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Will Cities Survive?

Lighting and daylight control strategies using LabVIEW for optimizing visual comfort and energy savings

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ABSTRACT: This study presents control strategies based on the National Instrument Laboratory Virtual Instrument Engineering Workbench (NI LabVIEW) platform to reduce energy consumption as well as maintain visual comfort by controlling lighting fixtures and window blinds. A model prototype is presented equipped with motorized blinds and dimming lights controlled by NI LabVIEW, and light sensors for monitoring the indoor illuminance value. The results show that the model prototype performs well in maintaining uniformity of illuminance value. An annual simulation using Rhino/Grasshopper predicted that visual comfort can be well maintained by window blinds that rotate 45^0 (half-closed) without turning on one lamp, mostly during the daytime when the sky condition is clear; therefore, lighting energy consumption can be reduced by around 16%.

KEYWORDS: LabVIEW, energy efficiency, visual comfort, building automation, integrated control

1. INTRODUCTION

According to data on U.S. building sector energy consumption, buildings consumed about 39% of the total energy in the U.S., of which about 35% is accounted for by lighting (Brasington, 2019). Daylight utilization in buildings shows great potential for energy savings. To evaluate the performance of daylight utilization technologies, illuminance levels and uniformity need to be considered (Chiou & Lin, 2016). Optimum visual performance requires a certain level of uniformity across the working plane (Freewan & Al Dalala, 2020). Therefore, useful daylight illuminance (UDI) is mostly used for the simple evaluation of lighting design in architecture and visual discomfort (Galatioto & Beccali, 2016; Tabadkani et al., 2019). Based on occupants' behavior, visual comfort has mostly focused on working plane conditions (Galatioto & Beccali, 2016; Husin & Harith, 2012). Working plane illuminance levels between 500 and 2000 lux are sufficient for the visual task and for achieving visual comfort (Chaloeytoy et al., 2020).

Hirning et al. (2017) indicate that some sustainable buildings across 10 countries have some issues of visual discomfort from glare, causing building occupants to usually close window blinds. To cope with that problem, several control strategies are applied. Control strategies for controlling window blinds and lighting are essential to improve visual performance (Chan & Tzempelikos, 2013) and achieve energy savings from 30 to 50% (Konstantoglou & Tsangrassoulis, 2016). There are two control strategies for lights and blinds: independent and integrated. In an independent control strategy, the control systems control the lights and blinds separately using different sets of points and controllers, whereas in an integrated control strategy both lights and blinds are controlled using the same set point. Rule-based algorithms and co-simulation with EnergyPlus, BCVTB, and MATLAB are the common methods used in those control strategies (Mukherjee et al., 2010; Plörer et al., 2021). However, the programming languages used in those methods, such as C++, Python, or MATLAB, involves advanced programming skills to run them.

Instead of using those programming languages, this study presents control strategies based on the LabVIEW (Laboratory Virtual Instrument Engineering Workbench) environment, a graphical programming environment widely used for measuring, monitoring, controlling, and recording operating conditions (Chinomi et al., 2017). LabVIEW is preferred because it supports thousands of hardware devices and recent technologies but keeps using common protocols and requires no programming skills (Hamed, 2012).

This study aims to maintain visual comfort by implementing an integrated control strategy to control the lighting fixtures and window blinds using LabVIEW, and to investigate the energy consumption reduction for lighting. A whole-year simulation is conducted to analyze the performance of the control system and annual energy saving.

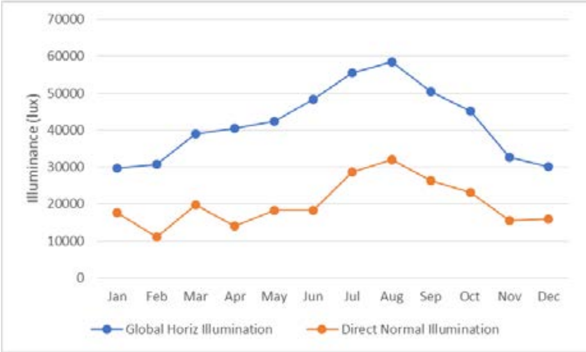
2. METHOD

This study applies an experiment method and a simulation method. An experiment using a model prototype was conducted to test and validate the algorithm building in LabVIEW while a simulation using building performance simulation software was used for simulating the indoor lighting performance and energy saving.

