Simulator for Predicting Vertical Illuminance of Window With External Venetian Blind

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Abstract

Many studies have shown that by installing external Venetian blinds on the transparent envelope and utilizing daylight efficiently, we can reduce cooling and heating load and lighting energy and improve thermal and visual comfort. Among many studies, most of them use light sensors or whole-building simulation tools to derive and control illuminance that affects the indoor luminous environment. However, this requires the cost of sensor installation and a large amount of information and modeling effort for simulation. In addition, it is difficult to understand the relationship between the inflow of visible light, the slat angle of blind, and illuminance. Therefore, this study proposes a stand-alone daylighting simulator based on artificial neural network using the visible transmittance of the window with external Venetian blind. Using the developed simulator, it is possible to easily predict indoor vertical illuminance under changing external environment by reflecting natural light inflows with only some information of the system and major environmental factors without sensor installation or simulation modeling effort.

In addition, due to the advantages of this simplicity, it can be easily used for model predictive control (MPC).

1. Introduction

In order to reduce cooling and lighting energy and improve occupant's thermal and visual comfort, many studies have been conducted to efficiently use transmitted daylight through an external Venetian blind (EVB) with transparent building envelopes. Many researchers have analyzed the effects of EVB on the thermal and light environment of buildings (Carletti et al., 2016; Fedorczak-Cisak et al., 2019) and analyzed the uncertainty and sensitivity of energy and visual performance due to various factors (window-to-wall ratio, glazing type, slat angles etc.) (Singh et al., 2016; Huo et al., 2021a). Moreover, based on the influence and analysis of these external Venetian blinds, many studies are being actively conducted to reduce the heating and cooling load and lighting energy of the building, and improve the visual comfort through the control of the slat angle of EVB (Huo et al., 2021b; Baghoolizadeh et al., 2023). Carletti et al. (2006) installed EVB in a full-scale test room and monitored temperature and illuminance through

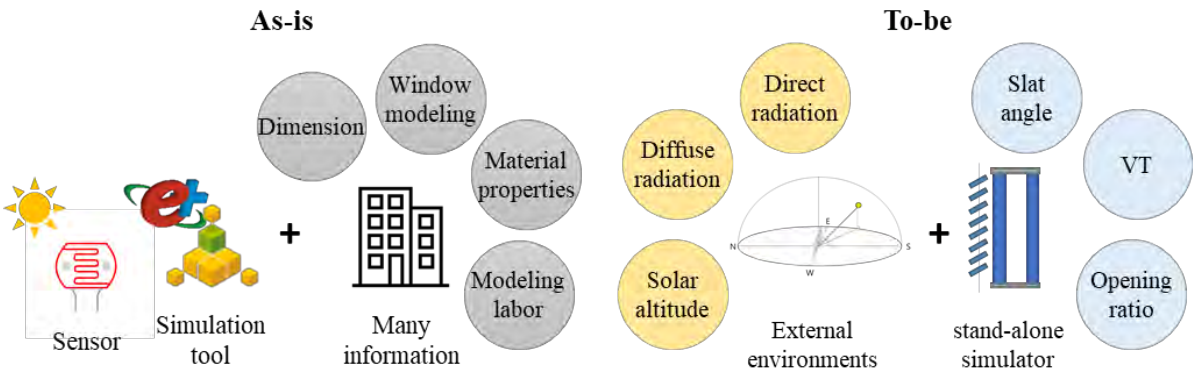

Fig. 1 – Simulator for indoor daylit environment: As-is vs. To-be

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thermometers and luxmeters, arguing that the different configurations of the Venetian blind can keep the mean radiant temperature lower and maintain a good level of internal illuminance. Fedorczak-Cisak et al. (2019) installed EVB in the office space and observed temperature and humidity through sensors (temperature, humidity, air velocity) during the transition season when the heating and cooling system did not operate, showing that the use of blinds reduced discomfort hours by 92% compared to rooms without EVB. Huo et al. (2021b) modeled a venetian blind with EnergyPlus, and evaluated the shading performance when EVB was installed in different climate regions in China. The results show that there is a maximum building energy saving potential per unit window area of EVB when the window is westward and has low WWR (window-to-wall ratio) and slat angle of EVB is 0°. Baghoolizadeh et al. (2023) conducted multi-objective optimization (energy consumption, visual & thermal comfort) of Venetian blinds in office buildings with EnergyPlus and NSGA-II algorithm. They showed that in the shading position (interior vs. exterior), the external blinds were optimally selected for all seasons, so the external blinds performed better than the internal blinds in terms of solar and luminous control, e.g. the smaller the slat angle of EVB, the better the visual comfort but the higher the lighting energy.

