Human-plant centric shading control: Considering the impact of shading systems on both occupants' and plants' requirements

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Abstract

Traditionally, control strategies are applied to automate switchable electrochromic glazing systems (EC) to save energy and provide comfort for occupants indoors. In addition, the plants' minimum requirements and the consequences of active shading on the supplemental artificial lighting for plants should be considered when designers want to embrace Biophilic design.

This paper introduces a simulation workflow to evaluate the impact of shading activation on both human and plant requirements year-round using combined climate-based daylight (Radiance) and building energy simulation tool (TRNSYS).

Finally, the simulated total electricity demand for supplemental lighting for plants in a prototypical office room in temperate climate condition are presented and discussed under different control strategies.

Introduction

Climate change and related issues draw attention to the impact of greenery on different scales from urban green infrastructures to green façades to lobbies and indoors due to their proven potential to mitigate urban heat island effect and thermal discomfort (Wong, Tan, Kolokotsa, & Takebayashi, 2021). While the importance of the biophilic design is acknowledged by standards (e.g. WELL v2), to date, there are only a limited number of tools available for simulating the plants' requirements to inform biophilic designers (Ganji Kheybari & Kasravi, 2022). After the Corona pandemic, people have been spending more time indoors. Consequently, the importance of biophilic design and the impact of indoor greenery on well-being became more obvious. Making decisions about having indoor plants and providing the requirements for their growth is a trade-off between the benefits and the costs.

Several publications reported a reduction in the operational energy and an improvement in comfort conditions through automation of electrochromic glazing (EC) by applying advanced control strategies (Ganji Kheybari & Hoffmann, 2019; Kheybari & Hoffmann, 2020; Tavares, Gaspar, Martins, & Frontini, 2015). The role of switchable EC is complex due to varying properties at different times of the year. EC glazing can dynamically adjust the level of solar and visible transmittance in response to an electrical voltage. This is a considerable advantage because their properties can be controlled according to outdoor conditions.

All the shading controllers have been developed based on providing thermal and visual comfort considering human occupants. Shading systems have been also applied for privacy protection or view retention. While the importance of considering dynamic shading is clear for the early stage of design, to the best knowledge of the authors, there is no single study about the impact of shading systems on the plants inside the buildings.

Due to the consequences of shading activation, lighting for indoor plants is not only a challenge for wintertime (dark and short days) but also for summertime (bright and long days) when the shading is used in favor of occupants.

Toward a biophilic design, estimation of the consequences of active shading on the additional supplementary lighting for plants in buildings with complex shading systems is the main objective of the paper.

Methods

This paper adopted a simulation workflow to evaluate the impact of shading activation on human and plant requirements year-round. This way the overall performance of an indoor space shared with both occupants and plants can be simulated using combined climate-based daylight (Radiance) and building energy simulation tool (TRNSYS).

Firstly the availability of daylight on the desks and the plants' foliage needs to be simulated in Radiance. Secondly, these values will be used in TRNSYS to control the artificial lighting and include the extra supplemental energy as internal gain into the hourly heat balance.

Finally, all simulated results under different control conditions are post-processed to calculate annual performance indicators and electricity demand. These steps are required to investigate the overall impact of an automated switchable EC glazing not only on energy savings and providing comfort for occupants but also on the requirements for indoor plants.

In the first following sub-section, two main metrics are explained that have been commonly used in agricultural lighting. Later a prototypical model of an office is described, where the occupants and plants are located and the large south-facing window is equipped with a switchable EC glazing. The settings and parameters for daylight and thermal simulations are explained in detail.

Lighting for plants

Photosynthetically Active Radiation (PAR) is the part of solar energy which contributes in photosynthesis expressed in μmol/m²·s. While the PAR radiation approximately corresponds to the visible spectrum (to the human eye 400–700 nm, see Figure 2), light absorption by photosynthetic pigments occurs especially in the blue (400–500 nm) and red (600–700 nm) (McCree, 1971).

Daily Light Integral (DLI) is expressed in mol/m².d and is recommended by scientist as the best quantum metric which explains the required light for plants (Ganji Kheybari & Kasravi, 2022). DLI is the amount of PAR delivered to the plant canopy over 24-hour photoperiod. Providing the recommended DLI range we can ensure the plants growth and optimal crop yield.

Prototypical office room model

A prototypical office room (floor area of 30 m²) with a large south-facing window and an attached overhang is modeled. A temperate climate condition (Mannheim, Germany) is used in this study which is a representative weather condition for a major region in Germany (region C) for minimum requirements of sun protection during summertime (DIN 4108-2).

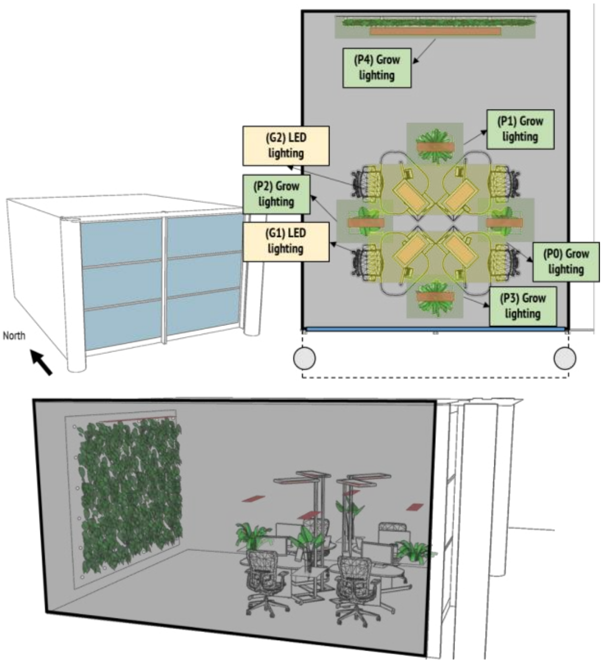

Figure 1: Visual representation of the prototypical room; plan layout of the workstations, luminaires (G1 and G2), and the indoor plants and the grow lightings (P0-4)