2.1 Daylight in Taiwan

Taipei, Taiwan, is selected as the location for this study. Located on 25°04'N 121°31'E, the hours of daylight/day in Taipei are between 10:35 hours (winter) and 13:39 hours (summer) while the annual hours of daylight are 12 hours (*Sunshine & Daylight Hours in Taipei, Taiwan*, n.d.). The average hourly global horizontal illumination is between 29,607 lux (winter) and 58,435 lux (summer); meanwhile, the average hourly direct normal illumination is between 11,128 lux (winter) and 32,066 lux (summer) (Fig. 1).

Figure 1:
Monthly daylight illumination in Taipei



Note: This figure is modified from the Taipei-Songshan weather data file.

To understand the daylight condition in a building, a simulation was conducted using Rhino/Grasshopper simulation software. Ladybug and Honeybee plugins were used to simulate the daylight and energy performance. A comparative study between Rhino/Grasshopper, DIVA, and Design Builder for analyzing illuminance level and energy consumption was conducted to validate the simulation model. The results showed that the indoor illuminance difference between Rhino/Grasshopper and Diva simulation is in the range of 10–20%, while the energy simulation difference between Rhino/Grasshopper and Design Builder is less than 10%.

A model with 8.2 m length x 3.6 m width x 2.8 m height (length:width was approximately 2 and length:height was approximately 3) and with a south-faced window was built in Rhino/Grasshopper simulation software (Fig. 2) to identify the daylight condition inside the building. The material reflectance of the ceiling, wall, floor, and surrounding ground was 0.8, 0.5, 0.2, and 0.8, respectively. Spatial daylight autonomy (SDA) and useful daylight illuminance (UDI) were simulated. The simulation results showed that there was a huge range of the illuminance level in the building, where the southern area near the window received abundant daylight and had a high illuminance level while the northern area did not receive any daylight. Figure 3 shows that the room was divided into three zones: high daylight zone (A), intermediate daylight zone (B), and low daylight zone (C). To solve that problem, a shading device was required to reduce the daylight for zone A while artificial lighting was required to provide enough lighting for zones B and C.

Figure 2:
Model built in Rhino/Grasshopper simulation software.

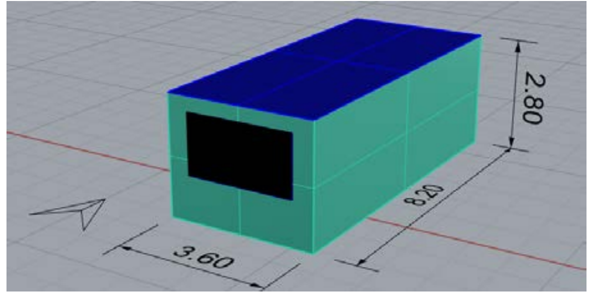
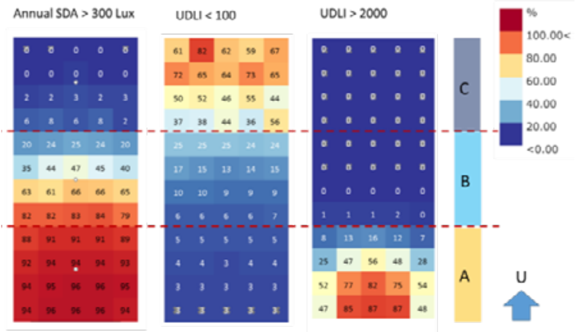


Figure 3:
Annual SDA and UDI simulation results.



