Daylighting simulation and analysis of buildings with dynamic photovoltaic window shading elements

Gao, Y.; Dong, J.; Isabella, O.; Zeman, M.; Zhang, G. Q.

DOI
10.1109/IFWS.2017.8245973

Publication date
2017

Document Version
Final published version

Published in
2017 14th China International Forum on Solid State Lighting

Citation (APA)
Gao, Y., Dong, J., Isabella, O., Zeman, M., & Zhang, G. Q. (2017). Daylighting simulation and analysis of buildings with dynamic photovoltaic window shading elements. In *2017 14th China International Forum on Solid State Lighting: International Forum on Wide Bandgap Semiconductors China, SSLChina: IFWS 2017* (pp. 52-55). (2017 14th China International Forum on Solid State Lighting: International Forum on Wide Bandgap Semiconductors China, SSLChina: IFWS 2017; Vol. 2018-January). IEEE. https://doi.org/10.1109/IFWS.2017.8245973

Daylighting Simulation and Analysis of Buildings with Dynamic Photovoltaic Window Shading Elements

Y. Gao[1,2,4], *J. Dong[3,4], O. Isabella[1], M. Zeman[1], G.Q. Zhang[5]
[1]PVMD/DIMES, Delft University of Technology, Delft, The Netherlands
[2]State Key Laboratory of Solid State Lighting, Changzhou, China
[3]Suzhou Institute of Biomedical Engineering and Technology, Chinese Academy of Sciences, China
[4]Beijing Research Center, Delft University of Technology, Beijing, China
[5]Department of Microelectronics, Delft University of Technology, Delft, The Netherlands
* jfeidong@hotmail.com

Abstract

Photovoltaic (PV) windows with shading devices benefit buildings in terms of power generation, daylighting control, glare protection, etc. In order to harvest the maximum solar energy from the window area, solar tracking is applied to the PV shading elements. The complicated movement trajectories and dynamic daylighting are difficult to simulate by conventional methods. In this work, we introduce an optical simulation method of daylighting in complex building environment using DIVA and Grasshopper, which are plug-ins of Rhinoceros, a commercial 3D computer graphics and computer-aided design (CAD) software. An algorithmic model of the PV blinds is built by Grasshopper based on amodified model of a reference office. Then DIVA is applied to evaluate the daylighting performance of the dynamic and static PV blinds. Simulation results show that the working plane reveals higher illuminance level and lower glare level with the dynamic PV blinds than that with their static counter parts. It is demonstrated that the proposed simulation method can deal with the daylighting evaluation of complex and dynamic building environment.

1. Introduction

Artificial lighting accounts for approximately 19% of the global electric energy consumption according to the statistical data provided by the International Energy Agency (IEA) [1]. In buildings, electricity use for lighting can be reduced by optimizing daylight harvesting, resulting in the mitigation of greenhouse gas emissions [2]. During daytime, sunlight not only contributes to the daylighting of buildings, but also benefits the energy generation of the building integrated photovoltaics (BIPVs) [3]. The electricity generated by BIPVs also compensates the energy consumption of artificial lighting. Therefore, window shading devices integrated with PV materials combine the functions of daylight control and electricity generation, leading to comfortable and energy-saving lighting environment.

Among all types of window shading devices, one-axis PV blinds are mostly reported due to the easy-access setups [4-6].Those studies conclude that PV blinds should stay at the optimal static tilt angles based on their models and experiments. However, in our study, we found that the slats of the PV blinds shall dynamically change the tilt angle according to the solar position in order to gain the maximum PV power generation. Therefore, it is difficult to evaluate the dynamic interior daylighting by conventional simulation methods, since it requires thousands of static models with slats in different tilt angles.