Figure 1 shows the room dimensions: 6 m in length, 5 m in width, and 3.3 m in height which is planned for four occupants. The luminaires related to the workstations are arranged into two groups: group 1 (G1: 1.26 m away from the window) and group 2 (G2: 2.74 m away from the window). They are categorized according to their distance from the window and can be controlled based on the average available daylight on the respective workstations during the occupied hours.

In addition, there are five separate lighting fixtures to provide the required grow lighting. Indoor plants (potted) are positioned between the users' desks on the same level. These four potted plants and their corresponding lighting fixtures are named P0, P1, P2, and P3. The whole green wall with about a 10 m² area is named P4. Table 1 shows the plant species and their requirements assumed for potted plants and the green wall.

Table 1: Different plant species and their requirements

Scientific Name (Common Name)	*ID*	*Recommended DLI Range*	*Other Requirements*
zamioculcas zamiifolia (ZZ Plant) 	*P0,P2*	*2-5 (Indoor)*	*Potted plant* *Hardiness Zone = 10-12* *Heat Zone = 10-11* *Plant type: Succulent* *Water need: Low*
dracaena deremensis (Dragon Tree) 	*P1,P3*	*10-18 (Partial sun)*	*Potted plant* *Hardiness Zone = 10-12* *Heat Zone = 1-12* *Plant type: Shrubs* *Water need: Average*
hedera helix (English Ivy) 	*P4*	*5-10 (Shade)*	*Green wall* *Hardiness Zone = 5-10* *Heat Zone = 6-12* *Plant type: Climbers* *Water need: Average*

It is worth mentioning that in addition to the location of individual plants within the room and its accessibility to the daylight, the minimum lighting requirement matters for estimating the supplemental artificial lighting accordingly.

Electrochromic glazing (EC) model

The mentioned prototypical room has a switchable EC which is an insulated double glazing unit with a low-E coating and 90% Argon gas filling. The total area of the EC (WWR= 85%) is 14 m² and divided into three zones: top, middle, and bottom. Each zone can be tinted independently which presents 64 possible configurations for EC with four states of tinting. Table 2 shows the overall performance of the EC glazing in each state of tinting (S0-S3) modeled and calculated by the LBNL Window software. For every state, EC transmittance in visible spectrum (T_{vis}) is calculated according DIN EN 410. Similarly, EC transmittance in PAR spectrum (T_{PAR}) can be calculated based on McCree response curve and CIE standard illuminant D65. T_{PAR} is the equivalent transmittance which shows the impact of spectrally selective glazing systems on plants growth (see Figure 2).

Table 2: Overall performance of the electrochromic glazing

State of EC	***U-value W/m²K***	***SHGC***	***T_{vis}****	***T_{PAR}****
Clear state (S0)	*1.3*	*0.43*	*0.561*	*0.486*
Low tinted (S1)		*0.21*	*0.165*	*0.137*
Middle tinted (S2)		*0.16*	*0.053*	*0.045*
Fully tinted (S3)		*0.14*	*0.009*	*0.008*

** T_{vis} is calculated according DIN EN 410, T_{PAR} is the equivalent transmittance based on McCree response curve and D65*

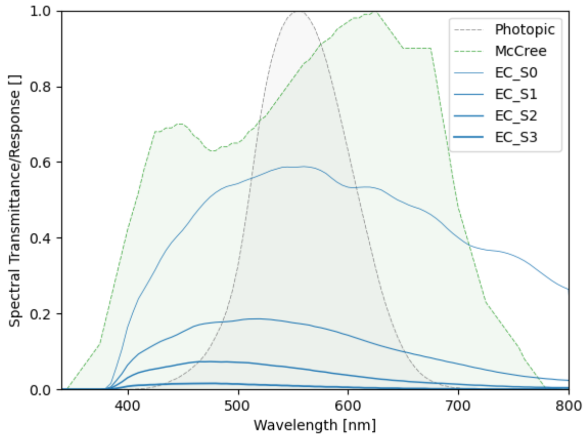

Figure 2: Spectral transmittance of different states of EC and the response function for photopic and McCree

Daylight Simulation Setups

Different Climate-based daylight simulation tools and methods have been used by architects and only a few methods work for plant grow lighting with some considerations (Subramaniam, S., Kyropoulou, M., & Hoffmann, 2020).

In this study, 3-phase method is applied for annual simulation. This method uses Radiance and adopts matrices for the transfer of radiant flux from sensors to the glazing (View matrix) and from the glazing to the sky (Daylight matrix). The transmission through the glazing and shading system is accounted for by BSDF matrix (bidirectional scattering distribution function). The annual values of illuminance (photometric) and photosynthetically active radiation (PAR) can then be computed by multiplying the matrices by the sky brightness based on Perez all-weather sky model.