According to many other studies (Jung & Kim, 2010; Shin et al., 2011; Park et al., 2012; Kim & Kim, 2015) when inducing and controlling the illuminance according to the slat angle of the EVB, the illuminance at a specific point is directly measured through a light sensor or derived using a simulation tool (EnergyPlus, Desktop Radiance 2.0, TRNSYS). However, this requires detailed and extensive information (dimension and material properties for zone and window & blind, etc.) for modeling process. Also, it is difficult to understand a clear interrelationship between the inflowing luminous flux (direct and diffuse solar radiation), which greatly affects indoor illuminance, and the slat angle of EVB (the control variable) and illuminance (subject to the control variable). For implementing optimal control of EVB, e.g. determining an optimal slat angle, accurate prediction of daylighting transmission in terms of the slat angle is a prerequisite. If this relationship can be explained in a simple simulation toolbox per se, it becomes easier and more convenient to implement MPC of EVB. In addition, such simulator must be developed as a 'stand-alone' fashion so that it can be independent from a room model or a zone model for its wide application in optimal control of daylighting system. Therefore, this study proposes a 'stand-alone' daylighting simulator that predicts the vertical illuminance passing through the EVB + double glazing window system (EVBW) under varying external environment and the slat angle of the blind. The proposed simulator predicts illuminance based on the inflowing luminous flux.

2. Daylight Simulator Methodology

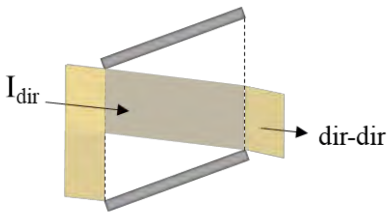
2.1 Key Information

1. In general, we perceive the luminous flux as the lumens [lm] or illuminance [lm/m²] caused by solar irradiance [W/m²] from the sun with a certain amount luminous efficacy [lm/W].
2. When daylight is introduced into interior zone, the luminous efficacy varies depending on the climatic and sky conditions (Littlefair, 1988; Umar & Chaiwiwatworakul, 2018). Therefore, we must acknowledge that luminous efficacy is not always constant and the luminous efficacies of direct and diffuse radiations are different from each other (Chaiwiwatworakul & Chirarattananon, 2013; Perez et al., 1990).
3. Solar altitude is a major factor that affects the luminous efficacies of direct and diffuse radiations (Aghimien et al., 2021).

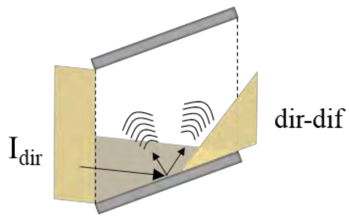
2.2 Visible Transmittance

Visible transmittance (VT) is a fraction of the visible spectrum of sunlight through the glazing of a window, weighted with respect to the photopic response of the human eye. When there is only a window, VT is used as one value, and only one reference value is presented for normal incidence in ASHRAE Fundamentals (ASHRAE, 2021). However, when EVB is installed in the window, VT is calculated by three categories: dir-dir, dir-dif, and dif-dif.

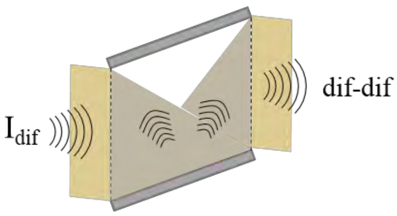
Dir-dir transmittance is the ratio of the incident beam radiation without distribution due to collision with slats when passing through the shading device (Figure 2 (a)). Dir-dif transmittance is used when the source is a beam incident radiation but outgoing radiation is diffuse due to collision with slats (Figure 2 (b)). Dif-dif transmittance is the ratio of the outgoing and incident radiant energy where the incident and outgoing radiation is diffuse (Figure 2 (c)) (Curcija et al., 2018). For overall VT estimation through the EVBW system, we need to consider the aforementioned three VT values ($VT_{dir\text{-}dir}$, $VT_{dir\text{-}dif}$, $VT_{dif\text{-}dif}$). These three VT values depend on solar position and slat angle of EVB, and accordingly, the ratio of direct (I_{dir}) and diffuse (I_{dif}) radiations entering the interior can be found.