In this study, we introduce a highly optimized daylighting tool, DIVA-for-Rhinoceros. DIVA is a daylighting and energy modeling plug-in for the Rhinoceros, a NURBS (non-uniform rational basis spline) modeler. DIVA was initially developed at the Graduate School of Design at Harvard University and is now developed by Solemma LLC [7].In the field of lighting, we usually use professional lighting design and analysis software, e.g. DIALux [8], to evaluate the lighting conditions of the target room. However, it is difficult to build complex geometries using DIALux. Also importing files drawn by CAD software may lead to model errors in DIALux. Though it is possible to simulate daylighting with plug-ins in SketchUp [9], it is difficult to realize the dynamic movements of PV blinds. To the best of our knowledge, using Rhinoceros with plug-ins is the best way to solve the problem mentioned above. In this work, we first use a modified Rhinoceros model of a reference office for standardized evaluations of daylighting with dynamic window blinds [10]. Then, we define the motion algorithm of the blinds in this model by using Grasshopper, a graphical algorithm editor tightly integrated with Rhinoceros and DIVA [11]. The combination of these two software tools enable us to simulateand evaluate the daylighting at any time in an entire year. At last, we will analyze the performance of the PV blinds with dynamic tilt angles in the aspect of illuminance and glare, comparing with that with static tilt angles.

2. Optimum Tilt Angle of PV Blinds

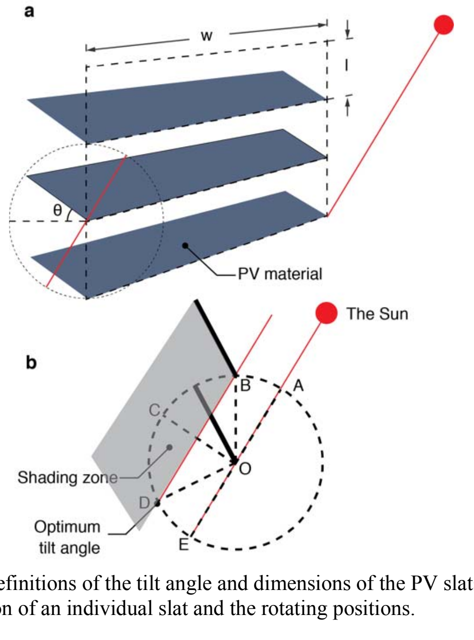


Fig. 1 (a) Definitions of the tilt angle and dimensions of the PV slats; (b) Cross-section of an individual slat and the rotating positions.

978-1-5386-4851-3/17/$31.00 ©2017 IEEE

To achieve the maximum power output, the slats of the PV blind should dynamically change the tilt angle θ, which is illustrated in Fig. 1a. Every individual slat rotates simultaneously in order to gain identical irradiance. The cross-section view of an individual slat is shown in Fig. 1b. It can be readily concluded that the slat receives the maximum solar power when it rotates within the sector ofBOD. The input power of the sunlight on an individual slat is derived as

$$\mathrm{P}_{in} = I_e^{dir}\, wl \cos\alpha_s\,(-\cos A_s) + G_{h,d}\, wl \qquad (1)$$

where I_e^{dir} denotes the direct normal irradiance (DNI) of the sunlight; w and l denote the width and length of the slat respectively (see Fig. 1a); α_s and A_s denote the altitude and azimuth of the Sunrespectively; $G_{h,d}$ denotes the horizontal diffuse irradiance of the sunlight. Apparently, the input power is independent of the tilt angle. However, the PV slat suffers from partial shading effects when it rotates within the sector ofBOD, except at the positions along withOB and OD. Since OB represents the closed position, the optimum tilt angle is in the position ofOD. The optimum tilt angle θ_{opt} is derived as

$$\theta_{opt} = \frac{\pi}{2} + 2\tan^{-1}(\tan\alpha_s \sec A_s) \qquad (2)$$

Here, θ_{opt} is a function of the solar position. Therefore, the tilt angle of PV slats should change dynamically according to Eq. 2, when we evaluate the quality of day lighting.

3. Rhinoceros Model of a Reference Office

To simulate the indoor day lighting, we use a reference office built by Rhinoceros. The reference office represents a typical 'shoebox' shape, which is comparatively 'deep', so that the performance of shading devices can be properly evaluated [10]. The dimensions of the office are shown in Fig. 2; the reflectance of critical geometries in this model is listed in Table 1.