Table 3 shows the properties of the model for daylight simulations. In this study, for each state of EC one representative BSDF matrix was generated by using the LBNL Window software.

Table 3: Daylight simulation setups

Item	*Description*	*Additional details*
Room optical properties	*Ref. of ceiling 80%* *Ref. of floor 30%* *Ref. of walls 70%* *all surfaces as a grey material*	*T_{vis} of each EC glazing state is represented by a BSDF matrix (Table 2)*
Weather data	*Mannheim, Germany 49.48° N, 8.46° E*	*Temperate climate (Cfb) epw weather file format*

The matrix-based method adopts the pre-calculated matrices (View, BSDF, Daylight, and Sky) which facilitates the rapid calculation of all possible combinations of shading. This feature matters especially when the shading system has multiple possible states (here 4 states) and the room has multiple windows (here 3 window zones), therefore the number of combinations and simulation run-time are significant (here 64 cases).

For simulating hourly illuminance/irradiance values on the horizontal desks (E_h, 75 cm above the floor), at eye positions (E_v at 120 cm height), on the potted plants (E_h, 80 cm above the floor), and the vertical green wall (E_v), separate sensor points with exact positions (x,y,z) and directions (vectors) were defined. Each simulated value is a triple RGB which can be weighted according to the relevant response functions.

The photopic weighting fractions were used to generate illuminance and other annual visual metrics such as Useful Daylight Illuminance (UDI). To estimate the annual glare, the simplified daylight glare probability (DGPs) was used based on the vertical eye illuminance (E_v) under different shading conditions.

Using the sensitivity of plants to photosynthesis (McCree weighting fractions), it is also possible to estimate the Photosynthetically Active Radiation (PAR μmol/m²s) values in the range of 400 to 700 nm for plants growth (Ashdown, 2019). Alternatively, to calculate the equivalent quantum light values from photopic values (lx) conversion factors can be used (Thimijan & Heins, 1983). The authors acknowledge that the correlated color temperature of the sky varies over a day and an accurate Photosynthetic Photon Flux Density (PPFD μmol/m²s) conversion factor can only be estimated by considering spectral power distribution (SPD) of the sky and multi-channel simulations. However, assuming one conversion factor (here 0.2 is assumed for daylight) can be recommended for the scene lit by natural/uniform sources.

The final step is to calculate Daily Light Integral (DLI) which is a particularly simple and useful metric to express a plant lighting requirement daily. In another word, it is the accumulated PAR photons over one given area, over 24 hours (mol/m²d). Growers have been recommended by the horticulture guidelines such as ANSI/IES RP-45-21 to provide a species-specific DLI target in each stage of cultivation (see Table 1).

Supplemental Electrical Lighting

The office room has four workstations and two groups (G1 and G2) each group includes two white LED light fixtures (50 Watts per luminaire) to illuminate the desks when daylight is not sufficient. During the simulations, artificial lights are controlled based on the occupancy schedule and the available daylight. A daylight depending control type (Type 4: continuous ON/OFF with dimming) in TRNSYS looks into the available daylight on the desks (provided as input) and switches the supplemental lighting ON when average illuminance falls below 300 lx and switches OFF once it exceeds 500 lx. At every timestep, the fraction of power used for electrical lighting is added to the internal gains in the room through convection or/and radiation.

For indoor plants, PAR from available daylight needs to be complemented with PAR from supplemental artificial grow light, especially during short and dark winter days. Since the room has already another lighting for occupants, total PAR lighting at every hour contains not only the supplemental grow lighting but also the contribution of lighting for occupants whenever it is turned ON.

$$PAR_{total} = PAR_{daylight} + PAR_{occupants\text{-}lighting} + PAR_{grow\text{-}lighting}$$

Most occupants' lighting is efficient to provide visible light, thus their contribution to PAR is determined by the SPD of the light source, the geometry of the fixture, and its distance to the target plant (or sensor). This contribution factor also known as the PPFD factor can be either simulated or estimated from available so-called "PPFD charts/ maps".

Based on the room layout, while the G1 and G2 luminaries contribute with PPFD of 25 µmol/m²s to the potted plants (P0-P3 with ≈1 m distance), the effect on the green wall (P4 with ≈3 m distance) is only 10 µmol/m²s (see Table 4). The resultant contribution of the artificial lighting depends on the projection area of lighting, the hourly dimming fraction (OFF: 0% to ON: 100%), and the distance between the light source and the selected plant.

In this study, the hourly $PAR_{occupants\text{-}lighting}$ values are carefully considered to estimate the grow light requirement of each plant ($PAR_{grow\text{-}lighting}$). The artificial lighting and the respective hourly dimming fraction profile are different under different shading condition and needs to be generated by TRNSYS in advance. While the supplemental lighting for occupants provides some PAR for the adjacent plants, extra lighting might be still required to ensure healthy growth, especially during weekends for the ones located far from window openings.

Grow lighting is commonly used in greenhouse production to increase plant photosynthetic rate, thus increasing crop yield and shortening the production cycle based on the DLI target value. As electrical consumption of lighting increases the production cost, more energy-efficient lighting sources (e.g. LEDs) in combination with optimal controllers have been applied recently. This way, the available daylight on the plants' foliage will be recorded on daily basis to provide plants with the optimal level of supplemental PAR at which plants reach the DLI target.

