Title
THE INTEGRATION OF OPERABLE SHADING SYSTEMS AND ELECTRIC LIGHTING CONTROLS

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ABSTRACT

Using daylighting in commercial buildings may significantly reduce electric lighting requirements if appropriate photoelectric controls are used to adjust the electric lighting output according to the available daylight. Prior analysis and results from monitored buildings and scale-model measurements suggest that the selection, placement, and installation of the control photosensor is a difficult task, even with simple non-operable fenestration systems, since the daylight contributions from sun, sky, and ground change continuously. The problem becomes even more complex for fenestration systems that incorporate operable shading devices, because every adjustment changes the system's optical properties. This paper presents results from measurements in a scale model under real skies, designed to better understand the problem of integrating fenestration and lighting controls. The scale model represented a typical office space and was equiped with motorized venetian blinds. Three control photosensors mounted on the ceiling were considered for the operation of the electric lighting system, and two control strategies were considered for the operation of the venetian blinds. Two ground-plane reflectances and two window orientations were examined. Results indicate that the signal from a ceiling-mounted control photosensor shielded from direct light from the window shows the best correlation with daylight work-plane illuminance, regardless of ground plane reflectance or venetian blind slat angle for all slat angles that do not allow penetration of direct solar radiation. Results also indicate that the control strategies of the venetian blinds that were considered for the purposes of this study may result in significantly different slat angles, and thus different daylighting work-plane illuminances and electric lighting requirements, especially when the ground-plane reflectance is high.

INTRODUCTION

Using daylighting in commercial buildings may significantly reduce electric lighting loads if appropriate photoelectric controls are used to adjust the electric lighting output according to the available daylight. Also, in order to avoid excessive thermal loads and visual discomfort, it is important to prevent direct sunlight from penetrating into the occupied space and to minimize the view of a sometimes uncomfortably bright sky using appropriate shading devices or reflective or tinted glass. While fixed shading devices, such as overhangs and vertical or horizontal fins, can block direct sunlight penetration on certain orientations, operable shading devices, such as venetian blinds, offer more flexibility with respect to controlling daylight admission, view, glare, and energy requirements for lighting, cooling, and heating. Operable shading devices, however, are more difficult to understand, because every adjustment changes the system's optical and thermal properties.

Operable shading devices may be operated with many different control strategies. Each strategy has different effects on view potential and on the luminous and thermal environments, resulting in different energy requirements for electric lighting, cooling, and heating. The trade-offs that are introduced by the various possible control strategies are not well understood. Moreover, results from prior studies (Collins 1979) indicate that occupants practice only limited window management. In the case of manually operated venetian blinds, the angle of the slats is practically never adjusted. This has led to the increased consideration of automated photoelectric controls for shading devices, in addition to the controls required for the electric lighting system, in order to maximize the efficiency of the fenestration system.

The objective of a daylight-following lighting system is to maintain a specified minimum work-plane illuminance while minimizing electric lighting output by responding to changes in available daylight. Daylight-following lighting systems incorporate a control photosensor that generates an electrical signal proportional to the amount of sensed light, which is processed according to a specified control algorithm by a controller that controls a dimming unit to vary the output of the electric lighting system. The importance of the placement and the spatial response of the control photosensor

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and the control algorithm used by the controller to process the signal from the photosensor have been analyzed in previous studies (Rubinstein et al. 1986), based on scale-model measurements under real skies for unshaded windows. Using a similar experimental setup, we extended the previous study to the case of windows shaded with venetian blinds by examining the impact of the venetian blinds' operational control strategy and ground reflectance on the electric lighting requirements.

METHODOLOGY

For the purposes of this study we used a scale model under real sky conditions, which could be rotated to orient the window wall toward any direction. The scale model represented a small office space (15 by 15 ft with 9-ft ceiling height) with window-to-wall ratio of 1:3, work-plane height of 30 in, and walls, ceiling, and floor reflectances of 0.51, 0.83, and 0.23, respectively. The work-plane illuminance distribution was measured by 16 photometers (cosine- and color-corrected) placed on a 4 by 4 array. Eight additional photometers of various orientation and spatial response were placed inside the scale model to act as control photosensors for the electric lighting system. Finally, two photometers, one equipped with a shadow-band, were placed outside the model to measure global and diffuse horizontal illuminance. The electric lighting system was designed to simulate a standard office ceiling system. The scale model is fuly described in a companion paper (Rubinstein et al. 1986). The fenestration system used was a combination of clear glass (0.88 transmittance) and commonly used, operable grey aluminum venetian blinds with ratio of distance between slats to slat width of 0.75 and slat reflectance of 0.4.

