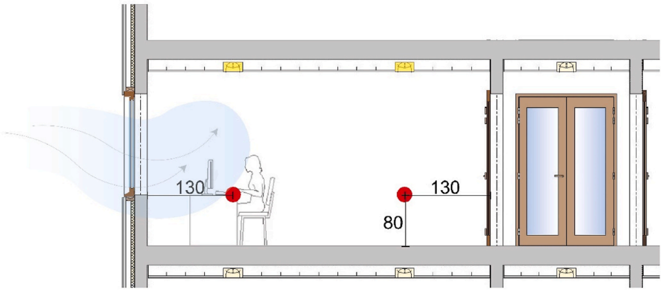

Fig. 5. Position of the lighting control points in the office.

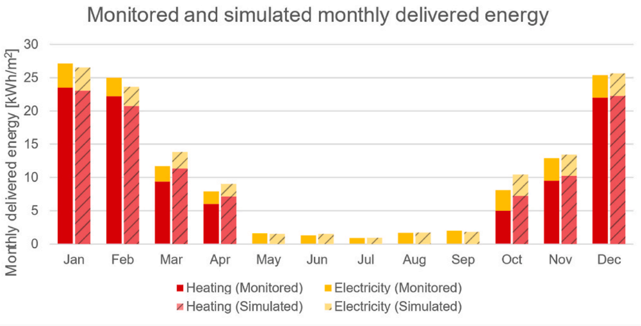

Fig. 6. Comparison of monitored and simulated monthly delivered energy for heating and electricity for the office's wing of the case study building.

$$MBE = \frac{\sum_{1}^{n} m_i - s_i}{\sum_{1}^{n} m_i}$$

$$CV(RMSE) = \frac{\sqrt{\sum_{1}^{n}\left[\frac{(m_i - s_i)^2}{n}\right]}}{\frac{1}{n}\sum_{1}^{n} m_i}$$

Where m_i and s_i are, respectively, the measured and simulated data at point i and n is the number of data points.

In the case of monthly calibrated data, MBE should be lower than ± 5 % and CV(RMSE) lower than 15 % [56]. In this project, MBE for heating and electricity are −4% and 0 %, respectively, and CV(RMSE) are 4 % and 2 %. Hence, ASHRAE requirements are satisfied, and the building energy model is reliable.

Subsequent simulations were run on the single office energy model. Four cases were simulated:

- Case 0: office without shadings (BC)
- Case 1a: office with VB and a fixed slat angle of 45° (VB45)
- Case 1b: office with VB and a fixed slat angle of 0° (VB0)
- Case 2: office with RB

The simulations were run for a typical meteorological year, with an hourly and 30-min timestep. The indicators listed in Table 5 were examined to evaluate and compare the algorithm performance in both Liège and Milan. The total monthly and annual electrical energy needs were calculated according to the following formula (Equation 1):

$$E_n = \frac{E_h}{COP_h} + \frac{E_c}{COP_c} + E_l$$

Equation 1 Total annual/monthly electrical energy needs.

where E_h is the thermal energy need for heating, E_c is the thermal energy need for cooling, E_l is the lighting energy need, and COP_h and COP_c are the annual averaged COPs of heating and cooling systems, respectively.

As for visual discomfort, the number of working hours with horizontal illuminance lower than 600 lux and higher than 2000 lux (which is the threshold corresponding to a too-bright environment [57]), and the number of working hours with a DGI higher than 22 were calculated. The percentage of discomfort hours over the total occupied hours was calculated for both indicators and was subsequently lowered by 5 % according to EN 16798-1 [54], which states that comfort is ensured if the parameter does not overcome its defined threshold for more than 5 % of occupied hours.

Finally, according to the research delineated within Section 2, shading activation keeps users from looking outside, diminishing their overall satisfaction. The variable "user satisfaction" aims to quantify this aspect. Since this study constrains the operational states of shading devices to binary conditions (either "fully opened" or "fully closed"), occupant satisfaction regarding external views is calculated based on the percentage of working hours per year during which shading is activated.

Table 5
Dependent variables considered in the study, with correspondent sub-variables, indicators and units of measure.

Variable	Sub-variable	Indicator	Unit
Visual comfort	Light quantity	Working hours above/below the horizontal illuminance setpoint	Hours/y
	Glare	Working hours above the glare setpoint	Hours/y
Energy need	Heating	Annual heating need	(kWh/m^2)/y
	Cooling	Annual cooling need	(kWh/m^2)/y
	Lighting	Annual lighting need	(kWh/m^2)/y
User's satisfaction	View to the outside	Working hours with activated shading	Hours/y

4. Results

In this section, the designed control algorithm is presented. Its performance is evaluated with respect to its impact on office lighting, heating and cooling energy needs, visual comfort, and user satisfaction. Only the most significant outcomes are presented in this paper. Additional data, such as the analysis of the shading activation profiles throughout the year, monthly office energy needs, and daily visual comfort over the year, are available in the results chapter of Bertini's thesis [58].

4.1. How do we hierarchise daylight, glare, and energy needs?

Fig. 7 represents the designed shading control algorithm including glare evaluation (S1). The algorithm adheres to the following steps:

1. Initially, the office's occupancy status is ascertained to prioritise energy needs minimisation during periods of vacancy and enhance user comfort when occupied.

   Upon confirmation of occupancy:

2. The DGI at the occupant's head level is assessed in two distinct orientations (180° and 135°). Should discomfort arise in both positions, evidenced by a DGI exceeding 22 (according to the Hopkinson's scale, as described in section 3.3), shadings are activated, i.e., RB or VB are fully rolled down, and, in the case of VB, the slat angle is fixed at 0° or 45°. Otherwise, the analysis shifts to thermal loads.
3. Thermal load evaluation encompasses the consideration of two parameters: $I_{sol,w}$, exceeding 150 W/m^2, and $T_{op,in}$ surpassing 25 °C. Shading is not activated if at least one of the two parameters fails to

