Effect of Blind Control Strategies on Energy Demand of Office Buildings and Melanopic Effect for Occupants

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Abstract

The total energy demand of buildings consisting of heating, cooling, and artificial light demand is strongly depends on solar gains resp. daylight passing the façade. To prevent glare issues and overheating in summer, shading systems are widely used especially in office buildings. The majority of such systems involve venetian blinds. To provide a satisfying operation of the blind systems, the decision whether the façade should be opened or closed has to be based on live measurements of the external situation in terms of solar radiation, illuminance, and ambient temperature. The most commonly used control strategies operate rudimentarily, and often choose only between the two façade states, retracted blinds and deployed at a certain angle, mostly around 45°, based on simple criteria depending on single values of external sensors. This paper introduces a novel control strategy, which simulates the necessary artificial light and heating or cooling demand for each possible blind position in real time depending on external boundary conditions. This allows the determination of the best blind angle in terms of minimal total energy demand. The results show that these elaborate strategies can have a remarkable influence on the total energy demand of buildings. The evaluated test scene shows 30 % savings in terms of total primary energy demand could be achieved compared to conventional sun protection control strategies. In addition, daylight exposure of the occupants' faces can be improved and this represents an important factor for the melanopic effect. Two new strategies are applied to three different façade setups for a single office scenario and compared to a hypothetical reference system, which represents the state of the art.

1. Introduction

The transparent area and the insulation qualities of the façade define the total energy demand of the building. Solar gains reduce the heating demand in winter but can cause overheating or a high cooling demand in summer. To avoid that, a sun protection façade system can be installed, which is usually activated by exceeding external irradiation values in summer. Such façade systems often also fulfil a glare protection function, which is controlled by the occupant. Furthermore, it has an enormous influence on the daylight input and thus on the artificial lighting demand. However, this impact is usually not taken into account in the façade control strategy and energetically optimized façade system positions in terms of minimal heating, cooling, and artificial light demand cannot be determined.

Two elaborate integral control strategies for façade systems are introduced and compared to a commonly employed "reference strategy". In contrast to other studies introducing elaborate integral control strategies, which operate blinds at cutoff angle or optimize blind angles to improve daylight redirection in deeper regions of the room (Liu et al., 2015; Chan and Tzempelikos, 2015), a full factorial simulation of all possible blind positions in every time step is provided in this study. Both introduced strategies involve a daylight simulation based on the radiance three-phase-method (Ward et al., 2011). It is used to detect glare, calculate the vertical illuminance of the occupant's faces, and assess the horizontal room illuminance on certain points by daylight. Finally, the artificial light demand results from the difference to a requested illuminance of 500 lx on the working plane. While the first strategy only deals with lighting issues, the second strategy additionally includes a simplified thermal analysis and is therefore capable of considering concerning about the total energy demand in the choice of the optimal blind-positions. For the optimization, a target function is defined including the calculation of all possible blind-positions. The one that reaches the optimum for the target function will be chosen. A detailed description of both strategies, their optimization processes, and the daylight simulation routine is provided in Section 2.4.

Three different façade build-ups are investigated. All of them employ external blinds that form the second most investigated systems in literature (Konstantoglou and Tsangrassoulis, 2016) after the internal blinds, hardly capable of preventing overheating in summer. The systems differ in terms of adjustability and blind type. While the first and second system only use shading blinds, the third system consists of shading blinds in the lower part and daylight redirecting blinds in the upper part. System two and three differ from system one in the fact that blind angles can be chosen differently in the lower and upper part.

The influences and potential savings of this novel control strategy are evaluated with the dynamic thermal building simulation tool, TRNSYS. Only the first of the three façade-systems is operated by all three strategies, since the other two systems involve separately controllable blind systems for the upper and lower part and thus they cannot be handled by the "reference strategy".

The annual simulations are performed on a single office with a south façade, using an EnergyPlus weather file for Innsbruck, Austria. The thermal insulation of the room is chosen to fulfil passive house standards. The windows consist of three panes where shading blinds are used and an additional glazing to protect the daylight redirecting blinds. In Sections 2.1 and 2.4 the geometry respectively other parameters of the thermal model are described in detail.

