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Optimum Control of a Photoelectric Dimming System in a Small Office with a Double Skin Envelope

Soo Young Kim and Sung Kon Yum

Taubman College of Architecture & Urban Planning, The University of Michigan, Ann Arbor, MI, USA
Samsung Engineering & Construction, Housing Technology Team

Abstract

A photoelectric dimming control system for a small private office space with a double skin envelope system was analyzed for the purpose of examining optimum control performances under a variety of daylight conditions. Computer simulations were performed for the three different photosensor types positioned at the center of ceiling in the space. They were applied in both a south and north-facing room. Daylight conditions were a fixed horizontal venetian blind on an external envelope and a retractable shading device on an internal envelope under a clear, intermediate and overcast sky at different times of a day and year. Partially-shielded photosensors provided good control performances providing the required electric light output under clear and intermediate sky conditions. Unshielded photosensors failed to provide necessary illuminance levels producing less electric output and fully-shielded photosensors generally provided excessive light output. Reasonable electric lighting energy savings were achieved except under overcast sky conditions where the control system did not contribute to energy savings due to the less daylight through envelopes. The retractable shading device covering 50% of the internal envelope reduced energy savings up to 19.62%, but the workplane illuminance levels were maintained within recommended ranges. The coefficients of determination between workplane illuminance and photosensor illuminance due to daylight ranged from 0.74 to 0.98. Partially-shielded conditions provided best correlations and the north-facing room yielded stronger correlation than the south-facing room.

Keywords : Photoelectric Dimming Control System, Double Skin Envelope System, Photosenor Shielding, Electric Light Energy Savings

1. INTRODUCTION

Modern building designs appear to apply a higher ratio of a window to a wall on façades due to advanced building technologies. A curtain wall structure is a representative facade design using glass materials for the entire area of building envelope. Since energy consumption issue was critical for the past decades, the building envelope designs using higher glass ratios started to be tightly sealed with highly insulated materials. Moreover, the HVAC control system decreased a ventilation rate for the purpose of reducing energy consumption. These strategies resulted in various health problems against people in buildings. (Lelius,1984)

In order to solve the problems caused by the improperly designed building envelopes, a double skin envelope system emphasizing sustainable building designs has been suggested and used for the actual buildings constructed mainly in European countries (Lee, 2002; Compagno. 1999). This system has two envelopes, a cavity between them, and various types of shading devices. It causes unique daylight distribution patterns and contributes to daylight dimming performances in a space due to sophisticated shading devices and the top area of a cavity functioning as an overhang.

A double skin façade system is expected to improve the performance of photoelectric dimming control systems, since it provides relatively stable daylight compared to that of a single skin envelope. Therefore, this research aims at evaluating how a photoelectric dimming control system with three photosensor shielding types works in a small office space with a double skin envelope system, and providing optimum control performances. Computer simulations were performed for photosensors located on the ceiling with three different shielding conditions in a small office space under a variety of daylight conditions.

2. COMPUTER SIMULATION

(1) Description of Simulation Software (Ward, 1994; LBNL, 2000) and Computation Procedures

The computer simulation software used in this study was the Desktop Radiance Version 1.02 developed by the Lawrence Berkeley National Laboratory. It was used as a main analysis tool for the evaluation of dimming control performances.

Using ray-tracing techniques supported by the Monte Carlo theory, Radiance provides strong analysis results for daylight and electric light under various geometries of a space and daylight conditions. Rendering images and numeric data for the illuminance and luminance levels can be provided according to specific geographical data such as latitude, longitude, time and building sites. The results from Radiance simulations were very close to measured data and showed agreements with other currently used lighting analysis programs.

After photosensor signals due to daylight and electric light were modeled using Radiance, a series of analyses for electric light output were performed using luminaire candlepower distributions. The dimming levels based on the desktop illuminance levels under a variety of given daylight conditions were calculated using a spreadsheet program.

(2) Room and Daylight Conditions

The small private office space with a double skin envelope system used in this research was 3 m (width) × 3.6 m (depth) × 2.7 m (height). It was assumed that the ratio of a window to a wall on both the external and internal envelope was 100%. These two windows were oriented toward both the south and the north in simulation conditions. The transmittance and reflectance of the window used for the internal and external windows were assumed to be 60% and 7% respectively.

The depth of a cavity between the external and internal envelope was 0.9 m. The top area of a cavity was assumed to be opaque and accordingly it functioned as an overhang. The reflectance of the ceiling, walls and floor were 80%, 50% and 20% respectively. The opaque top and side areas of the cavity also had the reflectance of 80% and 50%.

The dimension of a desktop was 1.5 m (W) × 0.75 m (L) × 0.75 m (H) and it was located along the centerline of the space. The distance between the internal envelope and the geometric center of the desktop was 2.02m (6.75 ft). The reflectance of the desktop was 30%. The detailed dimension of the room is shown in Figure 1. It was assumed that the building site was Ann Arbor, MI, USA (Latitude: 42°14', Longitude: 83°32'). The ground reflectance was 0.1. Clear, intermediate and overcast sky conditions were used.