The scale model was placed on the roof of a building at the Lawrence Berkeley Laboratory. Measurements were taken over entire days at 20-minute intervals with the model oriented toward the south and west. For each orientation, we tested two different ground plane reflectances: the wooden deck of the roof of the building (0.25 reflectance) and a 10- by 20-ft white cloth (0.75 reflectance) placed in front of the model, with the 20-ft side parallel to the window wall.

Fenestration Control

Results from prior studies (Papamichael and Selkowitz 1986) indicate that the use of slat-type operable shading systems for blocking direct solar penetration introduces a trade-off between maximizing slat openness and view on the one hand and maximizing daylight admission on the other. To better understand the magnitude of this trade-off and its effect on electric lighting savings, two control strategies were considered for the operation of the venetian blinds. While both strategies aimed at blockage of direct sunlight penetration, the first provided maximum possible slat openness (strategy #1) and the second maximum possible work-plane illuminance (strategy #2).

The slat angles that result from control strategy #1 depend solely on the position of the sun in the window-facing hemisphere and require only downward movement of the slats, between 40° and 90° (Figure 1). However, the slat angles under control strategy #2 depend on the position of the sun in the window-facing hemisphere, on the luminous distribution of the window-facing hemisphere, on the optical properties of the venetian blinds, and on the optical properties of the interior surfaces. Therefore, control strategy #2 may require both downward and upward movement of the slats, potentially covering the whole range between 0° and 180°. For any sun position in the window-facing hemisphere, there are two critical cut-off angles for the venetian blinds. Any slat position outside the range defined by these two critical slat angles provides solar blocking (Figure 2). Our approach was to simulate control strategy #2 examining the whole range of possible slat angles and selecting the one that maximized the work-plane illuminance.

The slat angle of the venetian blinds was adjusted by an electronically controlled motor that allowed the slats to be moved to nine preset positions. Because the motor could only move the slats through a maximum range of 90°, we considered the downward and upward movement of the slats separately and then combined the results from two different days to simulate the second control strategy. For both downward and upward movement, the slats were moved at 10° intervals, from 10° to 90° for downward movement and 90° to 170° for upward movement. Eight clear sky days between early September and early October were then used for the combinations of west and south orientation, 25% and 75% ground reflectance, and downward and upward movement of the slats. Control strategy #1 was simulated from the data of the days with downward movement of the slats, and control strategy #2 was simulated from the data of the corresponding days with downward and upward movement of the slats.

Electric Lighting Control

The operational objective of the electric lighting system was to maintain a relatively constant minimum illumination level at the work-plane, regardless of the fenestration control strategy. The ability of the electric lighting control system to meet this objective was examined by measuring the signals produced by three control photosensors and the work-plane daylight illuminance. The three photosensors considered were mounted on the ceiling of the scale model, one being unshielded, one being partially shielded so that it did not accept light directly from the window wall, and one being fully shielded so that it accepted light directly only from the floor. Since prior studies (Rubinstein et al. 1986) indicate that integral reset and open-loop proportional control algorithms are less effective than closed-loop proportional ones, the latter were considered for the determination of the electric lighting system's output. A closed-loop proportional control algorithm adjusts the electric lighting system output so that the electric light level is a linear function of the difference between the signal produced by the control photosensor at a given time and the signal produced by the control photosensor at full electric light output without daylighting (i.e., at night).

The performance of the integrated daylighting/electric lighting system with respect to electric lighting requirements was determined by computer simulations that used the measured data to model the response of a properly calibrated closed-loop proportional control system. We considered only the partially shielded control photosensor, because this provided the most effective control. The electric lighting savings were determined by comparing the output of the daylight-following lighting system to its full output of 74 watts per ballast, required to provide a work-plane illuminance of 720 lux.

ANALYSIS AND RESULTS

The analysis of the measured data with respect to the effect of the control photosensors focused on the correlation between the signal from the three photosensors and the work-plane illuminance for south and west window orientations (Figures 3 through 8). The results indicate that the partially shielded control photosensor provides the best correlation (Figures 5 and 6), while the unshielded photosensor provides the worst (Figures 3 and 4). The detailed data from the statistical analysis are presented in Table 1.