2. Model Setup

Parameters like room ventilation and envelope insulation including window build-up, have a significant influence on the thermal balance of the model, and consequently on the energy optimizing blind control strategy. Since the introduced blind systems and control strategies are not expected to find their main application in the retrofitting of existing buildings, a new building with passive house standard is assumed for the present study.

2.1 Geometry

As a test scene, a two-person office with a floor area of 5 x 5 m, a room height of 3 m and a façade, which is opaque in the part below 1 m and fully glazed above, is assumed. For the window a three-pane glazing is considered, including an additional pane in case of the daylight redirecting blind, which measures 1 m in height.

2.2 Investigated Blind Systems and Daylight Calculation

As shown in Fig. 1 left, diffuse reflecting, downwards curved lamellae are assumed as external blinds. Highly specular reflecting lamellae, which show an upward curvature, form the daylight redirecting blinds and are shown in Fig. 1 right. For the daylight simulation, the blind systems were geometrically modelled and bidirectional scattering distribution functions (BSDF) data were calculated for eight different blind angles (0°, 10°, 15°, 25°, 35°, 45°, 60°, 75°) using the radiance genBSDF method.

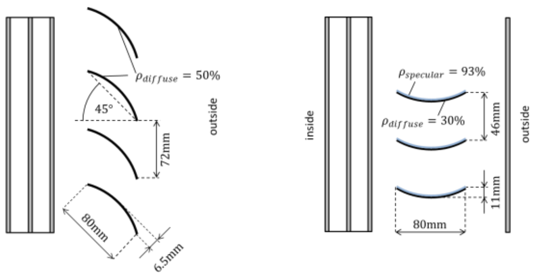

Fig. 1 – Left: External blinds; Right: Daylight redirecting blinds

The daylight calculations have to be carried out for all lamella positions in a very short timeframe to achieve real time results. Therefore daylight coefficients for diffuse und direct radiation are pre-calculated using the radiance three-phase-method (Ward et al., 2011). The BSDF-data in matrix format are multiplied by the daylight-matrix (diffuse and direct) from left, and by the view-factor-matrix from right. The multiplication of the resulting matrix by the daylight vector from the left, allows the calculation of the room illumination by daylight. The dimensions of the BSDF-matrix depend on the required angular resolution for the incoming and outgoing half-space. For the study at hand, Klems resolution was chosen, thus, the dimensions of the BSDF-matrix equal 145 x 145. For the daylight vector, the Tregenza discretization with 145 patches was chosen so the daylight-matrix also shows the dimensions of 145 x 145. The view-factor-matrix represents the mapping from the inner intensity distribution of the façade system to the measurement points (MP) inside the room, where the vertical and horizontal illuminance as well as the received luminance were calculated. The positions of the four MPs are shown in Fig. 2. At MP 1 and 2, which are 0.85 m above the ground, the vertical illuminance was calculated. The resulting values were used to calculate the artificial light demand that equates to the difference of the calculated daylight illuminance at the darker of the two MPs to the required 500 lx.

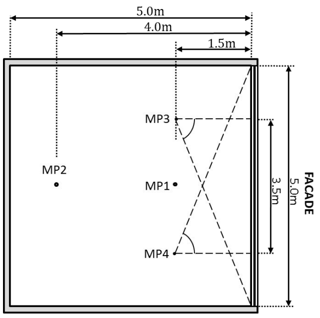

Fig. 2 – Positions of measurement points (MP) in the test room

MP 3 and 4 represent the sitting occupant's faces at a height of 1.2 m. Two different indicators are determined at these positions. The first is the vertical illuminance, used to evaluate the potential of gaining a nonvisual effect of the applied strategy and façade system. The second identifier is the maximum of the observed luminance. Glare is detected whenever this value exceeds 3000 cd/m² for either MP3 or MP4. This criterion was chosen according to DIN EN 12464-1, which defines an upper limit for the luminance of light fixtures that could cast reflections onto screens.