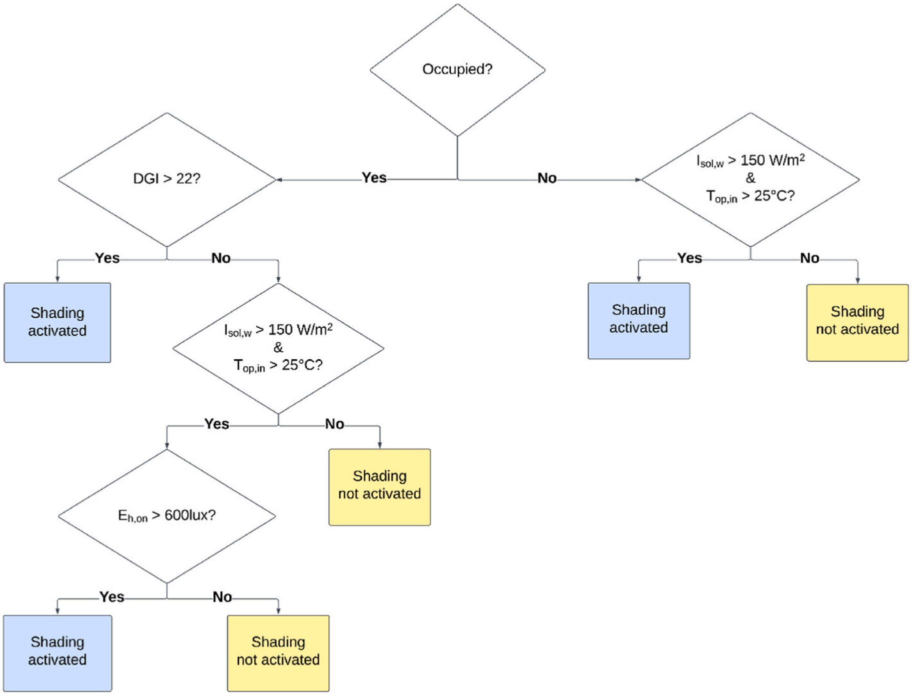

Fig. 7. Control algorithm – Strategy including the glare evaluation (S1).

meet its specified criterion. Conversely, if both these thresholds are met, $E_{h,on}$ is subsequently evaluated. As stated in section 3.3, $I_{sol,w}$ threshold is defined according to literature, type of building and fenestration, while $T_{op,in}$ is fixed at 25 °C to limit solar gains in the early morning. By combining these choices, this strategy endeavours to harness solar gains during Winter (deactivating the shading) while aiming to minimise them only throughout Summer.

4. To prevent the activation of artificial lighting and to offset the reduction in solar gains with an increase in lighting gains, $E_{h,on}$ is assessed post-shading activation, and shading is activated if $E_{h,on}$ remains above 600 lux. This latter threshold, as explained in section 3.3, aims to consider the user tendency of requiring higher illuminance levels on the work plane in case of natural lighting.

If the office is not occupied:

5. The strategy pivots towards minimising thermal loads, thereby mitigating the risk of overheating and the subsequent elevation of cooling loads upon system reactivation, particularly at the onset of the workweek and during morning hours. This objective is achieved by considering $I_{sol,w}$ and $T_{op,in}$, as delineated in step 3 of the algorithm.

S2 mirrors the logic of S1 but omits glare evaluation in step 2 (as depicted in Fig. 8).

Two observations regarding the control strategy are noted:

1. DGI in step 2 is evaluated when the shading is not activated. This precaution aims to stabilize the shading activation profile since activating the shading reduces DGI below 22, prompting the algorithm to deactivate the shading.
2. In step 4, $E_{h,on}$ is consistently evaluated with the shading activated to avoid the necessity for artificial lighting due to the shading's deployment.

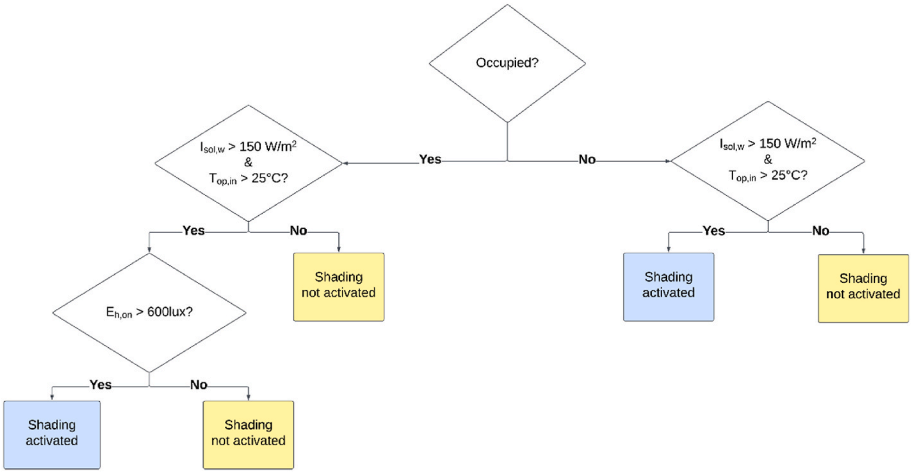

Fig. 8. Control algorithm – Strategy not including the glare evaluation (S2).

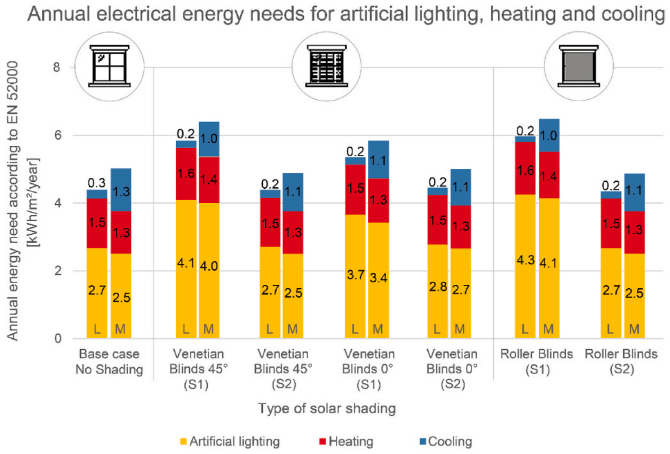

Fig. 9. Comparison of annual energy needs for artificial lighting, heating and cooling between the base case without shadings, and the cases with the integration of Venetian blinds with a slat angle of 0° and 45°, and of Roller blinds. Case of Liège (L) and Milan (M).

4.2. *How does the control strategy influence annual energy needs?*

Fig. 9 compares the annual lighting, heating, and cooling energy needs for the selected shading technologies, control algorithms, and locations.

Regarding artificial lighting and heating, Liège has higher energy needs than Milan. However, the significantly higher cooling energy needs make Milan the location with the highest total annual energy needs.