The analysis of the measured data with respect to the operation of the venetian blinds focused on the different effects of the control strategies on the slat angles and the resulting work-plane illuminance from daylighting and electric lighting.

South Orientation

For the case of low ground reflectance (0.25), both control strategies for the operation of the venetian blinds resulted in 90° slat angles throughout the day, with no difference in daylighting levels (Figure 9), electric lighting levels (Figure 10), or total lighting levels (Figure 11). The resulting electric lighting power requirements are shown in Figure 12 and correspond to 38.1% savings.

For the case of high ground reflectance (0.75), control strategy #1 resulted in 90° slat angles for most of the day, while control strategy #2 resulted in 60° slat angles as the solar altitude was increased, contributing to the luminance of the ground (Figure 13). The differences in daylighting levels between the two control strategies were not large (Figure 14), resulting in insignificant differences between the electric lighting requirements (Figure 15) as they occurred when daylight levels from control strategy #1 were exceeding the specified work-plane illuminance of 720 lux. The differences in total lighting and the electric power requirements are shown in Figures 16 through 18. The electric lighting savings for both control strategies were 55.3%.

West Orientation

For the case of low ground reflectance (0.25), control strategy #1 resulted in 90° slat angles for most of the day, and continuously lower slat angles after 2:00 p.m., as the solar altitude decreased toward the sunset (Figure 19). Control strategy #2 resulted in slight upward movement of the slats (100°) for the early morning and the early afternoon hours and in slight downward movement of the slats (80°) for the late morning hours, following control strategy #1 during the late afternoon hours for decreased solar altitudes (Figure 19). However, the differences in daylighting levels were insignificant (Figure 20), resulting in minimal differences in electric lighting and total lighting levels (Figures 21 and 22). The electric power requirements for the two strategies are shown in Figures 23 and 24 and correspond to 46.2% and 46.8% savings for control strategies #1 and #2, respectively.

For the case of the high ground reflectance (0.75), control strategy #1 resulted in slat angles identical to those for low ground reflectance, while control strategy #2 resulted in much lower slat angles for most of the day, especially for high solar altitudes when the direct solar radiation contributes greatly to the luminance of the ground (Figure 25). The differences in daylighting levels were large (Figure 26). However, the differences in electric lighting were relatively small (Figure 27), because the differences in daylight levels occured when light levels from control strategy #1 were exceeding the specified work-plane illuminance of 720 lux. The differences in total lighting and electric power requirements are shown in Figures 28 through 30. The electric lighting savings for control strategies #1 and #2 were 53.5% and 56.2%, respectively.

DISCUSSION

Our results have shown that the signal from a ceiling-mounted control photosensor that is shielded from direct light from the window exhibits the best correlation with the daylight work-plane illuminance. These results not only confirm those from previous studies (Rubinstein et al. 1986) but extend them, since they include consideration of the additional parameters of ground reflectance and venetian blind slat angle, thus covering a large range of window-candlepower distributions. The correlation of the work-plane daylight illuminance with the signal from the control photosensor is a measure of the effectiveness of the electric lighting system in obtaining satisfactory initial calibration and in maintaining electric lighting levels close to the minimum required to appropriately supplement daylighting.

Our results have also shown that the two different control strategies for the operation of the venetian blinds may result in significantly different daylight levels in the space, especially when the ground plane reflectance is high. However, the importance of these differences is a function of the design light level in the space as well as the location of the station point(s). The location of the station point also affects the position of the slats when these are operated under control strategy #2 (Figure 31). For the design work-plane illuminance of 720 lux at the station point 12 ft away from the window that was considered for the purposes of this study, there were relatively small differences in the electric lighting requirements between the two strategies. This was mainly because a major fraction of the differences in daylight levels between the two strategies occurred when daylight levels were exceeding the design light level of 720 lux and partially because the useful dynamic range of the dimming system was limited to 10% minimum output. Higher values for the design light level or station points further away from the window wall would result in higher differences, since the additional daylight from control strategy #2 would have a positive contribution to the work-plane illuminance.