Annual SDA > 300 Lux

0	0	0	0	0
0	0	0	0	0
2	2	3	2	3
6	8	6	8	2
20	24	25	24	20
35	44	47	45	40
63	61	66	66	65
82	82	83	84	79
88	91	91	91	89
92	94	94	94	93
94	95	96	96	95
94	96	96	96	94

UDLI < 100

61	82	62	59	67
72	65	64	73	65
50	52	46	55	44
37	38	44	36	56
25	25	25	24	24
17	15	13	14	15
10	10	9	9	9
6	6	6	6	7
5	5	5	5	5
4	4	3	4	4
3	3	3	3	3
3	3	3	3	3

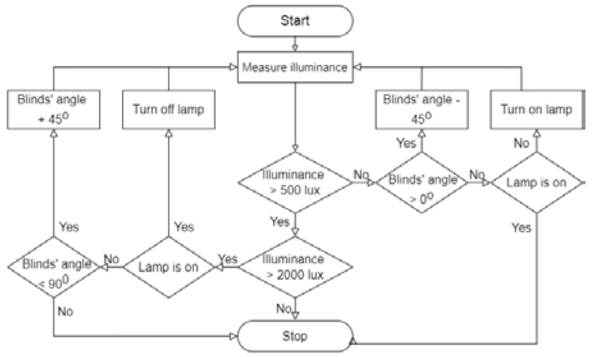
UDLI > 2000

0	0	0	0	0
0	0	0	0	0
0	0	0	0	0
0	0	0	0	0
0	0	0	0	0
0	0	0	0	0
0	0	0	0	0
1	1	1	2	0
8	13	16	12	7
25	47	56	48	28
52	77	82	75	54
47	85	87	87	48

2.2 Control strategies algorithm

The light and blind control strategies are used to maintain indoor illuminance in the range of 500–2000 lux. Figure 4 shows the algorithm flow of the control strategies. As the initial condition, the lamp is turned off and the blind angle is set to 0^0 (blind opened). When the indoor illuminance is lower than 500 lux, if the blind angle is higher than 0^0, then it will reduce by 45^0 until it becomes 0^0 (blinds opened) and the lamp will turn on. When the indoor illuminance increase is higher than 2000 lux, the lamps will be examined first; if the lamp turns on, it will turn off. Later, the blind angle will gradually rotate 45^0 until the angle becomes 90^0 (blinds closed). The lamp and blinds remain steady in their current condition when indoor illuminance is between 500 and 2000 lux. This process is repeated every minute.

Figure 4:
Algorithm flow of the control strategies.



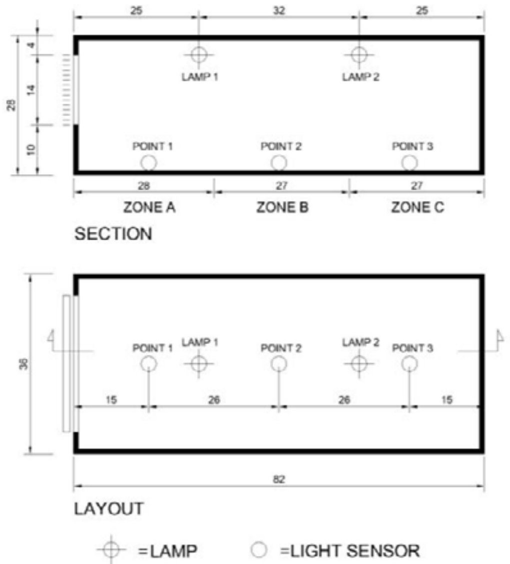
3. EXPERIMENTAL STUDY

3.1 Model prototype

A model with 82 cm length x 36 cm width x 28 cm height was built to analyze the illuminance level. The model had a window and was equipped with motorized blinds and light controlled by NI (National Instrument) LabVIEW. Several LED Fresnel lamps were placed outside the box and their lights were directed to the window to provide daylight. During the measurement, the LED Fresnel was brightened and dimmed gradually to change the light intensity penetrating the box (Fig. 5). Three illuminance sensors were presented inside the box in each zone for monitoring the indoor illuminance and an illuminance sensor was placed outside the box to monitor outdoor illuminance values. As using three lamps resulted in indoor illuminance exceeding 2000 lux, two lamps were used in the prototype, but only lamp 1 put between zone A and B was controlled by the control system because lamp 2 (put between zones B and C) needed to be turned on all the time to provide illuminance of more than 500 lux for zones B and C (Fig. 6).

Figure 5:
Model prototype equipped with motorized blind and lighting fixtures.

Figure 6:
Layout plan and section of the model



Note: The dimension is in cm.