A fixed horizontal venetian blind on the external envelope and a retractable fabric shading device on the internal envelope were considered. It was assumed that the distance between each venetian blind slat was 2.54 cm and the fabric shading device covered 0%, 25% and 50% of the internal envelope area from the top. The reflectance of blind slats was assumed to be 71%. The transmittance of the fabric material was 10%. The days considered were December 21, March 21, and June 21. The times used were hourly from 08:00 to 17:00. A summary of daylight conditions is in Table 1. The altitudes and azimuth angles of the sun used in this research are in Table 2.

The luminarie selected in this study was a recessed 0.6m (2ft) × 0.6m (2ft) parabolic fluorescent troffer with 7.62cm (3 inches) louvers. Two T8 'U' shaped lamps and 3×4 arrays of cells were applied to the luminaire. The task illuminance level on the desktop using the luminaire was 760 lx (70 fc).

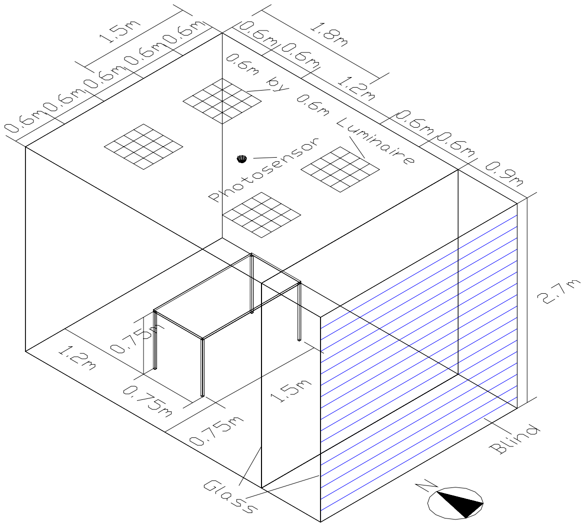


Figure 1. Dimension and Layout of the Room

Table 1. Daylight Conditions

Orientation	Day	Time	Shading on Envelope: Internal	Shading on Envelope: External	Sky Conditions
South	12/21	8:00 - 17:00	0%	Horizontal Blind	Clear (C), Intermediate (I/M), Overcast(O/C)
	3/21		25%		
	6/21		50%		
North	12/21	8:00 - 17:00	0%	Horizontal Blind	
	3/21				
	6/21				

Table 2. Altitudes and Azimuth Angles of the Sun

time	Altitude			Azimuth		
	3/21	6/21	12/21	3/21	6/21	12/21
8	16.12	31.86	**	-73.97	-93.95	-57.87
9	26.44	42.97	8.50	-62.26	-83.69	-47.30
10	35.60	53.81	15.87	-48.36	-70.85	-35.40
11	42.75	63.61	21.24	-31.30	-52.00	-22.04
12	46.79	70.34	24.09	-10.89	-20.72	-7.45
13	46.79	70.34	24.09	10.89	20.72	7.45
14	42.75	63.61	21.24	31.30	52.00	22.04
15	35.60	53.81	15.87	48.36	70.85	35.40
16	26.44	42.97	8.50	62.26	83.69	47.30
17	16.12	31.86	**	73.97	93.95	57.87

(3) Description of a Lighting Control System and an Optimum Setting

Fully-shielded, partially-shielded and unshielded photosensor conditions were modeled in this study. The field view of the photosensor was restricted by the shielding conditions, and the illuminance levels at the point of photosensor were calculated under each different shielding condition surrounding the calculation point.

The fully-shielded model provided 67.2° aperture. The partially-shielded photosensor was shielded from the window blocking half of the field view toward the window but open to the rear area of the room. The dome area of the photosensor located below the calculation point was not modeled in this research. The reflectance of the inside shielding material was assumed to be 71%. The shielding conditions of the phtosensors are shown in Figure 2. The photosensor was located at the center of the ceiling aiming directly downward. The location of a photosensor in the room is shown in Figure 1.

The dimming range of ballasts used in the computer simulations was from 10% to 100%. The dimming ballast provided the minimum light output when the photosensor illuminance was greater than 395 lx. The relationship was tested under a laboratory setting and was described in Figure 3.

In order to evaluate the performance of the dimming control system, an optimum setting for the necessary electric light output providing illuminance on the desktop was developed according to the variation of desktop illuminance due to daylight. The method of least square was applied to minimize the SSE (Error Sum of Squares) of the dimming levels and it linearly determined the necessary electric light output based on the desktop illuminance due to daylight under a variety of daylight conditions used in this research.