Comparing S1 (including glare evaluation in the algorithm) and S2 (not including glare evaluation), we can observe that (except for VB0 in Liège) independently from the location, we always register a reduction compared to the BC regarding cooling energy needs. In the case of Liège, with S1, the maximum is registered with RB (from 0.27 to 0.17 kWh/m^2/year, i.e., −36 %), while the less effective solution is the VB0 (from 0.27 to 0.24 kWh/m^2/year, i.e., −13 %). In the case of Milan, among the dynamic solutions with glare evaluation, the highest reduction is registered with RB (from 1.26 to 0.97 kWh/m^2/year, i.e., −23 %) and the lowest with VB0 (from 1.26 to 1.11 kWh/m^2/year, i.e., −12 %). With scenario S2, we register a lower reduction in cooling needs than S1. Despite this, S2 is the only scenario that allows the reduction of the total annual energy needs of the office. In fact, in both locations, the highest total annual energy needs reduction is registered with RB controlled with the strategy S2 (from 4.45 to 4.41 kWh/m^2/year, i.e., −0.9 %, in Liège; from 5.02 to 4.87 kWh/m^2/year, i.e., −3%, in Milan). This result is because, due to the logic of the strategy, heating and lighting are the same as the BC, while cooling is reduced from 0.27 to 0.23 kWh/m^2/year (−16 %) for Liège and from 1.27 to 1.11 kWh/m^2/year (−12 %) for Milan.

In strategy S1, instead, the cooling reduction is offset by an increase in heating and lighting increase. In fact, in all strategies including glare evaluation, heating and lighting energy needs increase compared to the BC. In the case of Liège, with RB, lighting and heating energy needs increase from 2.7 to 4.3 kWh/m^2/year (+60 %) and from 1.48 to 1.57 kWh/m^2/year (+6 %) compared to the BC, respectively, resulting in the highest increase in annual energy needs (+6 %). In Milan, with RB, lighting and heating energy needs increase from 2.5 to 4.1 kWh/m^2/year (+66 %) and from 1.26 to 1.37 kWh/m^2/year (+9 %), respectively (compared to the BC). The resulting total annual energy needs increase from 5.02 to 6.48 kWh/m^2/year (+29 %).

Lighting, heating and cooling trends agree with the shading properties presented in Section 0. Glazing with VB0 has the highest light transmittance among the selected shading technologies, while RB has the lowest. This property justifies the significant impact of RB activation on lighting energy needs compared to the other solutions. On the other hand, the solar energy transmittance of VB0 is the highest, inducing a lower impact of its activation on heating energy needs and reducing its advantage in terms of cooling energy needs compared to the other solutions.

Similar results have been found by Norouziasas et al. [59], who applied the control scenarios provided by ISO 52016-3 to a similar office building in Brussels. Like our study, they observed a reduction in cooling energy needs and an increase in lighting energy needs with the installation of RB and VB. However, unlike our study, they concluded that RB outperformed VB regarding energy performance. This outcome is because the office analysed by the other researchers has a comparable lighting energy need but a significantly higher cooling energy need than ours in the case without shading.

4.3. *How does the control strategy influence visual comfort?*

Fig. 10 compares the discomfort hours due to a too-high or too-low illuminance on the work plane for different shading solutions, control strategies and locations.

In Milan, a lower percentage of discomfort hours due to low and high illuminance levels is registered, leading to a lower total number of discomfort hours than in Liège. In Liège, we have 43.7 % of discomfort hours in the BC. 20.4 % are due to a low level of illuminance (lower than 500 lux); 23.3 % are due to a high level of illuminance (higher than 2000 lux). For Milan, we have 35.6 % of discomfort hours in the BC. 14.2 % are due to a low level of illuminance, while 21.4 % to a high level.

Comparing the control scenarios, we observe a reduction in the total discomfort hours by installing VB45 and VB0 with strategy S2. In fact, if shading is not included in control algorithm, the hours with a high level of illuminance are (−1 for VB45 and -4% for VB0 in Liège; −0.7 and −6.9 % in Milan). Instead, the percentage of discomfort hours given by a low level of illuminance remains unchanged. No difference is observed in the case of RB.

With scenario S1, instead, discomfort from a high illuminance level is brought to 0. However, due to the increase in the hours with low illuminance, a total discomfort hours benefit is obtained only with VB0, for which the total amount of discomfort hours is lower than the BC (−5.3 % in Liège, −8.4 % in Milan). With this control strategy, the worst result is obtained with RB, followed by VB45 (both with glare evaluation included in the control strategy). With RB, we arrive at 70.3 % of discomfort hours in Liège (+26.6 % compared to the BC) and 62.1 % in Milan (+26.5 % compared to the BC).

Also this trend is consistent with the study of Norouziasas et al. [59], who observed an increase in hours of insufficient illuminance with the

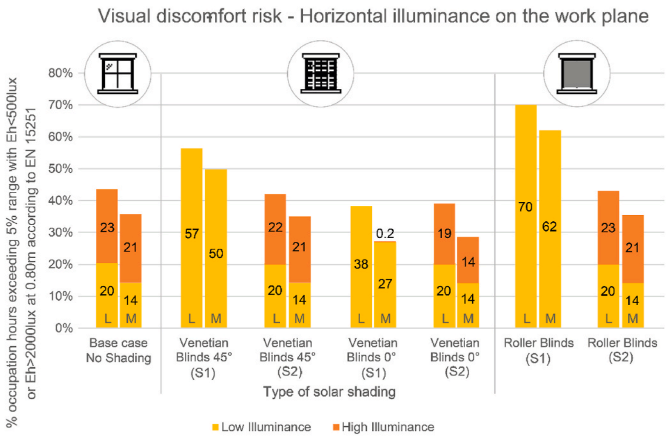

Fig. 10. Comparison of the impacts of shadings on yearly visual discomfort hours compared to the base case (no shading). Analysis of discomfort hours due to high and low illuminance on the work plane. Case of Liège (L) and Milan (M).

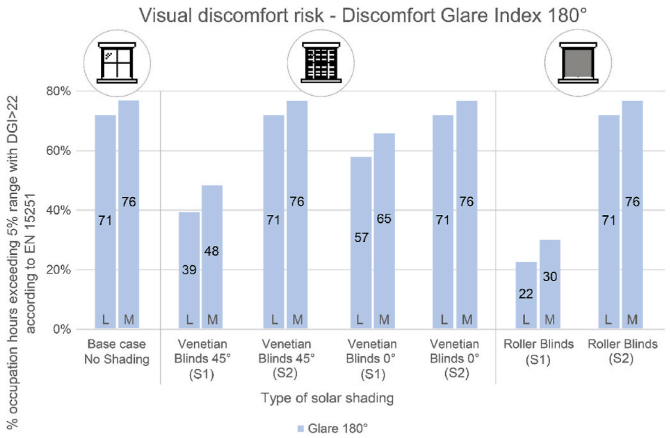

Fig. 11. Comparison of the impacts of shadings on yearly visual discomfort hours compared to the base case (no shading). Analysis of discomfort hours due to glare, with the user orientation at 180°. Case of Liège (L) and Milan (M).

installation of dynamic shading, passing from 4935 without shading to 6458 and 6693 with VB and RB, respectively. On the opposite, S2 has no impact on illuminance and glare discomfort.