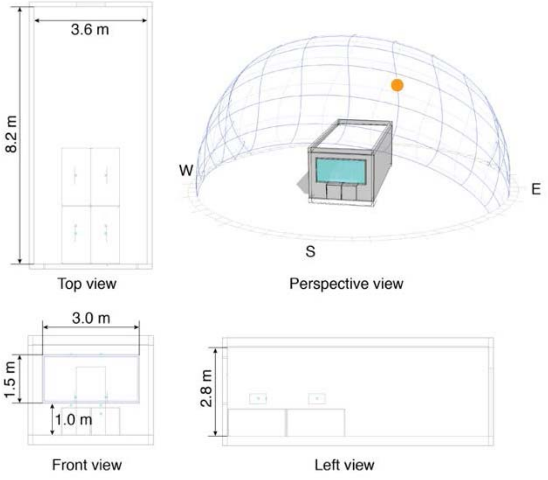


Fig. 2Dimensions of the reference office illustrated in four views: perspective, top, front, and left.

Table 1 Reflectance of critical geometries in the model of the reference office.

Geometry	Reflectance	Geometry	Reflectance
Ceiling	0.80	Furnishings	0.50
Floor	0.20	Glazing	0.20
Interior walls	0.50	Door	0.50

In the original reference office, there are six tables. We reduce the number of tables from six to four, and place them near the window area. Also we change the orientations of the tables to let people sit face-to-face.

As shown in Fig. 2, real-time display of sun paths and shadows are obtained by DIVA. It is worth mentioning that itis also possible to simulate the sun path and its shadows for a series of dates and times. All shadows will be shown in the same Rhinoceros model.

4. Algorithmic modeling by Grasshopper

Based on the Rhinoceros model mentioned above, now we intend to build an interior PV blind in the window area. Here, let w be equal to 3.0 m, and l be equal to 0.15 m. Thus, ten dynamic slats need to be built in Grasshopper [11].To link the optimum tilt angle with the solar position, we first build interconnections by several DIVA and math components in Grasshopper as shown in Fig. 3. The location is chosen as Beijing. All climate data are also available by choosing the data file obtained from the website of Energy Plus [12].The output of this diagram is the input of next one, i.e. the optimum tilt angle.

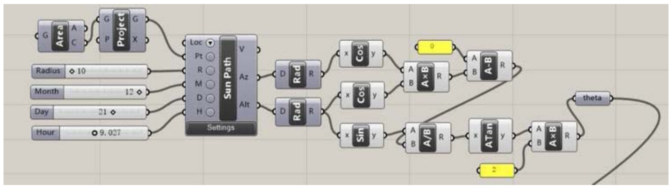
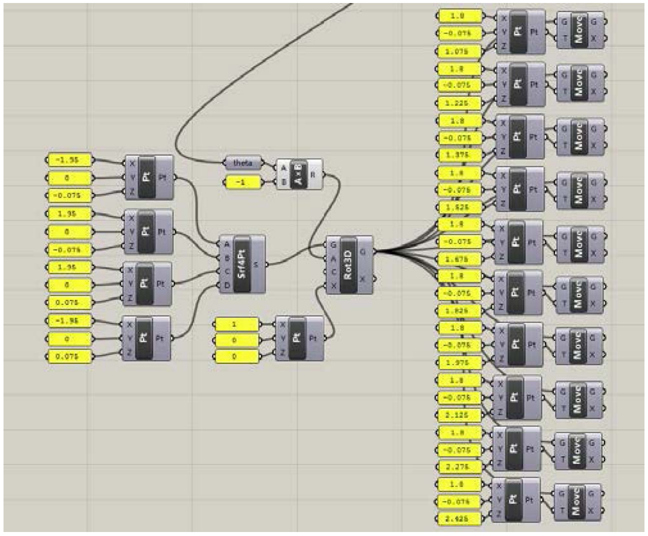


Fig. 3 Diagram of the link between the optimum tilt angle and an arbitrary time of an entire year.

Then, ten slats are formed in Rhinoceros by linking the initially defined surface with the rotation component. Since all slats rotate simultaneously, the rotated slats can be obtained from one original slat by certain translations using the Move component, as shown in Fig 4.Notice that another component named Selectable Preview is also required to connect to the Move component in order to have real geometries in the Rhinoceros model, which is capable to interact with the simulated sunray.