(a) $VT_{dir\text{-}dir}$



(b) $VT_{dir\text{-}dif}$



(c) $VT_{dif\text{-}dif}$

Fig. 2 – Visible transmittance according to the incidence and inflow of direct and diffuse solar radiation ((a) $VT_{dir\text{-}dir}$, (b) $VT_{dir\text{-}dif}$, (c) $VT_{dif\text{-}dif}$)

2.3 ANN Model

An artificial neural network (ANN) model was used to develop the aforementioned daylighting simulator. ANN is constructed based on a multilayer perceptron between the input layer and the output layer, and there are multiple nodes in each layer. ANN predicts output variables by learning the correlation between input and output variables through weight parameter updates between nodes that minimize errors between the model's output and measured values through backpropagation methods (Raza & Khosravi, 2015; Ra et al., 2017). Although the number of hidden layers can affect the accuracy of the ANN model, there are no clear rules for determining the best number of hidden layer units (Han et al., 2012). Therefore, the input and output variables of the virtual daylighting simulator developed in this study were selected in consideration of the characteristics of light according to the slat angle, solar radiation and the solar position when the EVB was installed. The input parameters are a slat angle, environmental conditions (direct & diffuse solar radiation, zenith angle), and variables depending on the slat angle (three VT values (Figure 2), opening ratio, and the rate of horizontal diffuse solar radiation reaching the vertical wall). For reference, the zenith angle is set to (90° - solar altitude, (°)), so the influence of the solar altitude can be reflected in the zenith angle. In addition, the sky condition (clearness) is also considered along with direct and diffuse radiation (Perez et al., 1990). The output parameter is the vertical illuminance of the EVBW system.

Table 1 – ANN parameters

The number of hidden layers	2
The number of nodes (each layer)	(40, 100, 100, 40)
epoch	500

To collect input data for ANN learning, we generated an EVB and double-window model using pyWincalc (Kohler et al., 2019), a Windows-CalcEngine (LBNL, 2016)'s python package developed by LBNL (Lawrence Berkeley National Laboratory). The specifications and properties of slat of EVB are tabulated in Table 2. The slat angle of 0° is the state in which the blind slat is horizontal, and the slat is positive when facing the sky and negative when facing the ground. The double window consisted of clear glazing 6mm + argon gas 12 mm + clear glazing 6mm and was 1 m x 1 m in width and height (Figure 3). The EVBW system was set to the south facing. Environmental conditions were selected from 9 am to 4 pm in the summer solstice, autumn equinox, and winter solstice by referring to the EnergyPlus weather data (EPW) of Seoul that reflect changes in the solar position and sky condition according to season and time. Then, for each time point, we discretized the slat angles at 10˚ intervals in the range of -80° - 80° and derived three VT values.

The three VT values show different characteristics because the inflow of direct and diffuse radiation varies depending on the solar position and slat angle. $VT_{dir\text{-}dir}$ shows a large value when the profile angle defined by the azimuth and altitude angles of the sun and the slat angle are parallel. $VT_{dir\text{-}dif}$ is affected by the profile angle of the sun and the proportion covered by the slats. Also, since diffuse radiation does not have a specific orientation, it is not affected by the solar position and only the difference according to the slat angle. Therefore, $VT_{dif\text{-}dif}$ is the largest at 0˚, where diffuse radiation can be transmitted the most, and decreases to a symmetrical form based on 0˚.