The daylight calculation was split up into a direct and a diffuse part from sun and sky respectively. The luminance of the sky is assumed to be homogenously distributed over the entire half-space. Using the three-phase-method, for each measurement point and blind position one diffuse and 145 direct daylight factors are simulated in advance and saved in a database. These 146 factors describe the quotient of internal and external luminance/illuminance by a diffuse sky and 145 sun positions. In each time step, the measured diffuse radiation is multiplied by the diffuse factor and the direct radiation is multiplied by the factor, which is chosen from the 145 direct values depending on the sun position. The results from direct and diffuse daylight calculation are summed up at the end resulting in internal luminance and illuminance values. These simplified calculations of two multiplications allow a real time determination of the daylight input for all possible blind positions, even in case of complex daylight redirection systems.

2.3 Coupled Thermal and Lighting Simulation

In order to evaluate the performance of this novel control strategy, the algorithm is tested within a TRNSYS simulation environment, which represents the building behavior using the multi-zone-building model Type56. Thus, the simulation routine comprises a thermal evaluation in TRNSYS, which is coupled to a thermal and lighting calculations based on the pre-calculated daylight factors described in Section 2.2 in the time step. The lighting and thermal calculations, as well as the optimization of blind positions are amalgamated in so-called VEC-modules (**V**isual and **E**nergy **C**ontrol), as described more closely in Section 2.5. The coupling routine works as follows: TRNSYS acts as master and hands over relevant parameters from the weather file to the particular VEC-module in every time step. The VEC-Module computes and returns values of the optimal blind position as well as the horizontal and vertical illuminances on the working plane, respectively the occupant's faces and the artificial light demand. TRNSYS considers the artificial light demand in the thermal simulation as an addition to the internal gain. Solar gains are calculated in TRNSYS using the newly introduced window model based on solar BSDFs and ISO 15099 algorithms (Hiller and Schöttl, 2014), provided by Transsolar as beta-version within this research work. Thereby, additionally to the solar transmittance, also the secondary heat flux is taken into account properly. The changing of the blind angle of the VEC-module is performed in TRNSYS by choosing the appropriate thermal BSDF of the system. The calculation of the thermal BSDFs were done in Window 7 using the previously calculated optical BSDFs. Almost the entire simulation setup is equal for all strategies and façade systems, except for the set of thermal BSDFs that change according to the investigated façade system, and the VEC-module is swapped according to the evaluated strategy and façade system.

2.4 Build-Up for Thermal Simulation in TRNSYS

Since the investigated office is assumed to be part of a large office building and adjacent room temperatures are considered equally, the heat flux through adjacent walls is neglected. To achieve a realistic simulation, some basic assumptions for the test setup were made.

Table 1 – Parameters of test room for the thermal simulation

Parameter	Value
U-value façade wall	0.1 W/m²/K
U-value window glazing (no shade)	0.7 W/m²/K
g-value window glazing (no shade)	0.5
Sensible heat emissions*	70 W/pers.
Operating hours*	7am-6pm
Internal loads* (equipment)	9.6 W/m²
Heating threshold*	20 °C
Cooling threshold*	26 °C
Air change rate domestic* (occupied/unoccupied)	0.96 / 0.2 h^{-1}
Air change rate night*	3 h^{-1}
Heat recovery rate	80 %
Infiltration rate	0.07 h^{-1}
Reflectance (ceiling/walls/floor)	80 / 50 / 30
Luminous efficacy of artificial light	70 lm/W

*according to SIA 2024

The occupation time and a schedule for internal gains were chosen by following the SIA 2024 standard. The chosen parameters for the test room for the thermal simulation are listed in Table 1.

2.5 VEC-Module

The VEC-module holds the control logic and is adapted to the particular façade system. As described in Section 2.2 the daylight calculation in the VEC-module is based on pre-calculated values. In each time step the diffuse and the direct daylight vectors are calculated based on the global and diffuse horizontal illuminance.