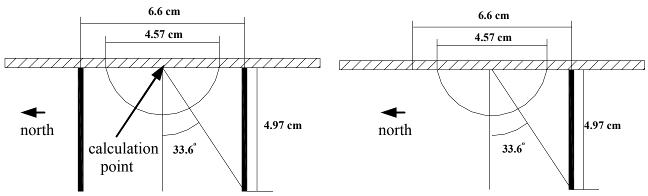


Figure 2. Shielding Conditions of Photosensors
(Left: fully-shielded, Right: partially-shielded)

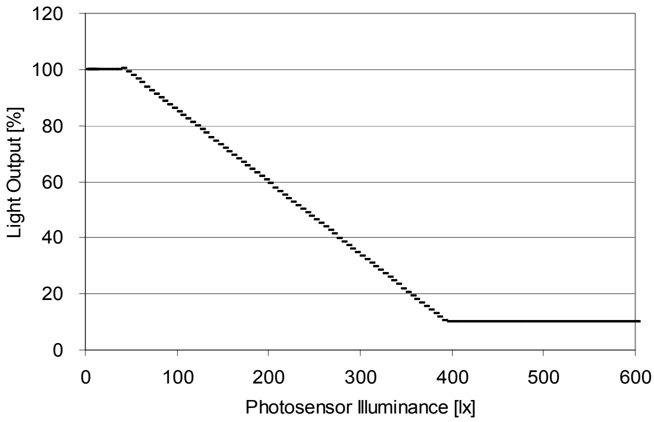


Figure 3. Photosensor Illuminance and Electric Light Output

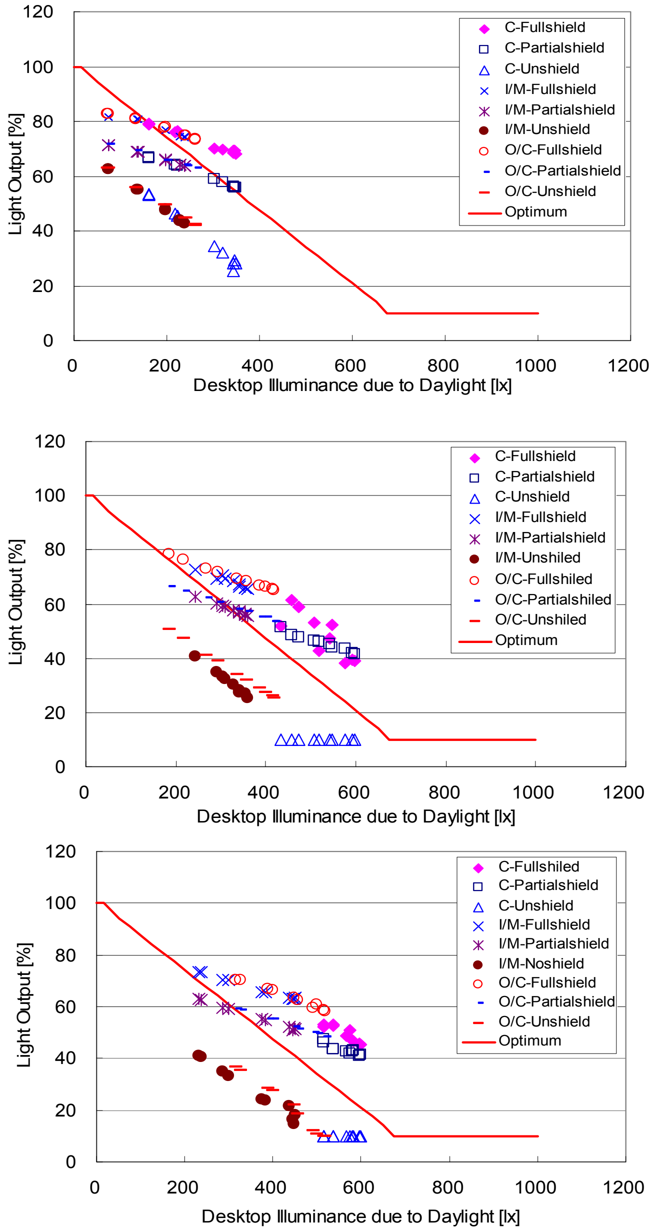


Figure 4. System Performance and Optimum Electric Light Output
(North-facing, 0% Fabric shading, Top: December 21,
Middle: March 21, Bottom: June 21)

3. SIMULATION RESULTS

(1) System Performance

Figure 4 - Figure 7 represent the dimming control performance for each of the three photosensor shielding conditions for each of the time conditions and room orientations. For the graphs, the each individual point stands for the electric light output used to provide illuminance levels according to the photosensor signals. The optimum line on the graphs represents the necessary dimming levels for the provision of required task illuminance levels under all test conditions and room orientations.

The dimming control performance was evaluated using the optimum line and electric light output on those graphs. In order to evaluate the system performance, it was decided that a recommended dimming performance should supply minimum 40 % of target illuminance using daylight for the purpose of providing target illuminance on the desktop.