It should be noted that the results of this study refer to specific days and do not necessarily represent annual performance. For example, since we collected data on days slightly before the autumnal equinox, most of the upward positions of the slats would allow penetration of direct solar radiation when the model was oriented facing south. This resulted in 90° slat angles for both strategies with low ground reflectance. Lower sun paths would allow upward movement of the slats under control strategy #2, which might result in significant differences in slat angles with accompanying differences in overall performance. Further research is needed to identify the annual impact of fenestration operation control strategies on the electric lighting at different geographical locations, so that different sun paths and climatic conditions are considered.

The venetian blind control strategies considered in this study are only two of a large number of possible strategies. Other control strategies, such as minimizing glare, maximizing visibility, minimizing cooling or heating loads, or combinations of the above are also possible and may be more desirable in some cases. Moreover, different control strategies may be considered during different seasons to further improve the annual performance of operable fenestration systems.

Finally, for the purposes of this study, we simulated the operation of the venetian blinds by examining all possible slat angles and then selecting the ones that corresponded to the control strategies considered. In real-building applications, the control criterion of blocking direct solar radiation can be met by appropriate photocell arrays to detect the presence and approximate direction of direct solar radiation. The additional criterion of maximum slat openness for control strategy #1 can be met easily, because slat openness is a linear function of the slat openness. However, it is not clear how the additional criterion of maximum work-plane illuminance for control strategy #2 can be met in real-building applications. Whether this can be acheived with the same photosensor that controls the output of the electric lighting system will be the focus of future research.

CONCLUSIONS

This study has shown that the signal from a ceiling-mounted control photosensor that is shielded from direct light from the window shows the best correlation with daylight work-plane illuminance, regardless of ground plane reflectance or venetian blind slat angle for all slat angles that do not allow penetration of direct solar radiation. Results also indicate that the operation control strategies of venetian blinds that were considered for the purposes of this study may significantly affect the luminous performance of the fenestration system and thus the magnitude of electric lighting savings, especially when the ground-plane reflectance is high.

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TABLE 1

Results from Statistical Analysis on the Correlation of the Work-Plane Daylight Illuminance and the Signal from the Various Control Photosensors

Control Photosensor	Window Orientation	Number of Data Points	Fitted† Parameter	Standard Error‡ of Estimate	Correlation Coefficient
Unshielded	South	676	0.401	130.988	0.928
Partially-shielded	South	676	3.911	46.120	0.991
Fully-shielded	South	676	8.074	61.152	0.985
Unshielded	West	1069	0.437	159.098	0.815
Partially-shielded	West	1069	3.893	55.455	0.979
Fully-shielded	West	1069	7.933	87.582	0.948

† Calculated from least square fit.

‡ Calculated as: $\left[\frac{(y_i - y_{fit})^2}{N-1}\right]^{1/2}$

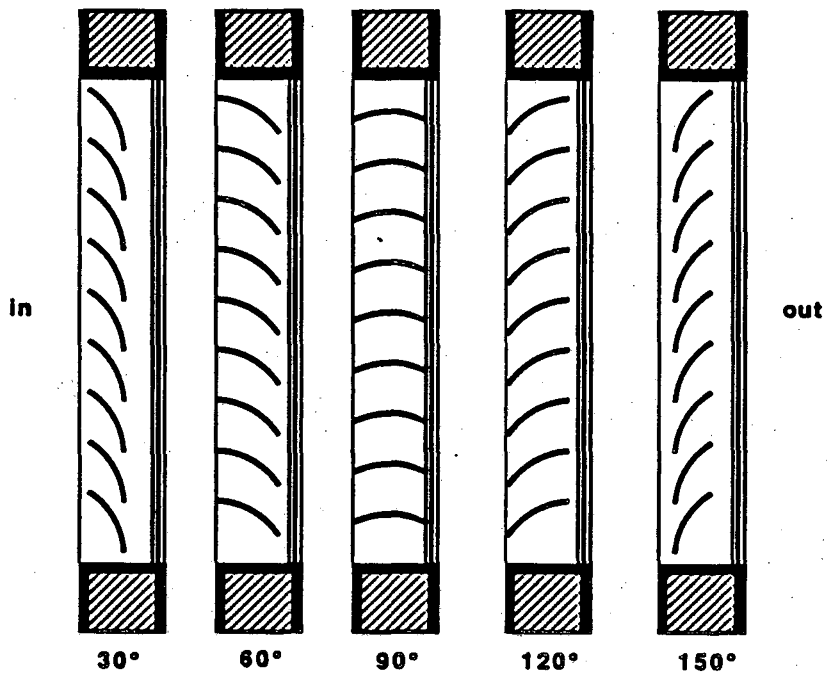

Figure 1. Schematic showing several representative slat angles.