Considering all the technologies and control strategies, both locations obtain the best results with VB0 in the scenario S1.

Fig. 11 compares the discomfort hours due to glare for different shading solutions, control strategies and locations. In terms of discomfort glare, in Milan, we register a higher percentage of discomfort hours if the user faces the window, independently from the shading technology and control strategy. Since the scenario S2 does not include the glare evaluation, in both locations, installing a shading system controlled by a scenario S1 is the most effective solution to reduce discomfort hours. The best results are obtained with RB in both locations: in the case of Liège, discomfort hours drop from 70.9 % to 22 %, while in Milan, from 76.4 %, we arrive at 29.7 %. VB0 provide the worst performance in both locations (57.1 % and 65.5 % of discomfort hours in Liège and Milan, respectively).

With a user orientation of 135° (Fig. 12), we observe an opposite situation compared to the orientation of 180°. In fact, we register a lower percentage of discomfort hours in Milan than in Liège. In both locations, installing a shading system controlled by the shading algorithm S1 allows us to bring to 0 the discomfort hour, except for VB0, where we still have 10.9 % and 8.3 % of discomfort hours in Liège and Milan, respectively. The most remarkable aspect is the significantly better performance of VB0 without glare evaluation in Milan compared to Liège. This result is because, in Milan, this shading solution has a higher activation time than in Liège. In all the other cases, the activation time is the same in both locations, as presented in the following section.

Glare results highlight the critical role of shadings in regulating visual comfort in office buildings. Shadings should be widely installed to provide users with proper indoor environmental quality, especially for those seated closer to the windows and exposed to outdoor weather conditions and variations. However, considering also the results obtained in terms of energy needs and illuminance on the work plane, the logic of the control algorithm should be carefully designed and evaluated due to its potentially negative impact on energy needs and visual comfort.

4.4. *How does the control strategy influence user's satisfaction?*

With control strategy S1, shadings are activated for 51 % of the working hours, a percentage reduced to 0-6% and 0-13 % (in Liège and Milan, respectively) with strategy S2 (Fig. 13). Hence, with glare control, natural daylight and view to the outside are precluded for half of the user's working time, limiting the user's satisfaction. This is particularly true for VB with a slat angle of 45°, which significantly obstruct the user's view, and for RB, which allow for the view to the outside thanks to shading material properties but limit the daylight availability due to the low light transmittance (7 %, as highlighted in Table 4). This result justifies the significant rise in artificial lighting described in section 4.2, and aligns with the conclusion of O'Brien et al. [60], who observed that discomfort often triggers blind closure. However, when the shades remain closed and electric lighting is used instead of daylight, overall energy use is significantly impacted.

Instead, without glare control, shading is rarely activated during working hours, explaining why S2 reduced annual office energy needs but had no impact on glare and illuminance discomfort. Except for VB0, the activation time is the same in both locations. This difference in shading activation for VB0 justifies the different trend in the cooling advantage observed with S2 explained in Section 4.2. According to the algorithm's logic explained in Section 4.1, the shading activation profile suggests that when the selected shading technologies are activated, the illuminance requirements on the work plane are never met, and shading is not activated. Finally, the analysis of the shading activation time suggests that the difference in visual and energy needs performance for the selected shading technologies are mainly related to the shading properties, being the results for each control scenario obtained at parity of activation time.

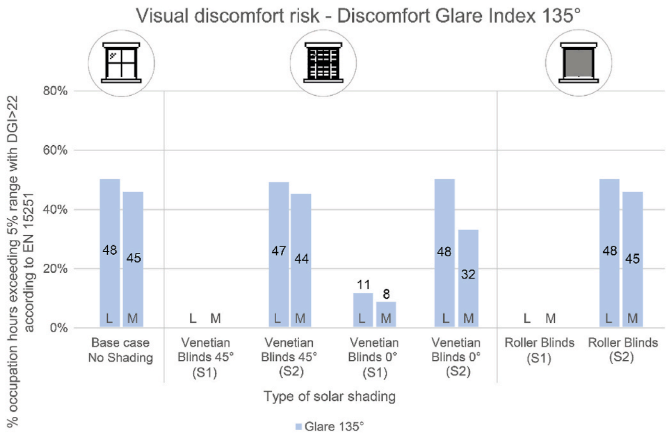

Fig. 12. Comparison of the impacts of shadings on yearly visual discomfort hours compared to the base case (no shading). Analysis of discomfort hours due to glare, with the user orientation at 135°. Case of Liège (L) and Milan (M).

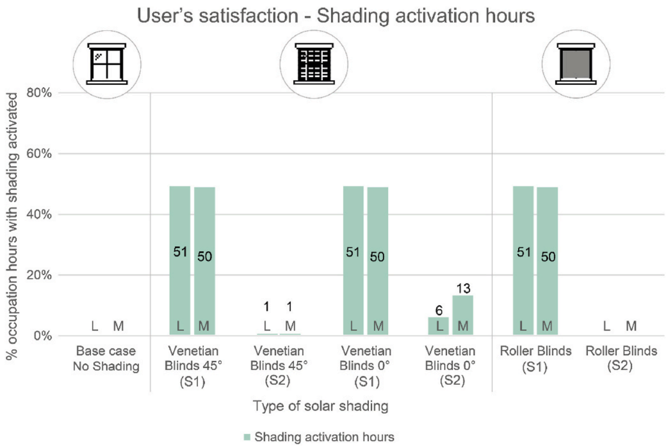

Fig. 13. Comparison of shadings activation hours during working hours. Case of Liège (L) and Milan (M).

5. Discussion

In this study, two control strategies are designed and evaluated, one including glare evaluation (S1) and the other without glare evaluation (S2). Both strategies have the same logic and algorithm blocks (except for the glare discomfort evaluation), and their main objective is to balance the user's visual comfort and building energy needs by maximising visual comfort during working hours and minimising thermal loads outside working hours. The results presented can be summarized in the following recommendations:

1. Using the control strategy S1 if visual comfort is the priority. If combined with the installation of VB0, this solution provides the best compromise between visual comfort improvement and impact on office energy needs.
2. Preferring S2, if the priority is reducing energy needs, since the shading activated only during non-occupied hours. However, in this case, we recommend allowing the user to modify its position to reduce glare discomfort.

The present study boasts different strengths, which contribute to the comprehensiveness and robustness of the research. Firstly, the designed control algorithm results from multiple iterations. Once the thresholds presented in Section 3.3 were fixed, parameters were progressively added to the control algorithm, different parameter sequences were tested, and the most appropriate combination was identified according to the results of all-year energy and visual comfort simulations. Secondly, the choice of the parameters to be included in the algorithm and the assessment of the designed control strategy is based on ISO 52016-3, a new standard yet to be applied in literature in its final version. Furthermore, simulations have been conducted for an office building in a temperate zone. As this latter is a climatic area relatively underexplored in the literature, two locations were selected to compare and validate the obtained results' trends. Finally, the user is included in the study not only in terms of office occupancy but also by evaluating the shading activation time, which affects the user's satisfaction with the designed control strategy, and by providing the user with the possibility to react to visual discomfort during working hours by modifying his/her position.