The dimming performance data providing electric light output close to the optimum line were considered as recommended system performances. The dimming performances under various daylight conditions were classified into five categories; Best, Good, Fail, Not Recommended, and Not Applicable. The evaluations for the performance were carried out using the individual data point that provided the electric light output on the graphs.

It was assumed that the ‘Best’ conditions were the data showing dimming levels very close to the optimum line with the electric light output of 10-65 % of the target illuminance on the desktop. The dimming level data located slightly below or above the optimum line and provided the dimming range of 10-65 % were considered as ‘Good’ system performance. The data points positioned below the optimum line and undershot target illuminance much of the tested periods were considered as ‘Fail’. The dimming levels located above the optimum line with excessive light output was regarded as ‘Not Recommended’. The performance used greater than 65 % of whole light output was considered as ‘Not Applicable’.

Table 3 represents the summary of dimming control performance for the daylight and photosensor shielding conditions. The partially-shielded photosensor with a clear sky condition generally provided best or good performance

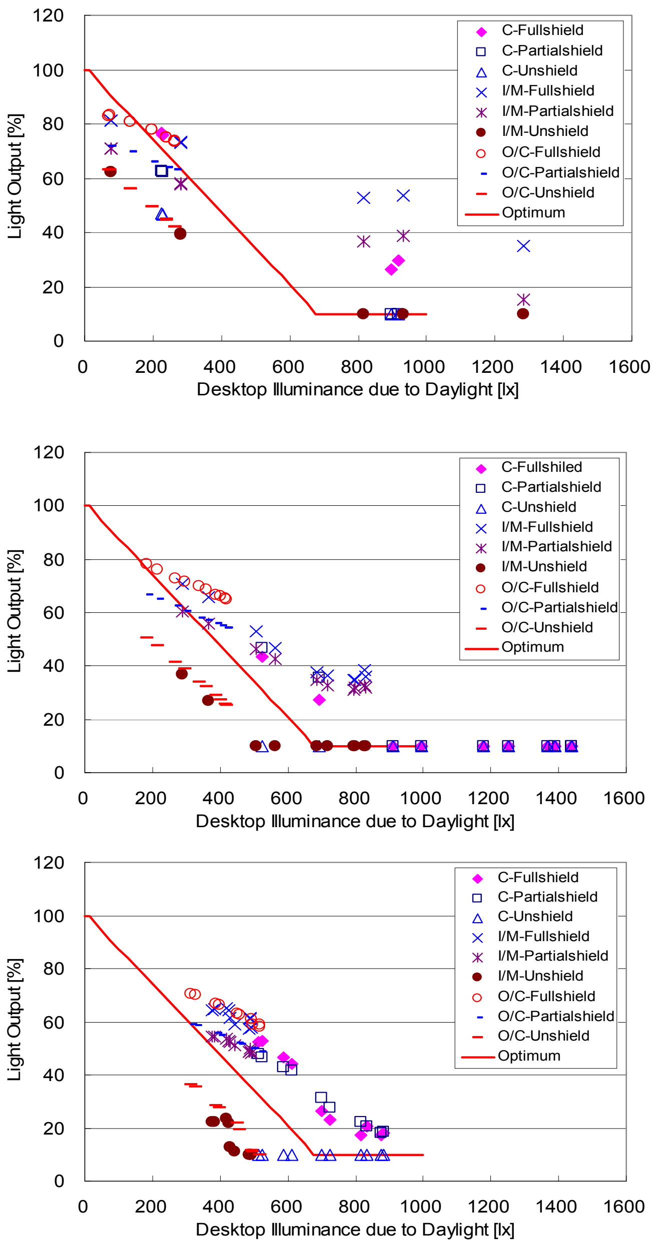


Figure 5. System Performance and Optimum Electric Light Output (South-facing, 0% Fabric shading, Top: December 21, Middle: March 21, Bottom: June 21)