For applying a DLI-based control, we assumed the same light source (Grow light LED) but four individually controllable lighting fixtures were set 0.5 above each plant's foliage for each potted plant (P0-P3) which provides PPFD of 215 µmol/m²s. In addition, to cover the whole area of the green wall (P4), three fixtures with the same light source were installed at 1.5 m distance to illuminate the whole green wall area which lead to a PPFD of 78 µmol/m²s. Table 4 shows the supplemental electrical lighting used in this study for occupants and plants.

Table 4: Supplemental electrical lighting

for occupants	*White LED lighting For each luminaire (50 Watts) PPFD (1m) = 25 µmol/m²·s PPFD (3m) = 10 µmol/m²·s*	*Daylight based control for art. lighting in TRNSYS Ill set-points: 300 lx - 500 lx*
for plants	*Grow light LED For each luminaire (50 Watts) PPFD (0.5m) = 215 µmol/m²·s PPFD (1.5m) = 78 µmol/m²·s*	*DLI based control for art. Lighting (Python code) DLI target: species dependent (see Table 1)*

Thermal Simulation Setups

To simulate the operational energy of the office room TRNSYS software was used (for the simulation framework, refer to (Ganji Kheybari & Hoffmann, 2019). The usual work schedule of the building occupants in the prototypical office is Monday through Friday from 8:00 to 18:00.

The setpoint temperatures for heating and cooling are assumed 21 °C and 25 °C respectively which should provide a comfortable condition. However, due to a highly-glazed façade, high transmitted radiation may lead to thermal discomfort on some sunny days without shading protection. Therefore we evaluate the performance of the shading systems by looking into the local hourly predictive mean vote (PMV).

In addition during unoccupied hours, a setback of 3 K is assumed for cooling and heating set-point temperatures. Considering the "Hardiness Zone" and "Heat Zone" of the selected plants, this temperature range (18°C to 28°C) still does not disturb the acceptable thermal condition for plants (see Table 5). The infiltration and ventilation during the occupied hours and unoccupied hours are set following the conditions requested by DIN 4108-2.

Table 5: Boundary conditions in the office rooms

Item	*Description*	*Additional details*
Thermal properties	*Light-weight Construction Based on DIN 4108-2*	*Overall effective heat capacity = 47 (Wh/m²K)*
	Ext. Wall (External) Area: 22.3 m², U-value: 0.83 W/m²K	*Solar Absorption. of ceiling 10% walls 10% floor 80%*
	Floor, Ceiling, and Int. Walls (Adiabatic)	
Weather data	*Mannheim, Germany 49.48° N, 8.46° E*	*Temperate climate (Cfb) epw weather file format*
Internal gains	*4 people, light work (4*145 W) 4 computers (4*140 W) Artificial lighting (6.7 W/m²)*	*Daylight based control for artificial lighting in TRNSYS ill-setpoints: 300-500lx*
Infiltration	*Occupied: n = 1.21 h-1*	*Unoccupied: n = 0.24 h-1*
Increased ventilation	*Occupied: n = 3 h-1 Unoccupied: n = 5 h-1*	*Tin>Tout & Tin>23°C Tout-avg24h>18°C & Tin>Tout & Tin>21°C*
Heating/ Cooling set-points	*Heating set-point = 21°C Cooling set-point = 25°C*	*Unoccupied = 18°C Unoccupied = 28°C*
Assumed energy factors	*$COP_{Heating}$ (heat-pump) = 4.2 $COP_{Cooling}$ (chiller) = 4 $COP_{Lighting}$ = 1*	*Electricity primary energy factor (f_P) = 3.31 Specific CO_2 emission factor = 0.469 $KgCO_2e/kWh$*

Control strategies for electrochromic glazing

Many different control strategies for automating EC glazing can be implemented in simulations to evaluate the annual performance of the shading system. While different control strategies have been investigated for smart EC glazing by the first author (Kheybari & Hoffmann, 2020), in this paper, we limited the number of control conditions to two commonly used automation:

1. Radiation-based control (CtrlRad) is a conventional control based on the incident of global radiation on the facade. The window zones are switched to a "low-tinted" state when the global radiation is equal to or beyond 200 W/m² as prescribed by DIN EN 4108-2 for south-oriented windows for non-residential buildings.

2. Penalty-based control (CtrlPen) is an optimal predictive control that was introduced previously by the first author (Ganji Kheybari, Steiner, Liu, & Hoffmann, 2021) and shows the full potential of an optimal multi-objective control strategy. According to the predefined priorities for energy, visual, and thermal comfort indicators, the algorithm searches hourly simulated results of all possible shading combinations (here 64 tinting combinations for EC) to identify the top-ranked combinations with the minimum penalties. The total penalty is a sum weighted function including penalties for individual performance indicators and their corresponding weighting fraction (here weighting fractions were assumed equally).

In this paper, the "CtrlPen" only considers the human-based performance indicators. However, the minimum requirements are investigated by observing the influence of the controller on the plants' needs and extra electricity for supplemental lighting.

In addition to these automated EC conditions, one static case was used representing a not-controlled EC, always clear state (AllClr) as the baseline. This means the EC is kept always in its clear state on all three window zones (top, middle, and bottom). Table 6 summarizes different control conditions.