3.2 Model prototype testing

The control strategies applied to the prototype indicate that it can maintain indoor illuminance values in a range of 500–2000 lux regardless of large changes to outdoor illuminance. Figure 8 shows the results of indoor and outdoor illuminance monitoring and Fig. 9 shows the blind angle and lamp condition for 120 minutes. Blind angle 90^0 indicates that the blinds are closed while 0^0 indicates the blinds are opened; 0 indicates that the lamp turns off and 1 indicates that it turns on.

During the experiment, the illuminance values of points 1 and 2 change because they are greatly affected by the outdoor condition (the LED Fresnel lamps), and lamp 1 controlled by NI LabVIEW; however, the illuminance values of point 3 do not change significantly because lamp 2 always turns on. In the beginning, the outdoor illuminance value is very low, which causes lamp 1 to turn on. As the outdoor illuminance value increases, at minute 20, the indoor illuminance value point 1 exceeds 2000 lux, resulting in lamp 1 being turned off at the next minute and the indoor illuminance values decreasing below 2000 lux. At minute 42, the illuminance values of point 2 exceed 2000 lux. Because lamp 1 is already turned off, the blinds rotate 45^0 at the next minute to reduce the indoor illuminance values.

Starting from minute 70, the LED Fresnel lamps were dimmed gradually to reduce the outdoor illuminance. From minute 43 to minute 95, the condition of the blinds and lamp do not change. But at minute 95, indoor illuminance values at points 1 and 2 are under 500 lux, causing the blinds' angle to change to 0^0 and illuminance points 1 and 2 to increase higher than 500 lux. As outdoor illuminance is reduced continuously, at minute 108, lamp 1 turns on because illuminance values of points 1 and 2 are lower than 500 lux. The condition of the blinds and lamp do not change until the end of the measurement (minute 120).

Figure 8:
Indoor and outdoor illuminance monitoring.

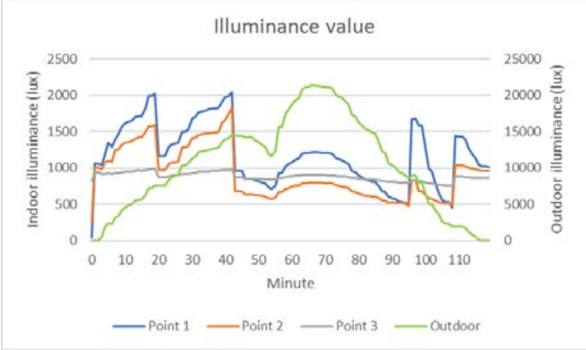
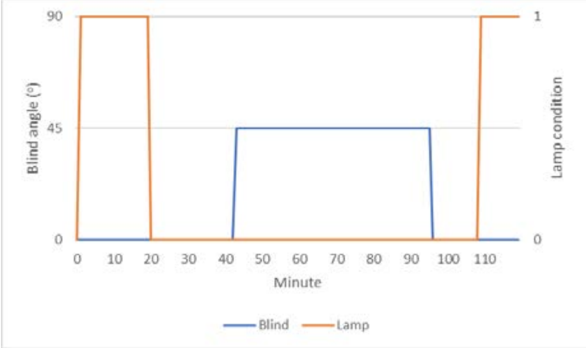


Figure 9:
Blind angle and lamp condition monitoring.



4. SIMULATION STUDY

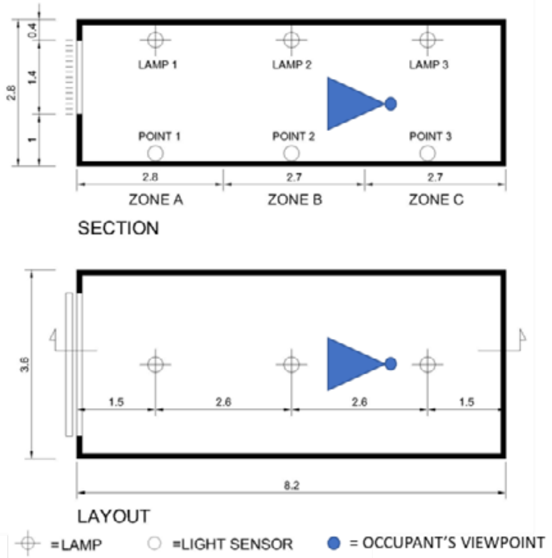
4.1 Simulation setting

The control system was implemented in the form of simulation in Rhino/Grasshopper software with Ladybug and Honeybee plugins to analyze the annual energy saving. A model with 8.2 m length x 3.6 m width x 2.8 m height was built in Rhino/Grasshopper simulation software. A window blind was installed on the south-facing window and three lamps were installed inside the model to provide uniform illuminance values when there is no daylight in the room; however, only lamp 1 in zone A was controlled because lamps 2 and 3 in zones B and C were needed to be turned on all the time to achieve the working plane illuminance levels between 500 and 2000 lux (Fig. 10).