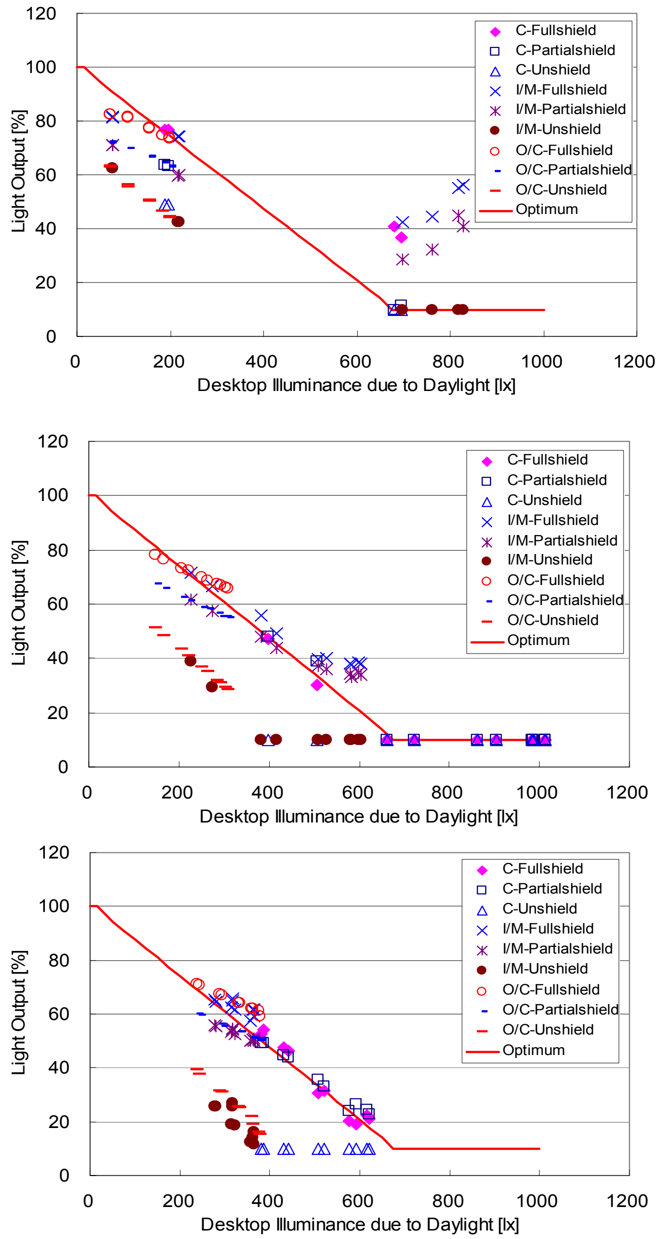


Figure 6. System Performance and Optimum Electric Light Output (South-facing, 25% Fabric shading, Top: December 21, Middle: March 21, Bottom: June 21)

for most of days. Fully-shielded conditions only provided good performance with clear and intermediate skies when 50% of shading was considered on the south-facing internal envelope. Under the overcast sky conditions, the control system using the fully-shielded photosensor did not contribute to reduce electric light energy providing greater than 70% of whole light output.

The unshielded conditions failed to provide necessary desktop illuminance under all sky conditions providing less electric light output and are not recommended when the intense light from the sun and sky to the photosensor exist. The fully-shielded condition generally provided excessive light output and overshot the desktop for most of the sky and shading device conditions.

For the north-facing conditions, the partially-shielded photosensor under a clear sky in December provided 'Good' system performance showing the light output from 56.24% to 66.93%. In March and June, the partially-shielded photosensor under an intermediate and overcast sky conditions showed 'Best' and 'Good' performance respectively. Due to the lack of direct influence of the sun, the change of light output between minimum and maximum did not exceed 12.9% showing stable patterns. Under all seasons, more excessive light output was maintained by fully-shielded photosensors but less light output was provided by unshielded photosenosrs which resulted in unsatisfactory dimming control system performance.