Table 6: Control strategies for electrochromic glazing

Control strategies		Condition	EC tinting state [Top, Middle, Bottom]
Static	Always Clear (AllClr)	Always clear state of EC	[S0,S0,S0] Clear
Automatic	Radiation based control (CtrlRad)	Radiation $_{global}$ < 200 W/m² Radiation $_{global}$ ≥ 200 W/m²	[S0,S0,S0] Clear [S3,S3,S0] Fully tinted but the bottom zone
	Penalty based control (CtrlPen)	A predictive simulation-based control considering all thermal, visual, and energy aspects in the optimization process	[var., var., var.] 0,1,2 or 3

Results and Discussion

The main objective of this paper is to investigate the impact of automated switchable EC glazing on not only energy savings and providing visual and thermal comfort for occupants but also the requirements for indoor plants. To evaluate the performance of the room for both humans and plants, we defined some annual human-centric performance indicators which need to be provided during occupied hours and a species-dependent DLI target that should be ensured by using supplemental electrical lighting year-round.

The annual electricity demand for providing these requirements is calculated under different control conditions. This demand includes electricity for heating, cooling, occupants-lighting, and grow-lighting.

Minimum requirements for occupants

For the assessment of thermal comfort via Predicted Mean Vote (PMV), environmental parameters (e.g. mean radiant temperature and air velocity) and personal factors (e.g. clothing factor and metabolic rate) are assumed following the seated occupants working in an office room.

For visual comfort, useful daylight illuminance (UDI) and glare probability is analyzed. UDI expresses the percentage of the occupied hours when the horizontal illuminance is less than 3000 lux but greater than 300 lux. Annual glare probability is evaluated based on DGPs driven by simulated vertical illuminance (Ev) at different eye levels using Radiance 3-phase method. DGPs values are later rated according to the established categories and thresholds. Table 7 presents the conditions regarded in the simulation and the performance categories of each criterion that are presented and discussed as results.

Table 7: Control strategies for electrochromic glazing

	Indicators	Details	Criteria
Min. requirements for occupants	Predicted Mean Vote (PMV)	Clothing factor: Clo = 0.5 clo: Tout-avg24h > 18°C Clo = 1 clo: Tout-avg24h ≤ 18°C Metabolic rate: 1.2 met Air velocity: 0.1 m/s	Cold: PMV<-0.5 Neutral: -0.5≤PMV≤+0.5 Warm: +0.5<PMV
	Simplified Daylight Glare Probability (DGPs)	DGPs is calculated based on vertical illuminance (Ev) at eye levels using Radiance 3-phase method	Acceptable: 0.35<DGP Perceptible: 0.35≤DGP<0.4 Disturbing: 0.4≤DGP<0.45 Intolerable: 0.45≤DGP
	Useful Daylight Illuminance (UDI)	Horizontal illuminance (Eh) simulated in workplaces using Radiance 3-phase method	Dark: Eh < 300 lux Useful: 300 lux ≤ Eh ≤3000 lux Bright: Eh > 3000 lux

Figure 3 shows the overall performance of the room with a switchable EC under three different control conditions (AllClr, CtrlRad, and CtrlPen; see Table 6). Three aspects of energy, visual comfort, and thermal comfort are illustrated as color-coded bar charts.

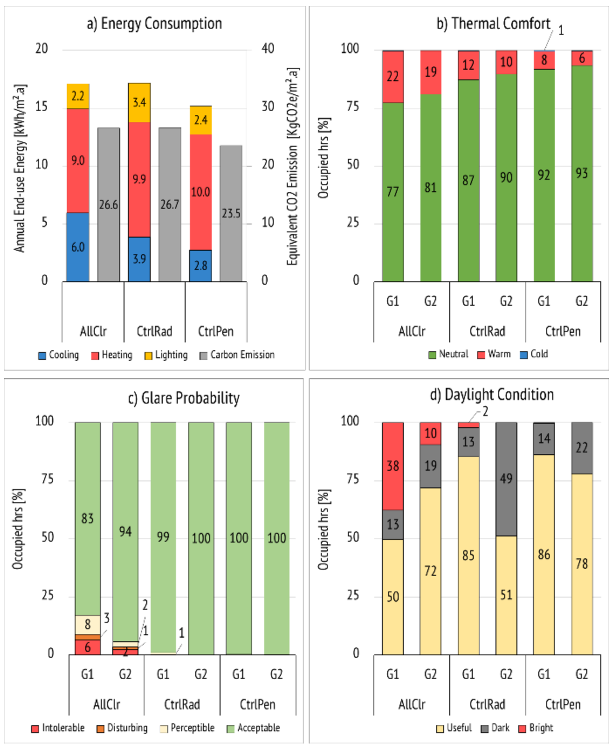

Figure 3: overall performance of the room with a switchable EC under three different control conditions (AllClr, CtrlRad, and CtrlPen): a) electricity consumption, b) thermal comfort, c) glare probability, and d) useful daylight

Figure 3.a indicates the annual end-use electricity consumption of the room for cooling (blue), heating (red), and electrical lighting (yellow) for occupants in kWh/m²a

on the left axis. In this study, a heat pump and a chiller system were assumed for heating and cooling (see Table 5). Total equivalent CO_2 emission is also presented (grey) on the right axis using electricity primary energy factor (f_P) of 3.31 and a specific CO_2 emission factor equal to 0.469 $KgCO_2e/kWh$ for electricity production mix factor in Germany (carbonfootprint.com). This is mainly the cost of providing thermal and visual comfort for occupants indoors.