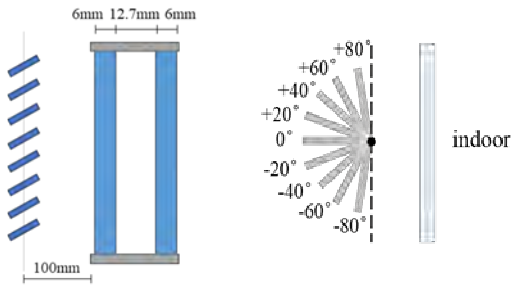


Fig. 3 – Double window with external Venetian blind and slat angle

Table 2 – Specification and properties of external Venetian blind slats

Slat property	Value
Slat width	50 mm
Slat spacing	50 mm
Slat thickness	15 mm
Transmittance	0.0
Reflectance	0.47
Distance from the window	100 mm

Next, to collect output data for ANN learning, we generated a zone (5 m x 5 m x 3.4 m) for simulation and the same EVBW system as pyWincalc (dimension, material properties etc.) using Climate Studio, a light simulation tool developed by Solemma (Figure 4). Thereafter, as with the collection of input data, we discretized 10˚ intervals (-80° - 80°) and conducted a total of 408 simulation runs (3 days x 8 hours x 17 slat angles) under the same environmental conditions. Then, we measured the vertical illuminance for the vertical surface grid immediately behind the system.

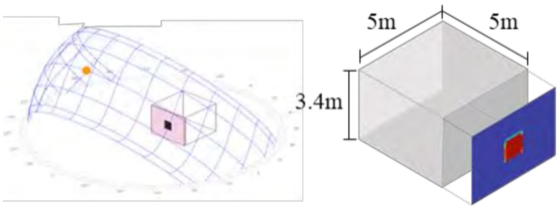
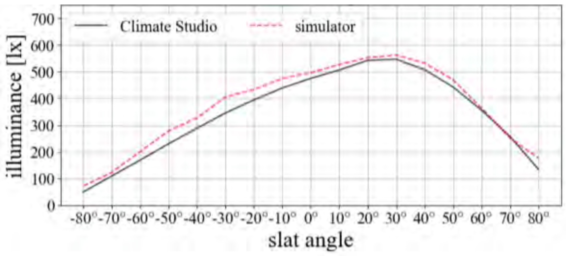


Fig. 4 – Lighting simulation using ClimateStudio

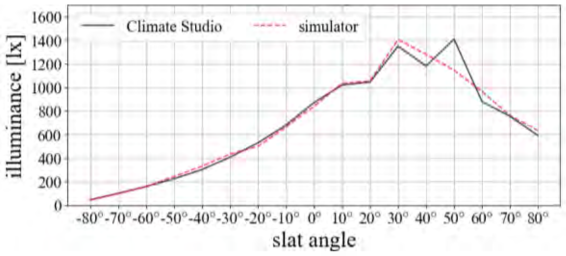
Based on the pyWincalc and the ClimateStudio simulation runs, we trained an ANN model. The accuracy of the ANN model was 13.0% based on Coefficient of Variance of Root Mean Square Error (CVRMSE), showing a prominent accuracy.

2.4 Validation

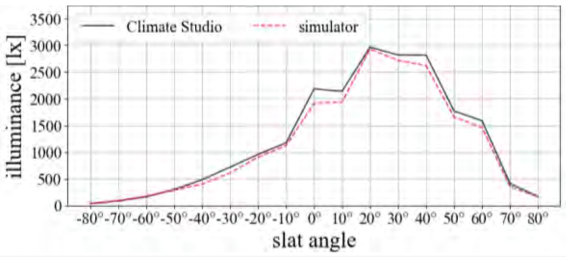
To validate the developed 'stand-alone' daylighting simulator, the author compared with ClimateStudio simulation results for an office room under an arbitrary summer, autumn equinox and winter day under one hour and 17 slat angles (total 51 cases = 3 days x 1 hour x 17 slat angles). The CVRMSEs between the 'stand-alone' daylighting simulator and a 'whole-building' ClimateStudio simulation runs were 9.1% in summer (Figure 5 (a)), 11.1% in autumn (Figure 5 (b)), and 9.3% in winter (Figure 5 (c)), respectively. The predicted illuminance in all seasons showed high accuracy, which means that the proposed daylighting simulator can account for the visible light transmittance according to the solar position and slat angle and accordingly, the vertical illuminance passing through the system can be well predicted.