In addition to indoor illuminance, glare analysis was conducted to evaluate visual comfort. DGP (daylight glare probability) and DGI (daylight glare index) are the common indices to analyze glare discomfort (Galatioto & Beccali, 2016). The glare analysis point of view was set 6 m from the window and at a height of 1.2 m (Fig. 10).

A typical day in spring, summer, and winter (March 21st, June 22nd, and December 21st) was simulated to represent the lighting condition for the shoulder (spring and fall), summer, and winter seasons in a year, respectively. The simulation was carried out using the weather data file of Taipei-Songshan under the clear sky condition. Based on the simulation, the window blind angle and lamp schedule for a year were obtained. Later, an annual energy simulation was conducted using the blind angle and lamp schedule.

Figure 10:
Layout plan and section of the model built in Rhino/Grasshopper simulation software.



Note: The dimension is in m.

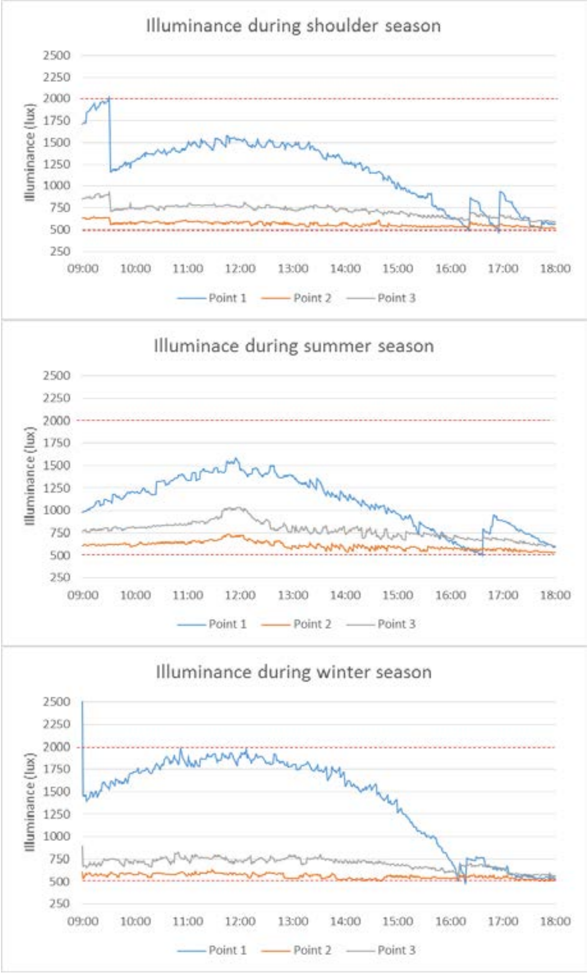
4.2.1 Indoor visual comfort

The control system built in the LabVIEW platform was applied to the Rhino/Grasshopper simulation to control the window blind angle and lamp condition. Figure 11 shows the illuminance values of the simulation results. Because lamps 2 and 3 placed on zones B and C always turn on, the illuminance values of points 2 and 3 are in a range of 500–2000 lux; however, the illuminance value of point 1 changes based on the daylight and blinds and lamp 1 condition. In the shoulder season, the illuminance value of point 1 exceeds 2000 lux at 9:30, causing the blinds to rotate 45^0 (half-closed) at 9:31 to reduce the illuminance value. The blinds maintain that position until 16:20 and rotate to the initial condition at 16:21 because at 16:20 the illuminance value of point 1 is 488 lux, which is lower than the requirement. After return to the initial condition, the indoor illuminance value of point 1 raises to 870 lux at 16:21 but gradually decreases. At 16:57, it decreases to 463 lux, causing lamp 1 to turn on after 16:57. Figure 12 shows the blind angle and lamp 1 condition.