The work also has some limitations, that can be detected in the control algorithm, shading technology and its modelling. Concerning the control algorithm, the definition of the most appropriate threshold for all parameters was based on Standards and literature. However, there is a lack of related literature on multi-criteria control algorithms, and threshold suggestions for single parameters, such as vertical irradiance on the window, are not consistent [9,30,49]. Hence, a sensitivity analysis should be conducted to consolidate the choices done. Regarding the shadings, the technologies used in this study are the ones included in ISO 52016-3. However, there are more innovative technologies that are more effective for thermal load and visual comfort control (e.g., VB with movable slats). Furthermore, the shading technologies were only applied on/off (without allowing for a partial activation) and with fixed VB slats. In ISO 52016-3, the reference control scenarios allow partial extension of the blinds and changing slat positions. Moreover, ISO 52016-3 includes control scenarios for automated and manual control, thereby considering the impact of less-responsive occupants and the hysteresis in the activation of the blinds. In an extensive case study report [61], using a publicly available Excel tool, all these options were tested and demonstrated, which resulted in recommendations for further refinement of the control scenarios, aiming at a future amendment of ISO 52016-3. This latter case study report raises the importance of providing open access control algorithm codes and tools to test many control strategies on the same case study and define key criteria to develop an effective shading control algorithm.

Our study raised different questions to be tackled in future works. Our study followed a simulated-based methodology. Observation field research should be conducted in future using properly designed surveys [62] and on-site experimental data collection. On the one hand, collecting experimental data would allow us to compare and validate simulation results and consider the user's perception and acceptance of the suggested algorithm. On the other hand, this approach would enable us to refine the parameter thresholds according to user preferences and not only to literature.

The effectiveness of the proposed control algorithms could also be evaluated on mixed-mode and free-running buildings. This test would be helpful to analyse the effectiveness of this retrofit solution in those areas historically characterised by a heating-dominated climate, where buildings are not widely equipped with cooling systems and that, due to the effects of climate change, are no more thermally comfortable for users. Finally, we suggest further implementing the algorithm by introducing, firstly, a combination of internal and external shadings to integrate technologies suitable for thermal load control to solutions more appropriate for glare control and, secondly, the possibility to partially activate the shading to control direct solar radiation in the office, while providing enough daylight and view to the outside.

6. Conclusion

The study of dynamic solar shading entails several knowledge gaps, with the design of an appropriate control strategy being the most significant one. This work aimed to develop a new multi-criteria control strategy for a south-facing single office and two locations in a temperate climate zone (Liege and Milan) in line with the new ISO 52016-3. Two control algorithms were designed and applied to three types of shadings (VB0, VB45 and RB), one with glare control (S1), which aims to maximise the user's visual comfort, and the other without glare evaluation (S2), which focuses on controlling thermal loads.

The findings reveal that, regardless of the location and shading type, if a multi-criteria control strategy properly hierarchises the considered parameters and is designed to consider its impact on building energy needs, visual comfort and user satisfaction simultaneously, adaptive building envelope components allow to find a balance between visual comfort and building energy needs and to choose the most appropriate scenario according to the building management priorities. In fact, by adopting S1 here designed, it is possible to find a compromise between the reduction of glare discomfort and high-illuminance discomfort hours and the increase of total annual energy needs due to the significant rise in lighting energy needs caused by a high shading activation time (that compromises also daylight availability user's view of the outside). Conversely, with S2, shading moves only during non-working hours. Hence, visual comfort is not improved, but total annual energy needs are reduced, thanks to the positive impact of shadings on cooling load, and view to the outside and daylight availability are not limited.

Considering the shading technologies, RB induce the highest increase in lighting energy needs since it has the lowest solar energy transmission among the considered solutions. Conversely, VB0 limits the impact on artificial lighting, but has a lower impact on heating and cooling energy needs. Accordingly, RB has the worst performance in control of low-illuminance discomfort hours and the best in glare control. VB0 provides opposite results.

In conclusion, to balance visual comfort, energy needs, and user satisfaction, if visual comfort is the priority, S1 should be preferred, especially when coupled with VB0. Contrarily, if energy needs reduction is the primary objective, S2 should be adopted. Considering user satisfaction in the choice of the shading control strategy, it is important to note that, with S1, the worker has limited access to daylight and outside view for half of the working time. Hence, if this criterion is dominant, S1 should be coupled with the installation of RB to keep a good view of the outside. With S2, on the opposite, the user is exposed to important visual discomfort conditions since the shading is active only when the office is not occupied. Hence, if this control strategy is adopted, the user should at least be able to adapt his/her orientation to minimise glare discomfort.

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CRediT authorship contribution statement

Aurora Bertini: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Hervé Lamy:** Writing – review & editing, Resources. **Alireza Norouziasas:** Writing – review & editing, Resources. **Dick Van Dijk:** Writing – review & editing, Validation, Formal analysis. **Alessandro Dama:** Writing – review & editing, Writing – original draft, Validation, Supervision, Methodology, Investigation, Formal analysis, Conceptualization. **Shady Attia:** Writing – review & editing, Writing – original draft, Validation, Supervision, Methodology, Investigation, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Plans, elevations and sections of the building