One can see the cooling demand reduced by using tinted states of EC and the most energy savings are achieved by the penalty-based controller (CtrlPen). The use of shading reduced the amount of transmitted radiation and it has a direct impact on the supplemental lighting.

Thermal comfort can be achieved when PMV is between +0.5 and -0.5 which is also called a "neutral" condition (ISO 7730, Class B). PMV values above 0.5 and below -0.5 are considered respectively "warm" and "cold" conditions and should be limited. Figure 3.b depicts the percentage of thermally comfortable occupied hours (neutral: green) and thermally dis-comfortable (cold: blue or warm: red). The values are shown for two groups of occupants: G1 closer and G2 farther to the façade.

Figure 3.c shows the percentage of occupied hours with discomfort glare (either disturbing: orange or intolerable: red). Figure 3.d presents the percentage of occupied hours when useful daylight is not provided on the work desks group G1 and G2 (dark: grey or bright: red).

The penalty-based controller (CtrlPen) provides maximum thermally comfortable conditions for occupants in both groups (G1 and G2) for up to 93% of the occupied hours. This predictive controller also ensures avoiding discomfort glare (100%) and maintains the greatest useful daylight in both workgroups (up to 86%).

Minimum requirements for plants growth

Thus far, the results showed a switchable EC glazing is capable of saving cooling demand and improving both thermal and visual comfort for the occupants. This also proves the importance of control algorithms and their consequences on the supplemental lighting required for indoor plants.

While providing thermal comfort for occupants has a direct impact on maintaining an acceptable temperature range, a healthy plant needs a DLI target to be achieved daily. As mentioned earlier, in this study, the hourly $PAR_{daylight}$ and $PAR_{occupants\text{-}lighting}$ values are carefully considered to estimate the daily supplemental grow light required for each plant. Therefore the daily required electricity use can be calculated based on the species-dependent DLI targets (see Table 1).

Figure 4 shows the daily natural DLI received by each plant (P0-P4) over a year under different shading conditions: a) AllClr, b) CtrlRad, and c) CtrlPen. One can see that the hourly tinting state of the EC determined by the controller influences the amount of transmitted radiation through the EC glazing and its distribution within the room. For instance, the DLI accumulated on the plant close to the window (P3: bright green dotted line) goes beyond 8 mol/m²d when the EC is always in a clear state (AllClr), while it never reaches 4 mol/m²d under automation (CtrlRad or CtrlPen).

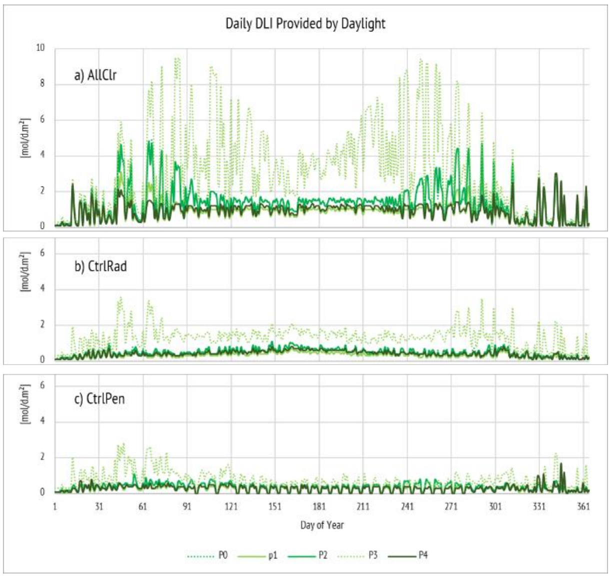

Figure 4: Daily DLI provided by natural light received by each plant (P0-P4) under three different control conditions over a year: a) AllClr, b) CtrlRad, and c) CtrlPen

Supplemental electrical demand

Considering available DLI from daylight and occupants' lightings the remainder should be provided by turning on the supplemental grow lightings. Figure 5 shows how much each lighting needs to be switched ON to provide the required DLI target for each plant (P0-P4) on a daily basis. One can see that the green wall requires about 16 hours of supplemental lighting almost every winter day since it is located far from the window (6 m) and the occupants' lighting.

Considering the electrical power usage of each luminaire (see Table 4) and the total number of hours when the lights are switched ON, the total electricity demand can be calculated for the individual supplemental grow lighting. Figure 6 shows the total annual supplemental electricity demand for occupant lighting (G1+G2), potted plants (P0-P3), and green wall (P4) under three different control conditions.

The major portion of the total demand is for illuminating the large green wall (P4) which almost does not get any natural daylighting. To maintain the minimum required DLI (here DLI_{min} 5 mol/m²d) the corresponding luminaires need to be ON for about 16 hours a day (see Figure 5 dark green line for P4). Sometimes it is recommended to use a light source with higher intensity to shorten the "photosynthesis period".

The potted plants with higher lighting demand (P1, P3: DLI_{min}10 mol/m²d) lead to the second big portion of electricity demand. One can see the demand for Plants closer to the window (P3) is lower than the same plant farther (P1) due to the available natural daylighting. The potted plants with lower lighting demand (P0, P2: DLI_{min} 2 mol/m²d) leads to the minor part of electricity demand.