In the summer season, the indoor illuminance values of three measurement points are within the range of 500–2000 lux during the daytime, but after

16:30 the illuminance value of point 1 is lower than 500 lux, causing lamp 1 to turn on. Different from the other seasons, in winter the blinds rotate to 45^0 from 9:00 until 16:10 and rotate to 0^0 at 16:11 — longer than in other seasons— and the lamp turns on earlier, at 16:20. This condition can be explained in the summer season as the south-faced window façade receives less daylight compared to other facades but in the winter season receives more daylight than other façades; however, the time duration is shorter than other seasons.

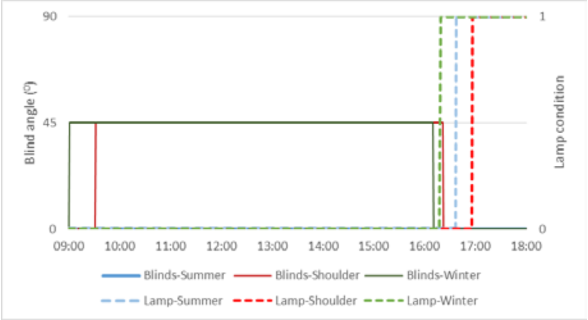
Figure 11:
Indoor illuminance values during the shoulder, summer, and winter seasons.


Illuminance during shoulder season

Illuminance during summer season

Illuminance during winter season

Figure 12:
Annual blind angles and lamp 1 condition.



The simulation results indicate that for almost the whole year, when the sky is clear, the blinds need to be half-closed (rotated to 45^0) in order to avoid excessive illuminance and visual discomfort. Because the illuminance value of point 1 is within the required range, lamp 1 does not need to be turned on mostly during the daytime.

Figure 13 shows the results of glare analysis for a typical day in the shoulder, summer, and winter seasons. Based on the values of DGP and DGI, the glare perceived is still able to be tolerated. All DGI values below 0.35, which indicates that the glare index is imperceptible while most DGP values are between 18 and 24, which indicates that the glare probability is perceptible and in the summer at noon the glare is disturbing.

Figure 13:
Glare analysis during the shoulder, summer, and winter seasons.


DGI

DGP

4.2.2 Energy savings

A simulation is conducted using the blinds and lamp schedule in Fig. 12 for analyzing energy consumption. The results are compared to the base case in which the simulation is conducted using a model without window blinds and all three lamps turn on from 9:00 to 18:00 for the whole year. An annual energy saving is presented in Table 1. Implementing the lighting control can reduce energy saving for lighting only by around 30% as the room depth is greater than the width, and only one lamp can be turned off during the daytime. By considering the energy consumption of the additional equipment for controlling the lights and blinds, the energy savings is about 16.19%.

Table 1: Annual energy savings prediction.

	Base Case	Model
Lighting (kWh/yr.m^2)	19.05	12.88
Equipment (kWh/yr.m^2)	-	3.09
Total (kWh/yr.m^2)	19.05	15.97
Savings (kWh/yr.m^2)	-	3.08
Savings (%)	-	16.19

5. CONCLUSION

This study presents lighting and daylight control strategies using LabVIEW to improve indoor visual comfort. The control strategies successfully maintain indoor illuminance between 500 and 2000 lux in various outdoor illuminance conditions. The simulation using the weather file of Taipei shows that shading devices are needed to control the indoor illuminance values and maintain visual comfort. In this case, venetian blinds rotated 45^0 need to be installed on the south-facing window. Only during the summer season, the venetian blinds do not need to be rotated 45^0. The simulation results show that applying the control strategies successfully maintains indoor illuminance within the comfort range and reduces glare discomfort.

The annual energy savings prediction indicates that control strategies implementation can potentially reduce energy consumption by 16.19%. Although the number is not great, implementing the control system is mostly able to achieve indoor visual comfort.