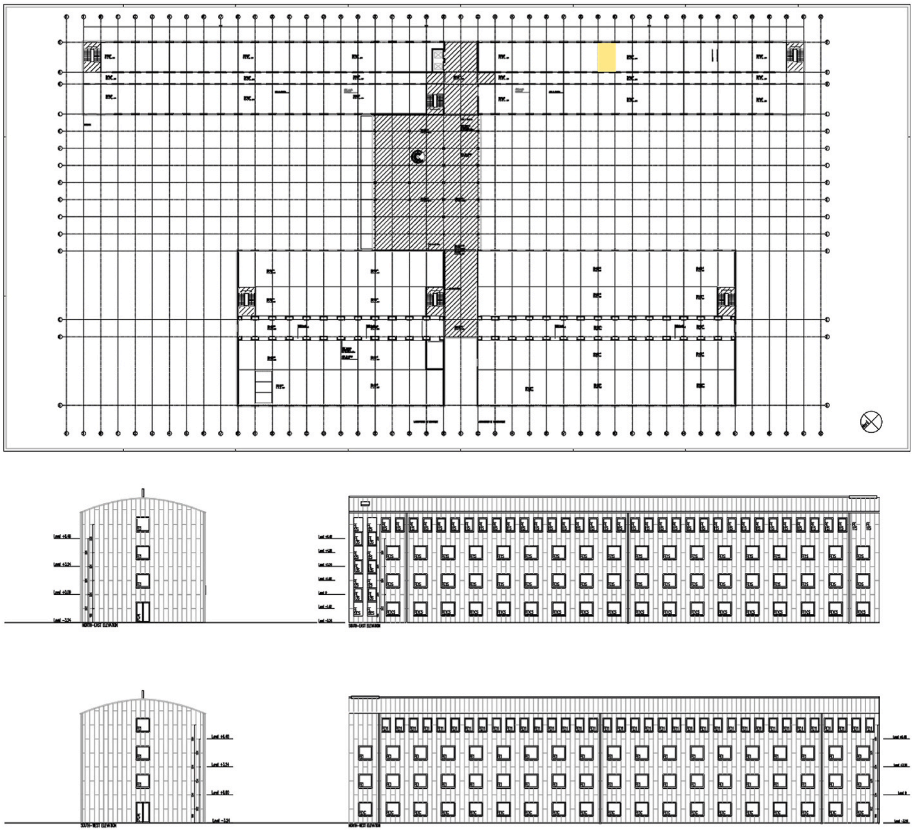

Fig. A.1. Plan of the typical floor and elevations of the building B52 of the University of Liege. In yellow the studied office.

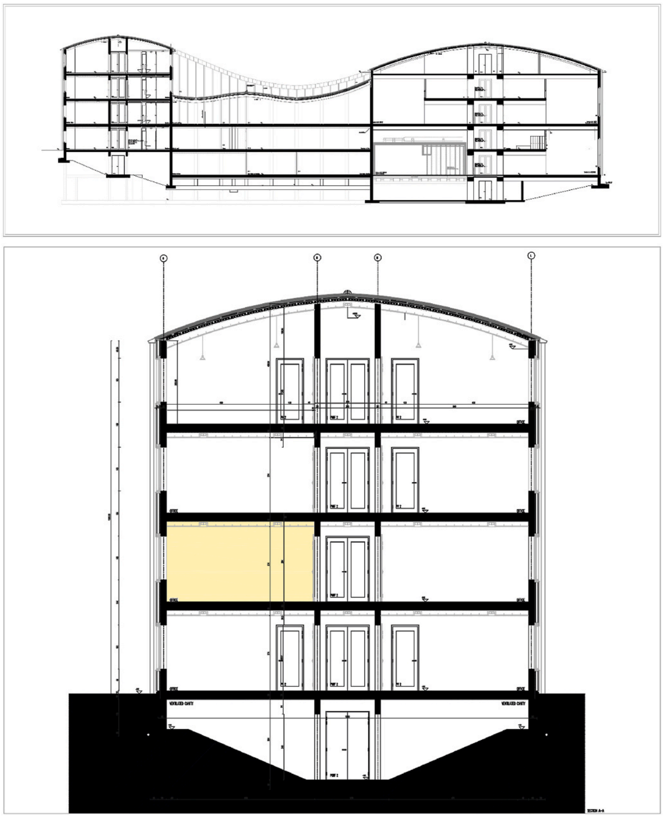

Fig. A.2. Longitudinal and transversal sections of the building B52 of the University of Liege. In yellow the studied office.

References

[1] P.R. Shukla, J. Skea, R. Slade, A. Al Khourdajie, A. Hasija, J. Malley, R. Fradera, M. Belkacemi, G. Lisboa, D. McCollum, P. Vyas, M. Pathak, R. van Diemen, S. Luz, S. Some, Climate Change 2022—Mitigation of Climate Change—Working Group III Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, Intergovernmental Panel on Climate Change (IPCC), Geneva, Switzerland, 2022. https://www.ipcc.ch/report/ar6/wg3/.

[2] M.A.D. Larsen, S. Petrović, A.M. Radoszynski, R. McKenna, O. Balyk, Climate change impacts on trends and extremes in future heating and cooling demands over Europe, Energy Build. 226 (2020) 110397, https://doi.org/10.1016/j.enbuild.2020.110397.

[3] European Commission, Proposal for a Directive of the European Parliament and of the Council on the Energy Performance of Buildings, recast), Brussels, Belgium, 2021. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52021PC0802.

[4] C. Becchio, S.P. Corgnati, G. Crespi, M.C. Pinto, S. Viazzo, Exploitation of dynamic simulation to investigate the effectiveness of the smart readiness indicator: application to the energy center building of turin, Science and Technology for the Built Environment 27 (8) (2021) 1127–1143, https://doi.org/10.1080/23744731.2021.1947657.

[5] Guidehouse Germany GmbH, Solar shading – synergising mitigation of GHG emissions and adaptation to climate change. The Potential to Disrupt Rising Cooling Demand and Overheating in European Buildings, 2021. Berlin, Germany, https://es-so.com/onewebmedia/onewebmedia/Policy_Brief_20211107_final-3.pdf.

[6] S. Nazari, P.K. MirzaMohammadi, B. Sajadi, P. Pilehchi Ha, S. Talatahari, P. Sareh, Designing energy-efficient and visually-thermally comfortable shading systems for office buildings in a cooling-dominant climate, Energy Rep. 10 (2023) 3863–3881, https://doi.org/10.1016/j.egyr.2023.10.062.

[7] J. Xiong, A. Tzempelikos, Model-based shading and lighting controls considering visual comfort and energy use, Sol. Energy 134 (2016) 416–428, https://doi.org/10.1016/j.solener.2016.04.026.

[8] W. Lu, Dynamic shading and glazing technologies: improve energy, visual, and thermal performance, Energy and Built Environment 5 (2) (2024) 211–229, https://doi.org/10.1016/j.enbenv.2022.09.004.

[9] L. Karlsen, P. Heiselberg, I. Bryn, H. Johra, Solar shading control strategy for office buildings in cold climate, Energy Build. 118 (2016) 316–328, https://doi.org/10.1016/j.enbuild.2016.03.014.

[10] A. Tabadkani, A. Tsangrassoulis, A. Roetzel, H.X. Li, Innovative control approaches to assess energy implications of adaptive facades based on simulation using EnergyPlus, Sol. Energy 206 (2020) 256–268, https://doi.org/10.1016/j.solener.2020.05.087.

[11] A. Tabadkani, A. Roetzel, H.X. Li, A. Tsangrassoulis, A review of automatic control strategies based on simulations for adaptive facades, Build. Environ. 175 (2020) 106801, https://doi.org/10.1016/j.buildenv.2020.106801.