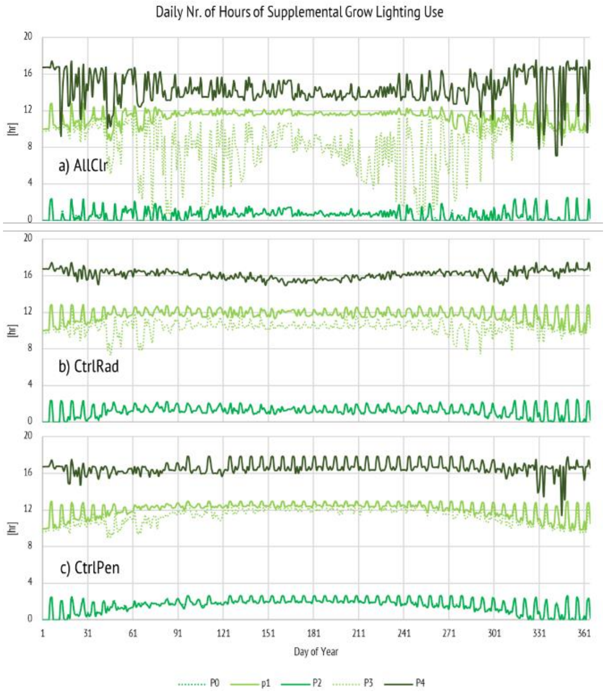

Figure 5: Daily number of hours when the supplemental grow lighting needs to be used to provide the DLI target for each plant (P0-P4) under three different control conditions over a year: a) AllClr, b) CtrlRad, and c) CtrlPen

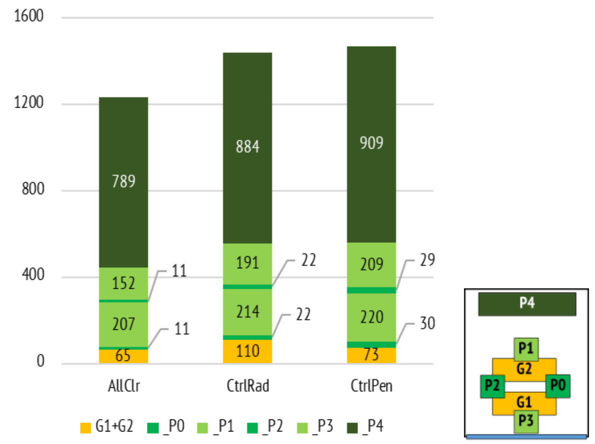

Figure 6: Total annual electricity demand kWh for supplemental lighting for occupants (G1+G2), potted plants (P0-P3), and green wall (P4) under three different control conditions

Table 8 shows the total supplemental electrical demand for lighting and its equivalent primary electricity and CO_2 emission under three different control conditions.

Table 8: Supplemental electrical demand for lighting and its equivalent primary electricity and CO_2 emission

Control strategies	*Supplemental electrical demand for lighting kWh/m².a*			*Total Primary Electricity kWh/m².a*	*Total Carbon Emission KgCO₂e/m²*
	Occupants G1+G2	*Potted plants*	*Green Wall*		
AllClr	*2.2*	*12.7*	*26.3*	*136.3*	*63.9*
CtrlRad	*3.4*	*14.9*	*29.5*	*159.1*	*74.6*
CtrlPen	*2.4*	*16.3*	*30.3*	*162.3*	*76.1*

Conclusion

Traditionally, control strategies are applied to automate switchable electrochromic glazing systems (EC) to provide comfort for occupants indoors by using minimum energy. With the rise of the biophilic trend, the way we design and control the buildings seems to require a major re-thinking considering the plants and their minimum requirements.

Therefore, this paper introduces a simulation workflow to evaluate the impact of EC glazing automation using combined climate-based daylight (Radiance) and building energy simulation tool (TRNSYS). It is possible to look into different performance indicators and investigate the impact of different control strategies on both human and plants requirements year-round.

The results showed that switchable EC under has a significant impact not only on occupants' comfort but also on plants' needs. By all means, the minimum lighting demand happens when the EC glazing is kept always in its clear state (AllClr), yet as far as comfort is concerned it is not a solution. Penalty-based control (CtrlPen) representing an optimal predictive control shows promising improvements both for visual and thermal comfort while saving about 11% of total electricity demand compared to the baseline (AllClr). Radiation-based control (CtrlRad) also shows meaningful improvements in comfort.

Toward a biophilic design that includes indoor plants and green walls, a trade-off needs to be conducted between the impacts of shading systems on thermal and visual comfort and the resultant extra electricity for supplemental lighting. The provided results for total electricity demand show the importance of these control algorithms and their consequences on the lighting required for indoor plants.

During the early stage of design, this information helps designers to picture both plants' and humans' requirements and find an applicable and sustainable design solution by adjusting the orientation, window opening, and plan layout for occupants and plants. The results also show that not only the location of the plants within the room but also the species-dependent DLI target play a major role in finding the right place for the right plant species.

In the future by acknowledging the significance of the biophilic concept and including indoor plants, it might be worth extending the previously introduced penalty-based controller to include minimum requirements for plants directly in the optimization process. The outcome could be a predictive controller which makes a trade-off between the occupants'/plants' demands and the total electricity cost.