(a) Summer (12pm)



(b) Autumn (2pm)



(c) Winter (1pm)

Fig. 5 – Comparison between daylighting simulator and ClimateStudio results

3. Model Predictive Control (MPC)

The energy use of large buildings is mainly dominated by cooling and lighting, and it is important to supply adequate daylighting and accordingly reduce cooling and lighting energy. To realize this, many studies have been conducted on optimal control of external venetian blind. In this regard, the authors applied the virtual daylighting simulator to MPC study for a given office space.

To quantify transmitted solar energy through EVBW system, Q_{solar} was introduced (Reddy et al. 2016). Please note that the direct and diffuse solar heat gain coefficients ($SHGC_{dir}$, $SHGC_{dif}$) can vary according to the slat angle and solar position, and the amount of direct and diffuse radiation (Equation 1).

$$Q_{solar} = SHGC_{dir} \bullet I_{dir} + SHGC_{dif} \bullet I_{dif} \quad (1)$$

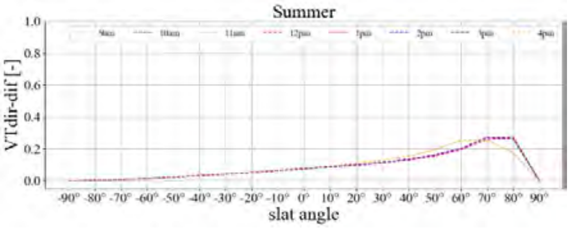
In addition, it is assumed that the transmitted daylight can be quantified by the vertical illuminance (E_{vg}) measured at the interior surface of inner glazing of EVBW. Accordingly, the objective function in MPC is to minimize Q_{solar} and maximize E_{vg} in cooling season, while to maximize both Q_{solar} and E_{vg} in winter. The constraints were set to have E_{vg} below 2,000 lux to avoid excessive glare in occupant's position about 1.1m away from the window by referring to the research of Karlsen et al. (2015). Optimal slat angles in summer and winter days were found through the exhaustive search method at intervals of 10˚ from -80˚ to 80˚. The baseline was assumed to have the slat angle of 0˚. The cost functions in summer and winter are as follows:

$$\arg\min J = -E_{vg} + Q_{solar} \quad \text{(summer)} \quad (2)$$

$$\arg\min J = -E_{vg} - Q_{solar} \quad \text{(winter)} \quad (3)$$

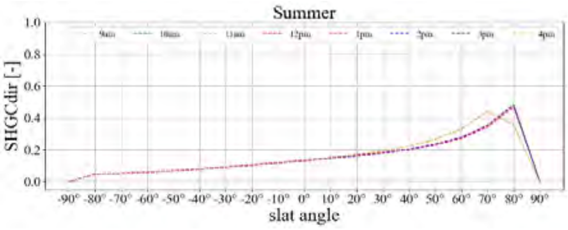
$$\text{s.t.} \quad Evg \leqq 2{,}000 \text{ lux}$$

Table 3 shows the results of summer control. In case of relatively large diffuse radiation (9 am, 2 pm) between 9 am and 4 pm, 0˚ was selected as the optimal angle because $VT_{dif-dif}$ of 0˚ is maximum (Figure 6 (b)) so large introduction of diffuse radiation maximized E_{vg} (9 am: 344 lm/m², 2 pm: 492 lm/m²). If the slat angle is negative, Q_{solar} can be reduced because $SHGC_{dir}$ and $SHGC_{dif}$ tend to decrease. Accordingly, VT and E_{vg} also decrease. Therefore, 0˚ was optimally selected according to the cost function in summer. When direct radiation was greater than diffuse solar radiation (10 am, 11 am, 12 pm, 1 pm, 4 pm), -20˚ was selected as the optimal angle because it reduced $SHGC_{dir}$ (Figure 6 (c)), although the values of $VT_{dir-dif}$ and $VT_{dif-dif}$ tend to decrease (Figure 6 (a), (b)), Table 3). When diffuse radiation was greatest but direct radiation was relatively small (3 pm), 10˚ was selected as the optimal angle. Compared to 0˚, the values of $SHGC_{dir}$ and $SHGC_{dif}$ at 10˚ are larger (Figure 6 (c), (d)), so Q_{solar} was increased (10˚: 187 W/m², 0˚: 154 W/m²). But, by choosing 10˚ with a high $VT_{dir-dif}$ value (Figure 6 (a)), E_{vg} was increased (10˚: 497 lm/m², 0˚: 410 lm/m²).