[12] U. Knaack, E. Koenders, Building Physics of the Envelope: Principles of Construction, Birkhäuser., Basel, Switzerland, 2018. https://birkhauser.com/books/9783035609493.

[13] A. Tabadkani, A. Roetzel, H. Xian Li, A. Tsangrassoulis, S. Attia, Analysis of the impact of automatic shading control scenarios on occupant's comfort and energy load, Appl. Energy 294 (2021) 116904, https://doi.org/10.1016/j.apenergy.2021.116904.

[14] E.S. Lee, S.E. Selkowitz, G.D. Hughes, D.A. Thurm, *Market Transformation Opportunities for Emerging Dynamic Facade and Dimmable Lighting Control Systems* (LBNL-55310), Lawrence Berkeley National Lab. (LBNL), Berkeley, CA (United States), 2004. https://www.osti.gov/biblio/834231.

[15] M.C. Pinto, G. Crespi, F. Dell'Anna, C. Becchio, Combining energy dynamic simulation and multi-criteria analysis for supporting investment decisions on smart shading devices in office buildings, Appl. Energy 332 (2023) 120470, https://doi.org/10.1016/j.apenergy.2022.120470.

[16] A. Vlachokostas, N. Madamopoulos, Quantification of energy savings from dynamic solar radiation regulation strategies in office buildings, Energy Build. 122 (2016) 140–149, https://doi.org/10.1016/j.enbuild.2016.04.022.

[17] H.H. Alzoubi, M.Z. Ali, Y.M. Al Manaseer, Performance study of a multi-objective mathematical programming modeling approach for energy optimization in building envelopes, Int. J. of Thermal & Environmental Engineering 14 (1) (2017) 17–26, https://doi.org/10.5383/ijtee.14.01.003.

[18] W. Beck, D. Dolmans, G. Dutoo, A. Hall, O. Seppänen, Solar shading: How to integrate solar shading in sustainable buildings, Rehva (Federation of European Heating, Ventilation and Air-conditioning Associations) 12 (2010).

[19] H. Ghorbani Naeini, A. Norouziasas, F. Piraei, M. Kazemi, M. Kazemi, M. Hamdy, Impact of building envelope parameters on occupants' thermal comfort and energy use in courtyard houses, Architect. Eng. Des. Manag. 0 (0) (2023) 1–27, https://doi.org/10.1080/17452007.2023.2254294.

[20] M. Mahdavinejad, H. Bazazzadeh, F. Mehrvarz, U. Berardi, T. Nasr, S. Pourbagher, S. Hoseinzadeh, The impact of facade geometry on visual comfort and energy consumption in an office building in different climates, Energy Rep. 11 (2024) 1–17, https://doi.org/10.1016/j.egyr.2023.11.021.

[21] A. Kirimtat, B.K. Koyunbaba, I. Chatzikonstantinou, S. Sariyildiz, Review of simulation modeling for shading devices in buildings, Renew. Sustain. Energy Rev. 53 (2016) 23–49, https://doi.org/10.1016/j.rser.2015.08.020.

[22] G. Flamant, W. Bustamante, A. Tzempelikos, S. Vera, Evaluation of view clarity through solar shading fabrics, Build. Environ. 212 (2022) 108750, https://doi.org/10.1016/j.buildenv.2021.108750.

[23] M. Thalfeldt, J. Kurnitski, External shading optimal control macros for 1- and 2-piece automated blinds in European climates, Build. Simulat. 8 (1) (2015) 13–25, https://doi.org/10.1007/s12273-014-0194-3.

[24] S.M. Al-Masrani, K.M. Al-Obaidi, N.A. Zalin, M.I. Aida Isma, Design optimisation of solar shading systems for tropical office buildings: challenges and future trends, Sol. Energy 170 (2018) 849–872, https://doi.org/10.1016/j.solener.2018.04.047.

[25] M.V. Nielsen, S. Svendsen, L.B. Jensen, Quantifying the potential of automated dynamic solar shading in office buildings through integrated simulations of energy and daylight, Sol. Energy 85 (5) (2011) 757–768, https://doi.org/10.1016/j.solener.2011.01.010.

[26] A. Luna-Navarro, R. Loonen, M. Juaristi, A. Monge-Barrio, S. Attia, M. Overend, Occupant-Facade interaction: a review and classification scheme, Build. Environ. 177 (2020) 106880, https://doi.org/10.1016/j.buildenv.2020.106880.

[27] J.K. Day, B. Futrell, R. Cox, S.N. Ruiz, A. Amirazar, A.H. Zarrabi, M. Azarbayjani, Blinded by the light: occupant perceptions and visual comfort assessments of three dynamic daylight control systems and shading strategies, Build. Environ. 154 (2019) 107–121, https://doi.org/10.1016/j.buildenv.2019.02.037.

[28] S. Attia, S. Bilir, T. Safy, C. Struck, R. Loonen, F. Goia, Current trends and future challenges in the performance assessment of adaptive façade systems, Energy Build. 179 (2018) 165–182, https://doi.org/10.1016/j.enbuild.2018.09.017.

[29] S. Abdelwahab, M.G. Kent, M. Mayhoub, Users' window preferences and motivations of shading control: influence of cultural characteristics, Build. Environ. 240 (2023) 110455, https://doi.org/10.1016/j.buildenv.2023.110455.

[30] G. Derbas, K. Voss, Assessment of automated shading systems' utilization and environmental performance: an experimental study, Build. Environ. 244 (2023) 110805, https://doi.org/10.1016/j.buildenv.2023.110805.

[31] C.T. Do, Y.-C. Chan, N.T.K. Phuong, Selection of spatial sensitivity curve and installation location of photosensors for daylight-linked control systems in space with dynamic shading devices, Build. Environ. 230 (2023) 109984, https://doi.org/10.1016/j.buildenv.2023.109984.

[32] W. O'Brien, H.B. Gunay, The contextual factors contributing to occupants' adaptive comfort behaviors in offices – a review and proposed modeling framework, Build. Environ. 77 (2014) 77–87, https://doi.org/10.1016/j.buildenv.2014.03.024.

[33] R. Tamas, M.M. Ouf, W. O'Brien, A field study on the effect of building automation on perceived comfort and control in institutional buildings, Architect. Sci. Rev. 63 (1) (2020) 74–86, https://doi.org/10.1080/00038628.2019.1695573.

[34] M. Konstantoglou, A. Tsangrassoulis, Dynamic operation of daylighting and shading systems: a literature review, Renew. Sustain. Energy Rev. 60 (2016) 268–283, https://doi.org/10.1016/j.rser.2015.12.246.