978-1-5386-4851-3/17/$31.00 ©2017 IEEE

Fig. 4 Diagram of the ten slats obtained by rotating the initially defined surface by the optimum tilt angle in Grasshopper. The component of Selectable Preview is not shown in this diagram to save space.

Till now, the Rhinoceros model of the reference office with a dynamic PV blind is built with the assistance of Grasshopper. All geometries in this model are assigned with custom materials defined in DIVA. Then we are ready to run the simulations that are mainly built by two DIVA components, Illuminance and Glare, as shown in Fig. 5. As an input of the Illuminance component, Grid is used to evaluate the illuminance distribution of the target plane. Here, the height of the target plane is defined as 1.0 mabove the floor. The spacing of the grid is defined as0.15 m. A virtual sensor is placed in the center of each square on the grid to collect simulated illuminance values. The Glare component requires an input of camera position, which is here defined as an observer view towards the monitor in the table near the window. Both Illuminance and Glare components share the same input of Sky component, whose type is chosen as clear sky. Also the Month, Day, and Hour components are the same as that in Fig. 3. In this way, the tilt angle and the input climate data are changing simultaneously according to the time instant we choose in Grasshopper.

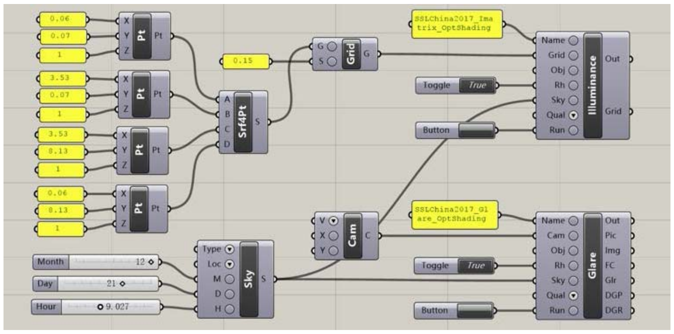


Fig. 5 Diagram of the daylighting simulation mainly achieved by the DIVA components of Illuminance and Glare.

Notice that Figs. 3-5 are drawn in the same canvas in the simulations. Here we introduce the function in three separate parts for clear explanations. Also, the output data of the simulations can be found under the folders named as the input Name components, as shown in Fig 5.

5. Results

Simulation results are obtained in terms of illuminance distribution and glare. Another group of simulations is used for comparison by replacing the dynamic tilt angle with a static angle (30°). The output of the illuminance matrix (I-matrix) [13,14] is visually shown in Rhinoceros. As shown in Fig. 6, it is obvious that the working plane reveals higher illuminance level with the dynamic PV blinds than that with the fixed ones. This means that the dynamic tilt slats allow more sunlight enter into the office so that less energy is consumed by supplementary artificial lighting. It is difficult to subjectively evaluate both two I-matrices. Because some occupants may think that high illuminance level in the working area helps them stay alert and work efficiently. While others may prefer lower illuminance level in the working area to reduce the uniformity ratio of illuminance for better visual comfort. Therefore, we evaluate the I-matrix simply based on the principle of energy saving. Thus the dynamic PV blinds performs better than the fixed ones in regards of the illuminance level.