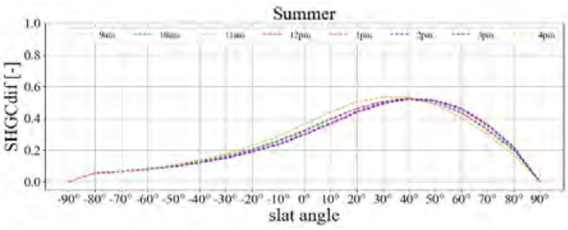


(a) $VT_{dir\text{-}dif}$ (Summer)

(b) $VT_{dif\text{-}dif}$ (Summer, Winter)



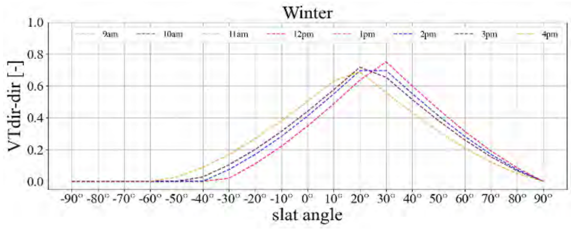
(c) $SHGC_{dir}$ (Summer)



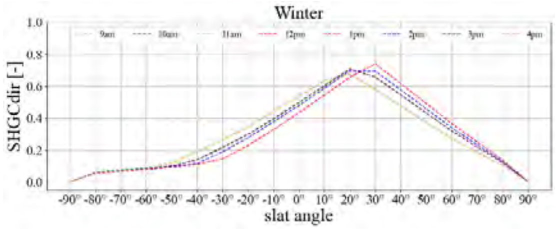
(d) $SHGC_{dif}$ (Summer)

Fig. 6 – VT and SHGC values in summer (using pyWincalc)

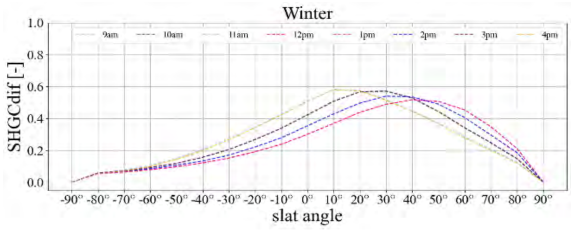
Similarly, Table 4 shows the results of winter control. Due to the low solar altitude, the introduction of direct solar radiation through the slat angle can be far greater than that in summer. Accordingly, $VT_{dir\text{-}dir}$ is large (max: 0.75, range: 0.0-0.75) (Figure 7 (a)). Therefore, E_{vg} could easily exceed 2,000 lx depending on the slat angle. When the solar altitude is low and direct and diffuse radiation were relatively low, the slat angles of 20˚ (9 am, 4 pm) and 30˚ (10 am) were selected as optimal. The profile angle according to the azimuth and altitude of the sun at those hours is between 15˚ and 30˚. Therefore, when the slat angle is parallel to the profile angle at 20˚ or 30˚, the values of $SHGC_{dir}$, $SHGC_{dif}$ and $VT_{dir\text{-}dir}$ are large (Figure 7 (a), (b), (c)), so more direct and diffuse radiation were introduced compared to the baseline (0˚). Thus, both Q_{solar} and E_{vg} become greater (Table 4). When direct and diffuse radiations are large (11 am, 12 pm, 1 pm, 2 pm, 3 pm), -10˚ was selected as the optimal angle. At 0˚, $VT_{dif\text{-}dif}$ is the maximum at every hour, but E_{vg} becomes beyond 2,000 lx. Therefore, compared to 0˚, the values of $SHGC_{dir}$ and $SHGC_{dif}$ at the slat angle of -10˚ are smaller (Figure 7 (b), (c)). Also, E_{vg} does not exceed 2,000 lx with reduced $VT_{dir\text{-}dir}$ and $VT_{dif\text{-}dif}$ (Figure 7 (a), Figure 6 (b), Table 4). Please note that Figure 6 (b) represents both seasons (summer, winter).