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Appendix

In this study two control strategies were considered: 1) Radiation based control (CtrlRad) which activates based on the global radiation on the façade. 2) Penalty based control (CtrlPen) which is a predictive simulation-based control considering all thermal, visual, and energy aspects in the optimization process (see Table 6).
Every hour, these strategies lead to different EC states on each window zone top, middle, and bottom. Figure A-1.a shows the hourly overall states of the EC under Radiation based control (CtrlRad). Every point represents an hour of year which is color coded based on the sum of the tint states on window zones (e.g. sum[S0,S0,S0] = 0 (clear), sum[S2,S2,S0] = 4, and sum[S3,S3,S3] = 9 (fully tinted)). Similarly, Figure A-1.b shows the hourly overall states of the EC under Penalty based control (CtrlPen).

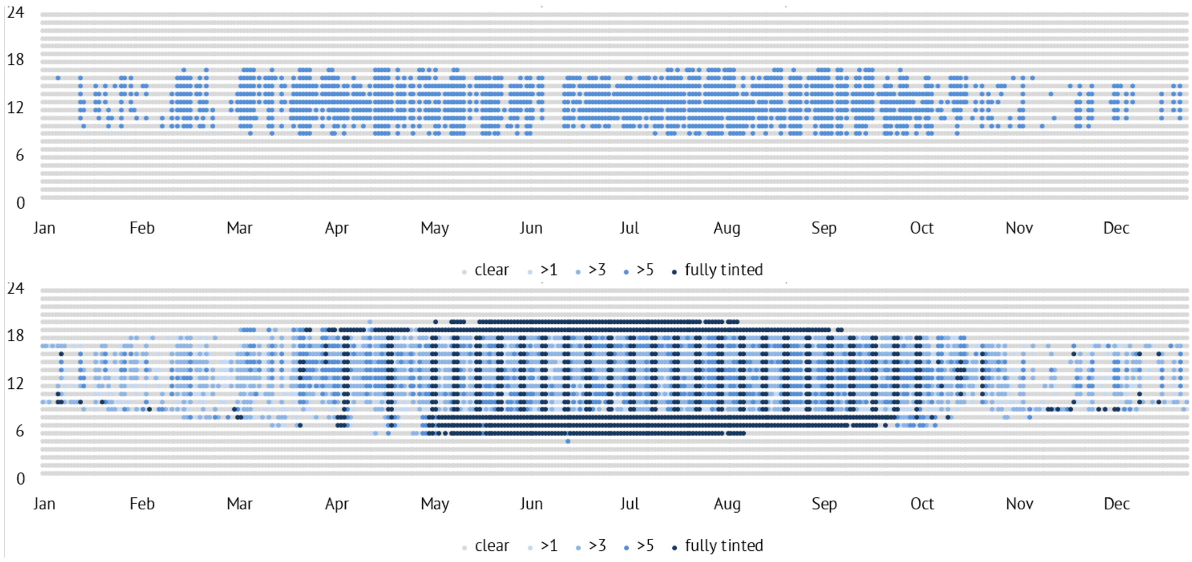

Figure A-1. a) Hourly states of the EC under Radiation based control (CtrlRad), b) Hourly states of the EC under Penalty based control (CtrlPen) as it was applied in simulations

https://doi.org/10.1051/e3sconf/202236208004

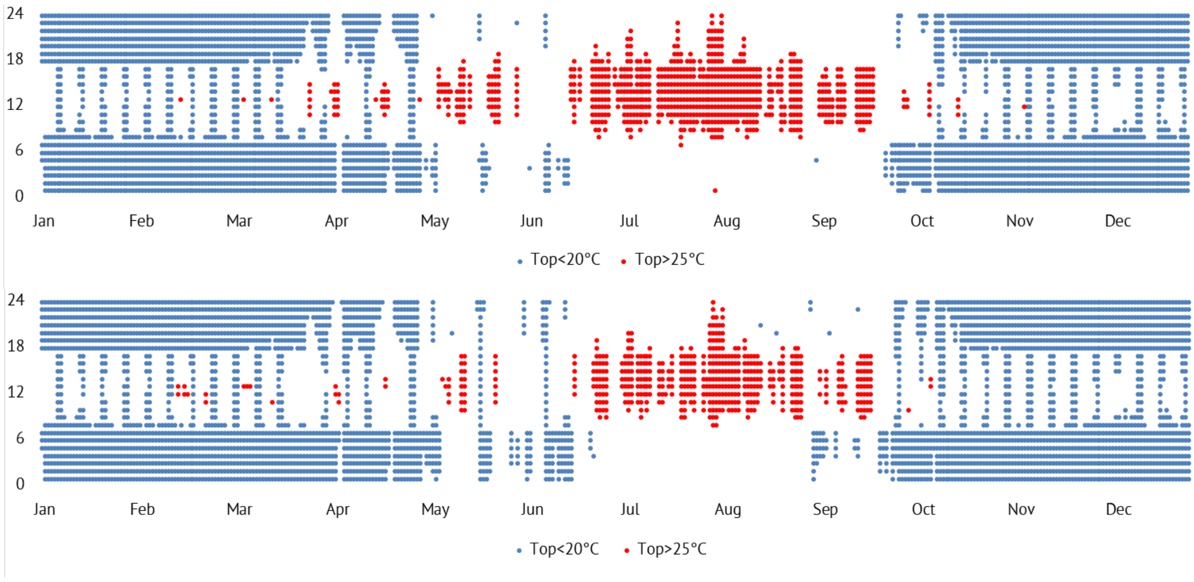

Figure A-2. Hourly simulated operative temperature (Top) inside the office room influenced by different control strategies: a) Radiation based control (CtrlRad), b) Penalty based control (CtrlPen)