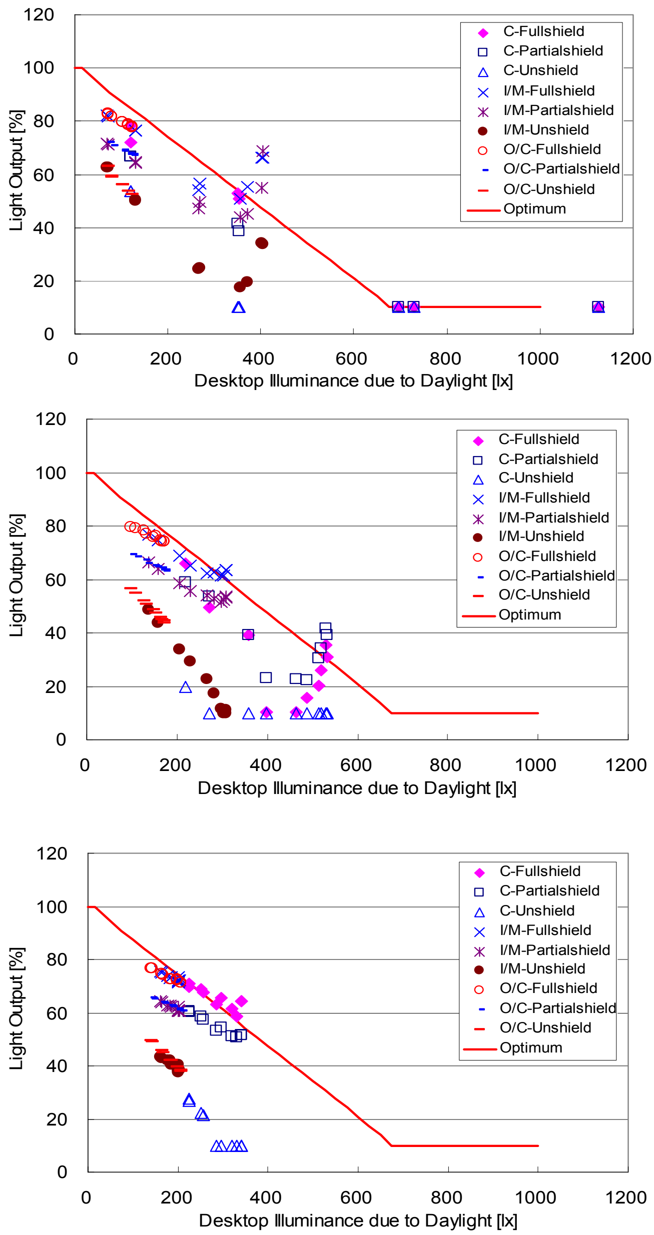


Figure 7. System Performance and Optimum Electric Light Output (South-facing, 50% Fabric shading, Top: December 21, Middle: March 21, Bottom: June 21)

For the south-facing conditions in December, the partially-shielded photosensor showed 'Best' performance under a clear sky condition when no area of the internal envelope was shaded. It provided the change of light output from 10% to 62.69%. As the shaded area increased up to 50%, the partially-shielded photosensor under an intermediate sky provided 'Best' performance showing the light output from 44.06% to 71.96%. In March when no shading device was considered on the internal envelope, the partially-shielded photosensor provided 'Good' performance under a clear and an overcast sky. But, as the shading area on the internal envelop increased, the fully-shielded photosensor under an intermediate sky condition provided 'Good' performance. In June, the partially-shielded photosensor provided 'Best' performance under a clear sky when 25% and 50% of shaded area were assumed. But, the intermediate and overcast sky condition provided 'Best' performance when the partially-shielded condition was used for the photosensor. Overall, the unshielded photosensors under all sky conditions and seasons failed to provide the necessary light output in order to maintain the target illuminance on the desktop.

(2) Correlation between Workplane Illuminance and Photosensor Illuminance

The shielding conditions of photosensors affect control performance since they impact the relationship between photosensor signals and required illuminance levels on a desktop. The correlations between the photosensor illuminance and desktop illuminance due to daylight were analyzed in this study. A linear regression method that minimizes error sum of squares (SSE) between those two quantitative variables was used for each photosensor condition. The correlation patterns are shown in Figure 8. The coefficients of correlation (R^2) are provided in Table 4. The R^2 values ranged from 0.74 to 0.98. The north-facing room provided comparatively higher correlations than the south-facing room. The partially-shielded condition yielded the best correlation while the fully-shielded condition provided the weakest correlation, which is consistent with other previous studies. (Rubinstein, 1989; Mistrick, 1997)

A partially-shielded sensor was shielded toward window and therefore was impacted least by the direct sun from the window and efficiently affected by the reflected light from the rear area of the test room. While the fully-shielded condition blocked the direct light from the window and reflected light from the room surfaces, the unshielded photosensor was strongly impacted by the direct sun and sky.

(3) Discussion of System Performance

The dimming control performance analyzed in this research is effective for a small space configuration with a double skin envelope system. Since the evaluation of dimming control performance in a space with a double skin envelope system is not common yet, this study compares the results with other research performed in a single envelope system.

Generally, the results from this research agree with the previous studies by others (Rubinstein, 1989; Mistrick, 1997; and Littlefair, 2001). According to their results, the partially-shielded condition provided comparatively better system control performance under the sky and shading device conditions used for their research.

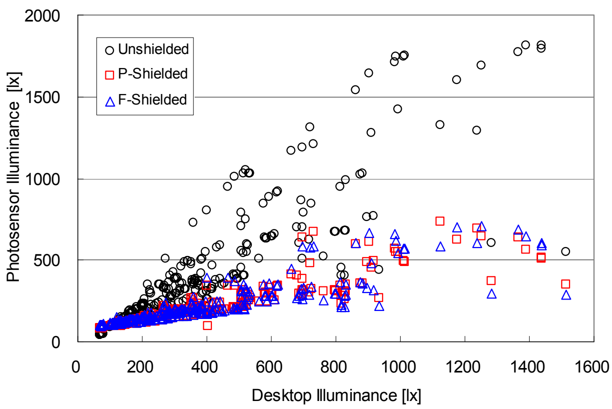
Rubinstein stated that partially-shielded photosensors showed the best correlation between photosensor signals and desktop illuminance levels. It was appropriately reported that fully-shielded conditions did not provide good correlations and unshielded photosensors provided the worst correlation among three photosensor shielding conditions considered in the research.