(a) $VT_{dir\text{-}dir}$ (Winter)



(b) $SHGC_{dir}$ (Winter)



(c) $SHGC_{dif}$ (Winter)

Fig. 7 – VT and SHGC values in winter (using pyWincalc)

4. Conclusion

In this study, an artificial neural network-based 'stand-alone' daylighting simulator was developed to predict vertical illuminance passing through a double window with external Venetian blinds. The novelty of the proposed simulator is the advantage of being 'stand-alone' because it relies on minimal information regarding the EVBW system and environmental factors (direct and diffuse solar radiation, zenith angle). As a result of verification under various environmental conditions, this daylighting simulator can easily predict the vertical illuminance at the interior surface of glazing by accurately calculating transmitted solar radiation through the EVBW system with the use of three VT values ($VT_{dir-dir}$, $VT_{dif-dif}$, $VT_{dif-dif}$) as a function of the slat angle. Therefore, this study contributes to overcoming the issue of capturing the dynamic relationship between the slat angle, transmitted direct and solar radiation through the transparent envelope, and any relevant illuminance. In addition, as part of MPC, the daylighting simulator was utilized for optimal control of EVB considering the heat and light transmission based on Q_{solar} and E_{vg} derived from the simulator. It is promising that the 'standalone' daylighting simulator could be freely applicable to MPC. As a further study, the authors will investigate how the daylighting simulator could be beneficially used for in-site experiments including a validation study between the predicted and measured illuminance values.

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Nomenclature

Symbols

ANN	Artificial neural network
E_{vg}	vertical illuminance (lm/m^2)
EVB	External Venetian blind
EVBW	EVB + double glazing window system
I_{dir}	direct solar radiation (W/m^2)
I_{dif}	diffuse solar radiation (W/m^2)
Q_{solar}	transmitted solar energy through EVBW (W/m^2)
$SHGC_{dir}$	direct solar heat gain coefficient (-)
$SHGC_{dif}$	diffuse solar heat gain coefficient (-)
VT	Visible transmittance
$VT_{dir-dir}$	direct-direct visible transmittance (-)
$VT_{dir-dif}$	direct-diffuse visible transmittance (-)
$VT_{dif-dif}$	diffuse-diffuse visible transmittance (-)

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Table 3 – Results of MPC using the daylighting simulator (Summer)

Time	I_{beam} (W/m²)	I_{dif} (W/m²)	Baseline (slat angle=0˚)		MPC		
			Transmitted Q_{solar} (W/m²)	E_{vg} (lm/m²)	Q_{solar} (W/m²)	E_{vg} (lm/m²)	Optimal slat angle (˚)
9am	129	280	119	344	119	344	0˚
10am	690	199	157	390	114	388	-20˚
11am	450	149	105	436	76	417	-20˚
12pm	520	165	119	455	86	444	-20˚
1pm	560	181	128	478	93	447	-20˚
2pm	747	259	176	492	176	492	0˚
3pm	222	395	154	410	187	497	10˚
4pm	696	202	166	344	118	311	-20˚
Total	-		**1,124**	**3,349**	**969**	**3,340**	-

Table 4 – Results of MPC using the daylighting simulator (Winter)

Time	I_{beam} (W/m²)	I_{dif} (W/m²)	Baseline (slat angle=0˚)		MPC		
			Transmitted Q_{solar} (W/m²)	E_{vg} (lm/m²)	Q_{solar} (W/m²)	E_{vg} (lm/m²)	Optimal slat angle (˚)
9am	78	46	66	399	80	1,095	20˚
10am	423	120	260	1,487	346	1,964	30˚
11am	500	76	266	2,616	208	1,991	-10˚
12pm	620	120	305	2,878	233	1,416	-10˚
1pm	720	150	358	2,849	271	1,448	-10˚
2pm	700	200	406	2,616	322	1,642	-10˚
3pm	650	95	364	2,356	290	1,921	-10˚
4pm	452	93	288	1,304	358	1,795	20˚
Total	-		**2,313**	**16,505**	**2,108**	**13,272**	-