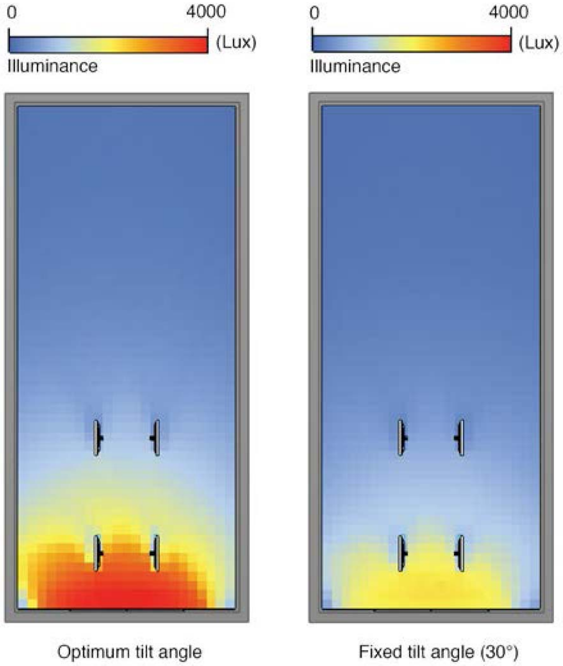


Fig. 6Color maps of the illuminance distribution on the working plane at 11:00 AM, on Match 20th,in Beijing. The daylighting is simulated in the model with dynamic tilt angle (left) and fixed tilt angle (right) respectively.

In regard to the glare, the same models as above are used for the simulations. Here, two criteria are mainly used to evaluate the daylight glare: discomfort glare rating (DGR) and daylight glare probability (DGP). Definitions of DGR and DGP can be found in [15]. The outputs of the glare simulations are not only DGR and DGP, but also luminance false-color images and rendered images as shown in Fig. 7.

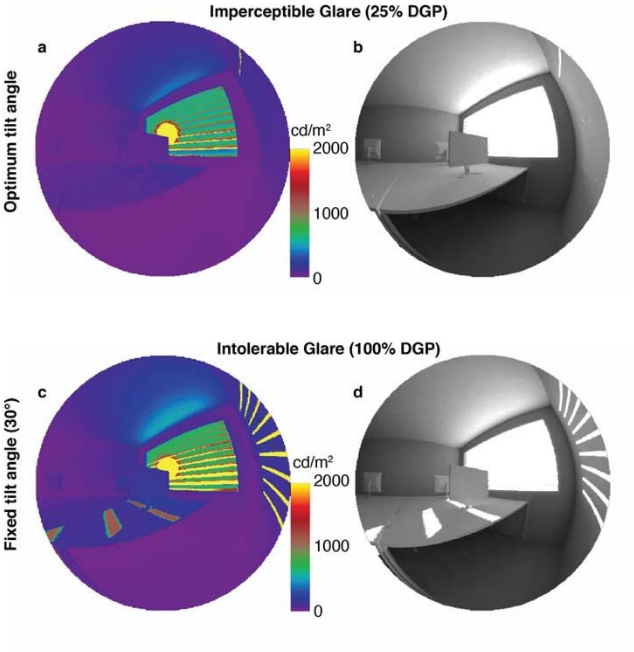


Fig. 7Fisheye views in the camera position. (a) Luminance false-color images and (b) rendered images of fisheye view with dynamic PV blinds; (c) luminance false-color images and (d) rendered images of fisheye view with static PV blinds. Images are produced by the simulations at 9:00 AM, on December 20th,in Beijing.

Simulation results show that both dynamic and static PV blinds can properly protect observers from glare when the Sun is in the high altitude, e.g. in the Summer. However, the performance of the PV blinds with fixed tilt angle get worse when the Sun is in lower altitudes. As shown in Fig. 7, direct sunlight passes through the gaps between the fixed slats of the PV blinds and leads to an intolerable glare (100% DGP). In contrast, the dynamic PV blinds reveal an imperceptible glare (25% DGP). The dynamic slats block most of the direct sunlight and reflect natural diffuse sunlight into the office. It means that the dynamic PV blinds not only achieve the maximum power output, but also provide occupants with comfortable daylighting environment.

6. Discussions and Conclusions

In this work, we have demonstrated that DIVA is a powerful tool of daylighting simulation and analysis. Besides illuminance and glare, DIVA can also simulate and evaluate the energy performance of buildings, since it is built on thoroughly validated and tested simulation engines. Not only daylighting, DIVA is also capable to simulate artificial lighting by importing IES files of luminaires [16]. Thermal evaluations like heating and cooling are also available in DIVA. Comparing with other similar software, DIVA can deal with more complex building environment with the aid of Rhinoceros, and more dynamic structures with the assistance of Grasshopper.