According to the applied control strategies and façade systems, different variants of the VEC-module were used, but for convenience all of them use the same set of input and output parameters, listed in Table 2. The global and diffuse vertical radiation is only used in the VEC-module, which employs the energy optimizing strategy. While the artificial light demand is the only energy output delivered by the VEC-module, heating and cooling demand were calculated in TRNSYS based on the blind position chosen by the VEC-module, as described in Section 2.2.

Table 2 – Input and output parameters of VEC-modules

Inputs	Outputs
- Timestamp [hour in year]	- Deployment of blinds [bool]
- Ambient temperature [°C]	- Blind angle middle façade part [deg]
- Global vertical radiation [W/m²]	- Blind angle upper façade part [deg]
- Diffuse vertical radiation [W/m²]	- Vertical daylight illuminance MP3 [lx]
- Global horizontal radiation [W/m²]	- Vertical daylight illuminance MP4 [lx]
- Diffuse horizontal radiation [W/m²]	- Horizontal Illuminance [lx]
- Global horizontal illuminance [lx]	- Artificial light demand [W/m²]

Each variant of the VEC-module is defined by pre-calculated daylight factors depending on the deployed façade system and the employed control strategy. The three façade systems are external blinds with continuous hanging, external blinds whereby the blind angle can be chosen separately for the upper and middle façade part and a combination of daylight redirecting blinds in the upper part and, finally, external blinds in the middle part. The three strategies are the "reference strategy" which decides to close the façade with a blind angle of 45° whenever the vertical global radiation rises above 150 W/m², the "light strategy" which always uses the blind position allowing maximal daylight entry without causing glare, and the "energy strategy" which performs an energetic analysis of all the blind positions and chooses the one generating the lowest primary energy demand. For heating and cooling heat pump systems with coefficients of performance of 3.5, respectively 2.5 are assumed. The primary energy demand is calculated by adding up heating, cooling, and artificial light demand weighted by the primary energy factors, for which values of 0.67, 0.96 and 2.4 are assumed respectively. The strategies "light" and "energy" avoid glare, since they exclude all blind positions, which meet the glare criterion during the office hours.

The energy analysis of the "energy strategy" comprises simplified calculations of the heating and cooling demand of the investigated room after the EN 13790 standard. Heating and cooling demands are calculated for every possible blind position, neglecting the thermal mass of the room. The consideration of the thermal mass is problematic, because the thermal situation in the time step before would strongly influence the decision for the optimal blind position. As an example in the morning of a hot summer day, the building's core temperature can still be relatively cold due to night ventilation and thus the cooling demand can be strongly underestimated. In that case, the strategy would not take into consideration the possible overheating in the morning hours and thus open the blind angles up to glare limitation. Due to the thermal mass of the building, the solar gain in the morning would have a negative repercussion on the rest of the day. That means a realistically calculated cooling demand is not the optimal criterion for the choice of the blind position. The stationary cooling demand was found to form a much more useful criterion for the optimization of the blind positions, since it sets the thermal insulation of the building in relation to the solar gain, and that parameter is directly influenced by the variation of the blind positions.

3. Evaluation of Simulated Data

The main goal of the present study is to evaluate blind control strategies according to the primary energy demand they cause, and for their ability of gaining a melanopic effect. Since control strategies interact directly with façade systems, an independent comparison is not expedient. The performed simulations involved different façade systems and different control strategies. A comparison between different façade systems controlled by the same strategy, as well as a comparison between different control strategies acting on the same façade system is shown in Section 4. For the energy evaluation of the strategies and façade systems, the primary energy demands for heating and cooling calculated in TRNSYS, and artificial light calculated in the VEC-module, were evaluated on a monthly and annual basis. To evaluate the façade systems' and strategies' potential of reaching a melanopic effect, the vertical illuminance was evaluated in MP 3 and 4, and integrated in the office hours of each month and for the whole year, resulting in the vertical luminous exposure. The melanopic effect comprises several non visual effects of daylight on humans. The term melanopic originates from the protein melanopsin, which can be found in intrinsically photosensitive retinal ganglion cells and plays an important role for the circadian rhythm (Hattar et al., 2002; Provencio and Warthen, 2012). A proper definition of the melanopic effect is still missing, but it strongly depends on the vertical illuminance of the occupants faces. The vertical luminous exposure is calculated as an integral of the vertical illuminance of the occupants faces during the office hours. The monthly and annual sum of these values can be used to assess the melanopic effect potential of the investigated setup. Since the melanopic effect is critical in winter and not critical in summer, the vertical luminous exposure was only evaluated for those days in which the sun rises after 7 am. It can be assumed, that workers gain sufficient daylight on their way to the office outside that time of year. The calculated values of the monthly and annual vertical luminous exposure are used to compare the particular strategies and façade systems in terms of their ability to provide a melanopic effect for the occupants.