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REFERENCES

1. Brasington, L., (2019). *Heating, Ventilation and Air Conditioning (HVAC) Systems, the Next Building Load to Optimize*. [Online]. Available: https://www.cleantech.com/heating-ventilation-and-air-conditioning-hvac-systems-the-next-building-load-to-optimize/.
2. Chaloeytoy, K., Ichinose, M., and Chien, S. C., (2020). Determination of the simplified daylight glare probability (DGPs) criteria for daylit office spaces in Thailand. *Buildings*, *10*(10): p. 1–20. https://doi.org/10.3390/buildings10100180.
3. Chan, Y. C., and Tzempelikos, A., (2013). Efficient venetian blind control strategies considering daylight utilization and glare protection. *Solar Energy*, *98*(PC): p. 241–254. https://doi.org/10.1016/j.solener.2013.10.005.
4. Chinomi, N., Leelajindakrairerk, M., Boontaklang, S., and Chompoo-Inwai, C., (2017). Design and Implementation of a smart monitoring system of a modern renewable energy micro-grid system using a low-cost data acquisition system and LabVIEW TM program . *Journal of International Council on Electrical Engineering*, *7*(1): p. 142–152. https://doi.org/10.1080/22348972.2017.1345226.
5. Chiou, Y., and Lin, Y., (2016). A Portable Testbed for Integrative Daylighting Design. *PLEA 2016 Proceedings, Cities, Buildings People: Toward Regenerative Environments*, *II*, p. 706–713.
6. Freewan, A. A. Y., and AlDalala, J. A., (2020). Assessment of daylight performance of Advanced Daylighting Strategies in Large University Classrooms; Case Study Classrooms at JUST. *Alexandria Engineering Journal*, *59*(2): p. 791–802. https://doi.org/10.1016/j.aej.2019.12.049.
7. Galatioto, A., and Beccali, M., (2016). Aspects and issues of daylighting assessment: A review study. *Renewable and Sustainable Energy Reviews*, *66*: p. 852–860. https://doi.org/10.1016/j.rser.2016.08.018.
8. Hamed, B., (2012). Design & Implementation of Smart House Control Using LabVIEW. *International Journal of Soft Computing and Engineering*, *1*(6); p. 98–106.
9. Hirning, M. B., Isoardi, G. L., and Garcia-Hansen, V. R. (2017). Prediction of discomfort glare from windows under tropical skies. *Building and Environment*, *113*: p. 107–120. https://doi.org/10.1016/j.buildenv.2016.08.005.
10. Husin, S. N. F. S., and Harith, Z. Y. H., (2012). The Performance of Daylight through Various Type of Fenestration in Residential Building. *Procedia - Social and Behavioral Sciences*, *36*(June 2011): p. 196–203. https://doi.org/10.1016/j.sbspro.2012.03.022.
11. Konstantoglou, M., and Tsangrassoulis, A., (2016). Dynamic operation of daylighting and shading systems: A literature review. *Renewable and Sustainable Energy Reviews*, *60*: p. 268–283. https://doi.org/10.1016/j.rser.2015.12.246.
12. Kumar, A., Kar, P., Warrier, R., Kajale, A., and Panda, S. K. (2017). Implementation of Smart LED Lighting and Efficient Data Management System for Buildings. *Energy Procedia*, *143*: p. 173–178. https://doi.org/10.1016/j.egypro.2017.12.667.
13. Mukherjee, S., Birru, D., Cavalcanti, D., Shen, E., Patel, M., Wen, Y.-J., and Das, S. (2010). Closed Loop Integrated Lighting and Daylighting Control for Low Energy Buildings. *2010 ACEEE Summer Study on Energy Efficiency in Buildings*, p. 9–252.
14. Plörer, D., Hammes, S., Hauer, M., VanKarsbergen, V., and Pfluger, R. (2021). Control strategies for daylight and artificial lighting in office buildings-a bibliometrically assisted review. *Energies*, *14*(13): p. 1–18. https://doi.org/10.3390/en14133852.
15. *Sunshine & Daylight Hours in Taipei, Taiwan*. (n.d.). Clima Temps.Com. [Online], Available: http://www.taiwan.climatemps.com/sunlight.php.
16. Tabadkani, A., Valinejad Shoubi, M., Soflaei, F., & Banihashemi, S. (2019). Integrated parametric design of adaptive facades for user's visual comfort. *Automation in Construction*, *106*(August 2018); p. 102857. https://doi.org/10.1016/j.autcon.2019.102857.