Table 3. Evaluation of Dimming Control Performance

Day	Dimming Control Performance	North-facing		South-Facing					
		0% shading		0% shading		25% shading		50% shading	
		Sky Condition	Sensor Shielding	Sky Condition	Sensor Shielding	Sky Condition	Sensor Shielding	Sky Condition	Sensor Shielding
12/21	Best	**	**	C	P	**	**	I	P
	Good	C	P	**	**	C	P	C	F, P
								I	F
	Fail	C, I/M, O/C	U	C, I/M, O/C	U	C, I/M, O/C	U	C, I/M, O/C	U
								O/C	P
	N/R	C	F	C, I/M	F	C, I/M, O/C	F	**	**
		O/C	F	I/M	P	I/M	P		
	N/A	O/C, I/M	P	O/C	P, F	O/C	F	O/C	F
3/21	Best	I/M	P	**	**	I/M	P	**	**
	Good	O/C	P	C, O/C	P	I/M	F	I/M	F
						C	F		
	Fail	C, I/M, O/C	U	I, O/C	U	C, I/M, O/C	U	C, I/M, O/C	U
						O/C	P	C, I/M, O/C	P
	N/R	C	F, P	I/M	P, F	**	**	**	**
	N/A	I/M, O/C	F	O/C	F	O/C	F	O/C	U
6/21	Best	I/M	P	I/M, O/C	P	C	P, F	C	P
	Good	O/C	P	**	**	I/M, O/C	P	**	**
	Fail	C, I/M, O/C	U	C, I/M, O/C	U	C, I/M, O/C	U	C, I/M, O/C	U
								O/C	P
	N/R	C, I/M, O/C	F	C, I/M, O/C	F	**	**	**	**
		I/M	P	C	P				
	N/A	**	**	**	**	I/M, O/C	F	C, I/M, O/C	F

where,

- C : Clear Sky, - I/M : Intermediate Sky, - O/C : Overcast Sky
- U : Unshielded Photosensor - P : Partially-shielded Photosensor, - F : Fully-shielded Photosensor
- N/A : Not Applicable, - N/R : Not Recommended



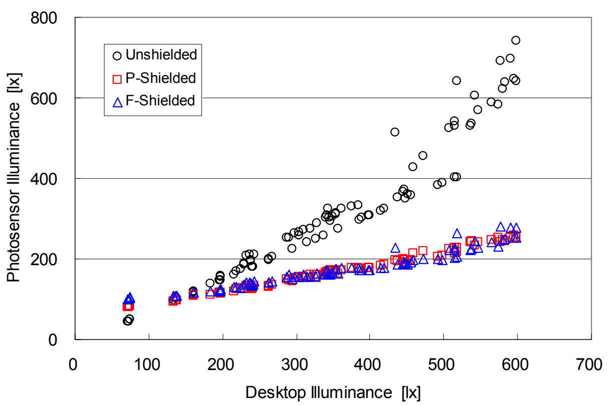


Figure 8. Correlation between Desktop Illuminance and Photosensor Illuminance due to Daylight (Top:South-facing, Bottom: North-facing)

Table 4. Coefficient of Determination between Workplane Illuminance due to daylight and Photosensor Illuminance due to daylight

Room Orientation	Photosensor Shielding Conditions	Coefficient of Correlation (R^2)
North	Unshielded	0.9187
	Partially-shielded	0.9891
	Fully-shielded	0.9353
South	Unshielded	0.7523
	Partially-shielded	0.7971
	Fully-shielded	0.7456

Mistrick stated that partially-shielded photosensors supplied reasonably better system performance under tested daylight and various shading device conditions. It was discussed that the north-facing room provided better control performance due to the absence of direct sun light that penetrates the window and impacts the photsensor signals. It was suggested that the unshielded and partially-shielded photosensors placed in the rear area of the room provided reasonably good control performance under the daylight conditions.

Littlefair stated that fully-shielded photosensors did not have good correlations with the illuminance levels on a desktop. It was pointed out that the results from fully-shielded conditions would be worse for an occupied space due to furniture and occupants. Littlefair reported that a partially-shielded photosensor containing open area to the

Table 5. Electric Lighting Energy Savings

		South-facing, 0 % shading			South-facing, 25% shading			South-facing, 50% shading			North-facing, 0% shading		
		Shielding Conditions			Shielding Conditions			Shielding Conditions			Shielding Conditions		
Day	Sky	F	P	U	F	P	U	F	P	U	F	P	U
12/21	C	73.09	79.50	82.64	70.87	79.17	82.20	68.59	72.66	81.25	27.42	39.75	62.46
	I/M	43.48	58.60	73.71	41.92	54.99	73.02	33.36	41.81	62.06	22.39	33.20	49.61
	O/C	21.97	33.16	48.94	22.11	32.82	47.97	19.83	30.62	43.14	22.00	33.23	48.92
3/21	C	84.94	83.77	90.00	84.28	83.30	90.00	69.68	63.47	89.02	51.53	54.32	90.00
	I/M	54.53	60.01	85.64	52.43	57.94	85.20	33.94	43.77	76.21	31.80	41.88	69.37
	O/C	29.92	41.15	64.82	29.40	40.30	62.28	23.63	34.49	51.06	29.85	41.25	64.81
6/21	C	68.10	68.31	90.00	65.47	64.76	90.00	34.53	45.12	84.18	50.42	56.65	90.00
	I/M	38.41	48.57	84.62	37.57	47.25	80.43	26.86	37.91	59.62	32.83	43.93	73.14
	O/C	36.27	47.14	78.83	35.16	45.95	73.76	26.45	37.31	57.10	36.28	47.16	78.86

where,
- C : Clear sky, - I/M : Intermediate sky - O/C : Overcast sk
- F : Fully-shielded photosensor, - P : Partially-shielded photosensor, - U : Unshielded photosensor

light from the rest of the space provided overall reasonable results over a limited period of data measurements.