4. Results and Interpretation

Fig. 3 shows the annual and monthly primary energy demand of the test room for the energy, light, and reference strategies.

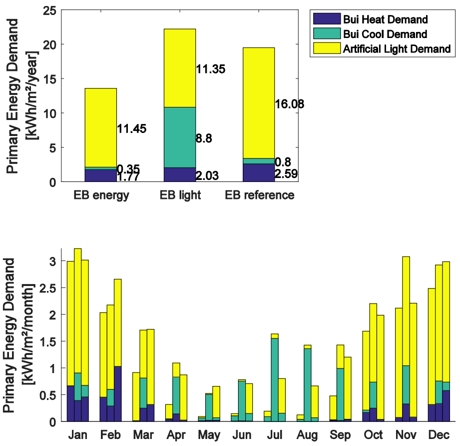

Fig. 3 – Annual and monthly primary energy demand of the test room equipped with external blinds (EB) for the energy, light, and reference strategies

The comparison of the three strategies shows that the cooling demand is the energetically most critical parameter for the control strategy. Since the investigated room was assumed to be well insulated according to passive house standards, for suboptimal control strategies a cooling demand can also be observed in winter. This is a rather hypothetical problem, since overheating in winter could be easily solved by temporarily increasing the ventilation rate or simply by opening a window. In such a case, the control strategy of the ventilation system would have to be adopted. The ventilation system defined for the thermal simulation in TRNSYS was not adjusted to that case, but to interact well with the "energy strategy". An energetically optimized strategy can reduce the cooling demand to the minimum, and for the simulated location, Innsbruck, Austria, the blind strategy can make the difference whether a cooling system is required or not. The only strategy that really depends on a cooling system is the "light strategy", whereby the artificial light demand is the only parameter that was minimized, and the blind angles are always opened to a maximum just to avoid glare. This causes high solar gain also in summer. The "reference strategy" performs well enough in terms of the cooling demand, since cooling in winter must not be taken into account, and the demand in summer is comparable to the value given by the "energy strategy". The heating demand can be reduced by more than 20 % when the "light" or "energy strategy" is applied compared to the "reference strategy", but the absolute energy savings of 0.6 kWh/m²/year is not worth mentioning. Since the wall buildup is assumed to comprise a good thermal insulation and the ventilation system with energy recuperation is taken into account, the heating demand does not leave much room for improvement. The main energy demand remaining for a well-insulated building equipped with a solar shading system is the artificial light demand. Compared to the "reference strategy" the artificial light demand can be reduced by 28.7 % or 4.6 kWh/m²/year with the application of the "energy strategy". The "energy strategy" achieves nearly the same artificial light demand as the "light strategy". Due to the fact that during the winter there is less gain in heating and artificial light demand is higher, the "energy strategy" prefers open façade settings, which results in same blind position as with the "light strategy". During the summer, the available daylight mostly suffices for the room illumination, even for the blind positions, which are chosen to prevent overheating. In this test setup the total primary energy saving for the "energy strategy" compared to the "reference strategy" is 29.6 % or 5.9 kWh/m²/year.