Moreover, we have also introduced a simulation method in order to evaluate the daylighting performance of dynamic PV blinds. A Rhinoceros model of a reference office and an algorithmic model of dynamic slats are built assisted by Grasshopper, and are then evaluated by DIVA. Comparing with the fixed PV blinds, the dynamic PV blinds have better daylighting performance in terms of both illuminance level and glare protection. This work also shows that the proposed method can handle the problems of daylighting simulations with dynamic shading elements involved.

References

1. IEA, SHC Task 50 Advanced Lighting Solutions for Retrofitting Buildings, 2013.
2. S. Attia, M. Hamdy, and S. Ezzeldin, “Twenty-year tracking of lighting savings and power density in the residential sector,” *Energy Build.*, vol. 154, pp. 113–126, 2017.
3. B. P. Jelle, C. Breivik, and H. Drolsum Røkenes, “Building integrated photovoltaic products: A state-of-the-art review and future research opportunities,” *Sol. Energy Mater. Sol. Cells*, vol. 100, no. 7465, pp. 69–96, 2012.
4. W. Bahr, “A comprehensive assessment methodology of the building integrated photovoltaic blind system,” *Energy Build.*, vol. 82, pp. 703–708, 2014.
5. M. Mandalaki, T. Tsoutsos, and N. Papamanolis, “Integrated PV in shading systems for Mediterranean countries: Balance between energy production and visual comfort,” *Energy Build.*, vol. 77, pp. 445–456, 2014.
6. S. Kang and T. Hwang, “Theoretical analysis of the blinds integrated photovoltaic modules,” *Energy Build.*, vol. 46, pp. 86–91, 2012.
7. J. A. Jakubiec and C. F. Reinhart, “DIVA 2.0: Integrating daylight and thermal simulations using rhinoceros 3D, DAYSIM and EnergyPlus,” *Proc. Build. Simul. 2011 12th Conf. Int. Build. Perform. Simul. Assoc.*, pp. 2202–2209, 2011.
8. R. A. Mangkuto, “Validation of DIALux 4.12 and DIALux evo 4.1 against the Analytical Test Cases of CIE 171:2006,” *LEUKOS - Journal of Illuminating Engineering Society of North America*, vol. 12, no. 3. pp. 139–150, 2016.
9. S. K. Wittkopf, A. Kambadkone, H. Quanhui, and N. P. Khai, “Development Of A Solar Radiation And Bipv Design Tool As Energyplus Plugin For Google Sketchup,” in *Eleventh International IBPSA Conference*, 2009, pp. 1989–1996.
10. C. F. Reinhart, J. A. Jakubiec, and D. Ibarra, “Definition Of A Reference Office For Standardized Evaluations Of Dynamic Façade And Lighting Technologies,” *13th Conf. Int. Build. Perform. Simul. Assoc.*, pp. 3645–3652, 2013.
11. K. Lagios, J. Niemasz, and C. F. Reinhart, “Animated Building Performance Simulation (Abps) – Linking Rhinoceros/Grasshopper With Radiance/Daysim,” *SimBuild 2010*, pp. 321–327, 321AD.
12. S. Carlucci, F. Causone, F. De Rosa, and L. Pagliano, “A review of indices for assessing visual comfort with a view to their use in optimization processes to support building integrated design,” *Renewable and Sustainable Energy Reviews*, vol. 47. pp. 1016–1033, 2015.
13. Y. Gao, Y. Lin, and Y. Sun, “A wireless sensor network based on the novel concept of an I-matrix to achieve high-precision lighting control,” *Build. Environ.*, vol. 70, pp. 223–231, Dec. 2013.
14. Y. Gao, Y. Sun, and Y. Lin, “A novel wireless lighting control strategy using RBF neural networks and genetic algorithm,” in *2013 IEEE International Conference on Computational Intelligence and Cybernetics (CYBERNETICSCOM)*, 2013, pp. 62–66.
15. S. Carlucci, F. Causone, F. De Rosa, and L. Pagliano, “A review of indices for assessing visual comfort with a view to their use in optimization processes to support building integrated design,” *Renewable and Sustainable Energy Reviews*, vol. 47. pp. 1016–1033, 2015.
16. IES Computer Committee, “IES Standard File Format for Electronic Transfer of Photometric Data and Related Information,” *Technical report IES LM-63-1991*, New York, 1991.