The control performance evaluated in this study according to the photosensor shielding conditions in a space with a double skin envelope system was similar to the results discussed above. While the partially-shielded conditions provided the best performance among three conditions, the unshielded conditions failed to provide required illuminance levels on the desktop for the majority of tested time under all sky and shading device conditions. The fully-shielded conditions provided greater illuminance levels on a desktop with excessive electric light output.

The partially-shielded photosensors provided the best correlations between deskop illuminance and photosensor illuminance in both the north and south-facing room due to the effective use of daylight. The north-facing room showed relatively strong correlations compared to the south-facing room.

Despite only photosensors with limited shielding types were considered in this research, the level of agreement suggested by these three types of photosensors is still acceptable. The evaluation of control system performances in this research should contribute to develop better control strategies for a small office space with a double skin envelope system.

(4) Electric Light Energy Savings

For the purpose of determining the relative impact of control performance to electric light energy savings caused by the three different types of shielding conditions, the energy savings for the range of sky and shading device conditions were analyzed

The analysis results shown in Table 5 represent that the difference of energy savings between 0% and 25% of fabric shading device conditions for the south-facing room is small for three photosensor conditions. As the shaded area increased up to 50%, the energy savings decreased up to 19.62% compared to the clear internal envelope condition with no shading.

Clear sky conditions provided much energy savings while overcast sky conditions provided less energy savings. The north-facing room with no impact from the direct sun provided less energy savings compared to those of the south-facing room. The quantitative illuminance levels on the desktop were maintained using the daylight and reasonably saved electric light energy.

4. CONCLUSION

In this study, computer simulations using the Desktop Radiance were performed for a small private office space with a double skin envelope system under a variety of daylight conditions. A summary of general findings of this study is as follows;

(1) The partially-shielded photosensor condition is generally recommended when a photoelectric control system is applied to a small office space with a double envelope system where direct and reflected light intensively exist due to a big window area and they critically impact photosensor signals. In this study, partially-shielded photosensor conditions generally showed good system performance without failing to provide target illuminance under the tested sky and shading device conditions. While the unshielded conditions failed to provide necessary illuminance levels causing less electric light output under all sky and blind conditions, the fully-shielded photosensors generally provided excessive light output and overshot the desktop.

(2) The photoelectric dimming control system generally showed good performance under clear sky conditions. For some cases, the dimming control system showed good performance under intermediate sky conditions showing reasonable light output. The dimming control system performance under an intermediate sky is acceptable, provided the daylight level does not fluctuate so often during the evaluation period. Generating light output greater than 75% of the entire light output of the lighting

system, the dimming system did not contribute to energy savings under overcast sky conditions.

(3) Reasonable energy savings were accomplished providing required illuminance levels on the desktop when the partially-shielded photosensor condition was used for the photoelectric control system. No shading and 25% of shading condition for the internal envelope provided similar energy savings. When 50% of the internal envelope was shaded, the energy savings decreased up to 19.62 % compared to the no shading condition.

(4) The coefficients of determination (R^2) between the workplane illuminance and photosensor illuminance due to daylight were best for the partially-shielded photosensor conditions that blocked the direct light from the window and received the reflected light from the rest of the wall surfaces. The worst correlation happened to the unshielded photosensor conditions that were directly impacted by the light from the sun and sky.

5. STUDY LIMIT AND FUTURE WORKS

Since this study was performed using only one computer simulation software which used its own specific calculation algorithms, the calculation results might be different from those of other software employing different modeling theories of sky and atmospheric conditions such as turbidity.

In addition, the daylight conditions assumed in this research were confined to the south-facing and north-facing space with a fixed horizontal blind and limited retractable shading device conditions. Further research examining the impact of different orientation of a space and various shading devices to the dimming control systems would be necessary.

A reasonable amount of electric light energy savings was achieved using the photoelectric dimming control system with limited types of photosensor shielding conditions and the illuminance levels on the desktop were maintained within recommended ranges. However, this research does not provide qualitative evaluations for the visual environments of the space controlled by a photoelectric dimming system.

Field measurements would help to examine the accuracy of these results and if the dimming control performance studied in this research could be applied to actual office room settings with furniture under a real world. The qualitative evaluations by occupants for the performance of a photoelectric dimming control system would be helpful, too.

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