In Fig. 4 the annual and monthly vertical luminous exposure of the occupant's faces is shown. When the "reference strategy" is used, the occupants gain slightly more daylight during the critical period compared to the "energy strategy", but this result has to be considered with caution, because the "reference strategy" does not include a proper glare protection. The "light strategy" achieves the maximum quantity of daylight on the occupants, whereby glare is avoided. Although lighting energy savings are negligible, the vertical luminous exposure is increased by 18 % in the critical time compared to the "energy strategy".

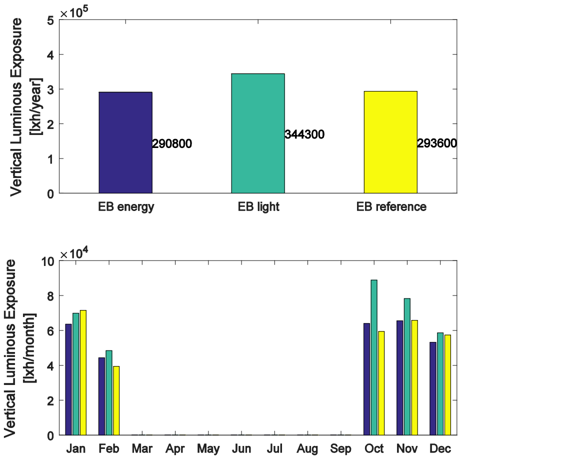

Fig. 4 – Annual and monthly vertical luminous exposure of the occupants' faces for the time range between October 5 to February 16, when sunrise is after 7 am

The reason for this discrepancy is that in time steps where several blind configurations neither cause glare nor artificial light demand, the "light strategy" tends to choose the configuration where the blinds are opened to a maximum. Since the target function of the "energy strategy" includes the heating and cooling demand in addition to the artificial lighting demand, it will choose a further closed façade configuration where still no artificial light is needed to avoid overheating in summer.

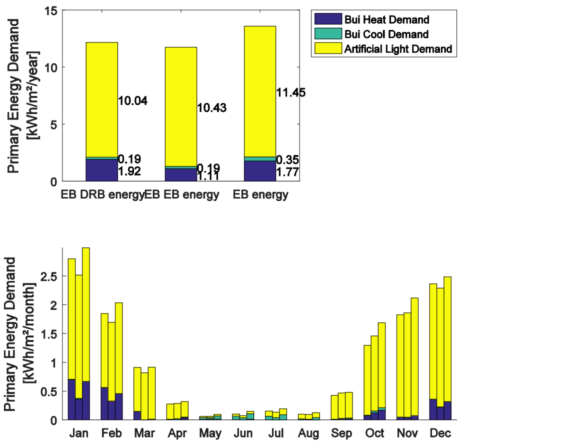

Fig. 5 – Annual and monthly primary energy demand of the test room equipped with the façade systems external blinds in combination with daylight redirecting blinds (EB DRB energy), external blinds two part hanging (EB EB energy) and external blinds (EB energy) controlled by the strategy energy

Fig. 5 shows the annual and monthly primary energy demand of the test room equipped with the façade systems external blinds (EB), external blinds with two-part hanging (EB EB), and external blinds in combination with daylight redirecting blinds (EB DRB) controlled by the strategy energy. The greater amount of possible façade configurations allows the simultaneous decrease of all three energy demands in total by 15 % using external blinds with two-part hanging compared to external blinds with continuous hanging. The façade settings "EB EB energy" and "EB DRB energy" achieve nearly the same energetic performance.

Fig. 6 shows the annual and monthly mean value of the vertical luminous exposure of the occupants' faces.