[35] G. van Moeseke, I. Bruyère, A. De Herde, Impact of control rules on the efficiency of shading devices and free cooling for office buildings, Build. Environ. 42 (2) (2007) 784–793, https://doi.org/10.1016/j.buildenv.2005.09.015.

[36] M. Skelly, M. Wilkinson, The evolution of interactive facades: improving automated blind control. Whole Life Performance of Facades, 2001, pp. 129–142.

[37] E.S. Lee, D.L. DiBartolomeo, S.E. Selkowitz, Thermal and daylighting performance of an automated Venetian blind and lighting system in a full-scale private office, Energy Build. 29 (1) (1998) 47–63, https://doi.org/10.1016/S0378-7788(98)00035-8.

[38] J. Xie, A.O. Sawyer, Simulation-assisted data-driven method for glare control with automated shading systems in office buildings, Build. Environ. 196 (2021) 107801, https://doi.org/10.1016/j.buildenv.2021.107801.

[39] S.M. Al-Masrani, K.M. Al-Obaidi, Dynamic shading systems: a review of design parameters, platforms and evaluation strategies, Autom. ConStruct. 102 (2019) 195–216, https://doi.org/10.1016/j.autcon.2019.01.014.

[40] L. Roche, Summertime performance of an automated lighting and blinds control system, Light. Res. Technol. 34 (1) (2002) 11–25, https://doi.org/10.1191/1365782802li026oa.

[41] S.-J. Choi, D.-S. Lee, J.-H. Jo, Lighting and cooling energy assessment of multi-purpose control strategies for external movable shading devices by using shaded fraction, Energy Build. 150 (2017) 328–338, https://doi.org/10.1016/j.enbuild.2017.06.030.

[42] J. Xiong, A. Tzempelikos, I. Bilionis, P. Karava, A personalized daylighting control approach to dynamically optimize visual satisfaction and lighting energy use, Energy Build. 193 (2019) 111–126, https://doi.org/10.1016/j.enbuild.2019.03.046.

[43] Statista Research Department, Volume of Office Real Estate Stock in Selected European Cities in 2023, Statista, 2024. https://www.statista.com/statistics/1175918/office-real-estate-stock-by-city-europe/.

[44] M.C. Peel, B.L. Finlayson, T.A. McMahon, Updated world map of the Köppen-Geiger climate classification, Hydrol. Earth Syst. Sci. 11 (5) (2007) 1633–1644, https://doi.org/10.5194/hess-11-1633-2007.

[45] H.E. Beck, N.E. Zimmermann, T.R. McVicar, N. Vergopolan, A. Berg, E.F. Wood, Present and future Köppen-Geiger climate classification maps at 1-km resolution, Sci. Data 5 (2018) 180214, https://doi.org/10.1038/sdata.2018.214.

[46] European Committee for Standardization (CEN), *Light and lighting—Lighting of work places. Part 1: Indoor work places* (European Standard EN 12464-1), Brussels, Belgium (2021), vol.1, p.61. https://www.cencenelec.eu/european-standardization/european-standards/.

[47] DesignBuilder Software Limited, *DesignBuilder user manual—V7.2.0*. Stroud, UK. https://designbuilder.co.uk/, 2023.

[48] A. Piccolo, F. Simone, Effect of switchable glazing on discomfort glare from windows, Build. Environ. 44 (6) (2009) 1171–1180, https://doi.org/10.1016/j.buildenv.2008.08.013.

[49] E. Piccoli, A. Dama, Modelling the performances of an innovative shading device integrating PV. Proceedings of Building Simulation 2019: 16th Conference of IBPSA, 2020, pp. 4879–4886, https://doi.org/10.26868/25222708.2019.210564.

[50] DesignBuilder Software Limited, DesignBuilder (Version 7.0.2.006), 2022 [Software], https://designbuilder.co.uk/.

[51] G. Di Nora, C. Pistoni, F. Zamboni, Energia netta: zona termica, in: Manuale d'uso del software CENED+, Cestec Spa, Milan, Italy, 2011, pp. 114–146. www.cened.it.

[52] Lawrence Berkeley National Laboratory, *Window* (7.8.74) [Software], https://windows.lbl.gov/software-tools, 2023.

[53] International Organization for Standardization (ISO), Energy Performance of Buildings—Indoor Environmental Quality—Part 1: Indoor Environmental Input Parameters for the Design and Assessment of Energy Performance of Buildings (ISO 17772-1:2017), 2017. Geneva, Switzerland, https://www.iso.org/standard/60498.html.

[54] European Committee for Standardization (CEN), Energy performance of buildings—ventilation for buildings—Part 1: indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics, European Standard EN 16798-1:2019 1 (2019) 51–54. Brussels, Belgium, https://www.cencenelec.eu/european-standardization/european-standards/.

[55] S. Attia, Energy audit report of building 52, Harvard Dataverse V1 (2024), https://doi.org/10.7910/DVN/VIDFKR.

[56] American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), *Measurement Of Energy And Demand Savings* (ASHRAE Guideline 14-2002), ASHRAE, Atlanta, GA, USA, 2002. https://www.ashrae.org/technical-resources/standards-and-guidelines.

[57] A. Nabil, J. Mardaljevic, Useful daylight illuminances: a replacement for daylight factors, Energy Build. 38 (7) (2006) 905–913, https://doi.org/10.1016/j.enbuild.2006.03.013.

[58] A. Bertini, *Control algorithm for dynamic solar shadings: A simulation study for the extension of ISO/DIS 52016-3 to office buildings* [MSc Thesis, Politecnico di Milano],, POLITesi - Archivio digitale delle tesi di laurea, edi dottorato (2023) 67–106. https://www.politesi.polimi.it/handle/10589/206812.

[59] A. Norouziasas, A. Tabadkani, R. Rahif, M. Amer, D. Van Dijk, H. Lamy, S. Attia, Implementation of ISO/DIS 52016-3 for adaptive façades: a case study of an office building, Build. Environ. 235 (2023) 110195, https://doi.org/10.1016/j.buildenv.2023.110195.

[60] W. O'Brien, K. Kapsis, A.K. Athienitis, Manually-operated window shade patterns in office buildings: a critical review, Build. Environ. 60 (2013) 319–338, https://doi.org/10.1016/j.buildenv.2012.10.003.

[61] D. van Dijk, Report on Case Study to EN ISO 52016-3, Impact of Adaptive Building Envelope Elements on Heating and Cooling Needs and Internal Temperatures, EPB Center publication, 2023. https://epb.center/support/documents/case-iso-52016-3/.

[62] S. Attia, S. Garat, M. Cools, Development and validation of a survey for well-being and interaction assessment by occupants in office buildings with adaptive facades, Build. Environ. 157 (2019) 268–276, https://doi.org/10.1016/j.buildenv.2019.04.054.