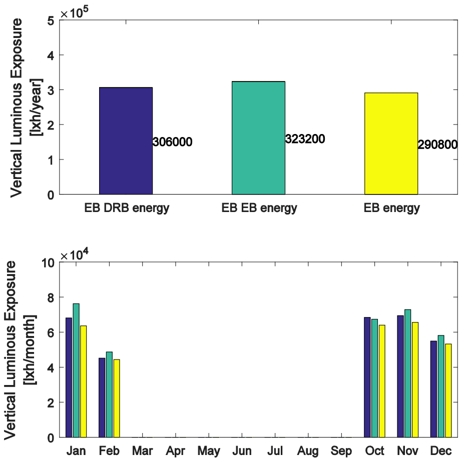

Fig. 6 – Annual and monthly vertical luminous exposure of the occupants' faces for the time range between October 5 to February 16, when sunrise is after 7 am

Even though the artificial light demand is higher, the vertical luminous exposure during the critical time is slightly higher, by 6 %, for the external blinds with two-part hanging compared to the daylight redirecting blind system. A possible reason for that curiosity is the fact that daylight redirecting blinds project daylight deeper into the room than diffuse reflecting external blinds. Since all workplaces in the test office are assumed to be close to the window, this illumination of the deeper space is not profitable for the occupants.

5. Conclusion

Energetically optimizing blind control strategies and ventilation strategies can work independently, but since they address the same optimization goal, namely minimizing the heating and cooling demand, they have to be adapted to each other in

order to keep them from working against each other.
A blind control strategy that only aims to avoid glare and has no included sun protection function can cause serious overheating problems. The addition of an energy optimization can make the installation of a cooling system unnecessary, depending on the climate at the specific site.
The performance of this integral control strategy at the evaluated test scene shows 30 % savings in terms of primary energy demand. Artificial light demand can be kept at its almost optimal level when an optimization of the total primary energy demand is performed. For the vertical luminous exposure of the occupants' faces, some room for improvement remains however still available.

6. Outlook

A scientific definition of the melanopic effect, which is still an object of research, so far is missing. Thereafter, a strategy to find a compromise between the minimal energy demand and the maximal melanopic effect can be investigated.
For future studies, a more realistic scenario could be achieved by a thermal simulation of an entire building including different façade orientations. The investigation of different sites would also be of interest.
The test room chosen for the study at hand does not show any benefits when using daylight redirecting blinds. A deeper office room with workplaces further away from the window should also be investigated to confirm or refute the expected benefit of using daylight redirecting blinds.
An implementation of the introduced energy blind control strategy at a test site and/or in a real building is necessary to investigate its applicability in the real world.

Acknowledgement

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References

Chan, Y.C., T. Athanasios. 2013. "Efficient Venetian Blind Control Strategies Considering Daylight Utilization and Glare Protection". *Solar Energy* 98: 241–254. doi:10.1016/j.solener.2013.10.005.

Hattar, S., H.W. Liao, M. Takao, D.M Berson, K.W. Yau. 2002. "Melanopsin-Containing Retinal Ganglion Cells: Architecture, Projections, and Intrinsic Photosensitivity". *Science* 295(5557): 1065–1070. doi:10.1126/science.1069609.

Hiller, M., P. Schöttl. 2014. "Modellierung komplexer Verglasungssysteme in TRNSYS". In: *Fifth German-Austrian IBPSA Conference*.

Konstantoglou, M., A. Tsangrassoulis. 2016. "Dynamic Operation of Daylighting and Shading Systems: A Literature Review". *Renewable and Sustainable Energy Reviews* 60: 268–283. doi:10.1016/j.rser.2015.12.246.

Liu, M., K. Bjarne Wittchen, P. Kvols Heiselberg. 2015. "Control Strategies for Intelligent Glazed Façade and Their Influence on Energy and Comfort Performance of Office Buildings in Denmark". *Applied Energy* 145: 43–51. doi:10.1016/j.apenergy.2015.02.003.

Provencio, I., D.M. Warthen. 2012. "Melanopsin, the Photopigment of Intrinsically Photosensitive Retinal Ganglion Cells". *Wiley Interdisciplinary Reviews: Membrane Transport and Signaling* 1(2): 228–237. doi:10.1002/wmts.29.

Ward, G., R. Mistrick, E.S. Lee, A. McNeil, J.C. Jonsson. 2011. "Simulating the Daylight Performance of Complex Fenestration Systems Using Bidirectional Scattering Distribution Functions within Radiance". *Leukos* 7: 241–261. doi:10.1080/15502724.2011.10732150.