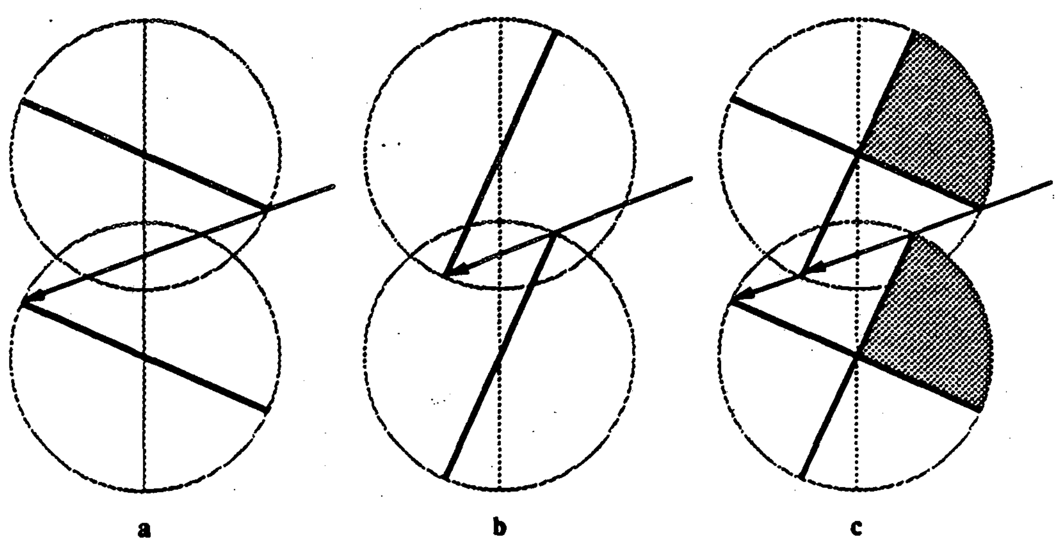

Figure 2. The two critical positions that just block an arbitrary direction of incoming direct solar radiation (a and b) and the range that they define, which includes all the slat positions that allow direct sunlight penetration.

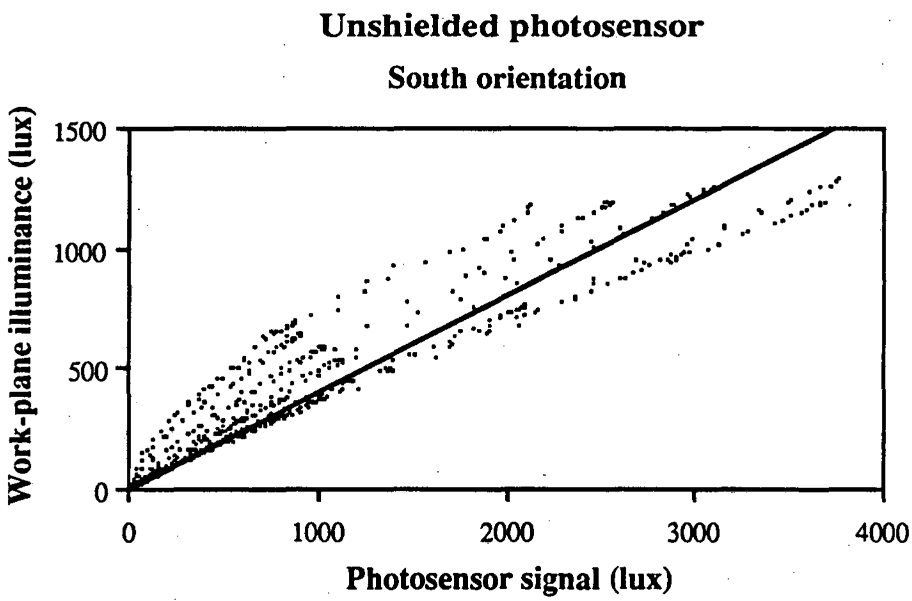

Figure 3. The relationship between the work plane illuminance due to daylighting and the signal from the unshielded photosensor for south orientation with 25% and 75% ground reflectance, considering all slat angles for which no direct sunlight penetrated into the space.

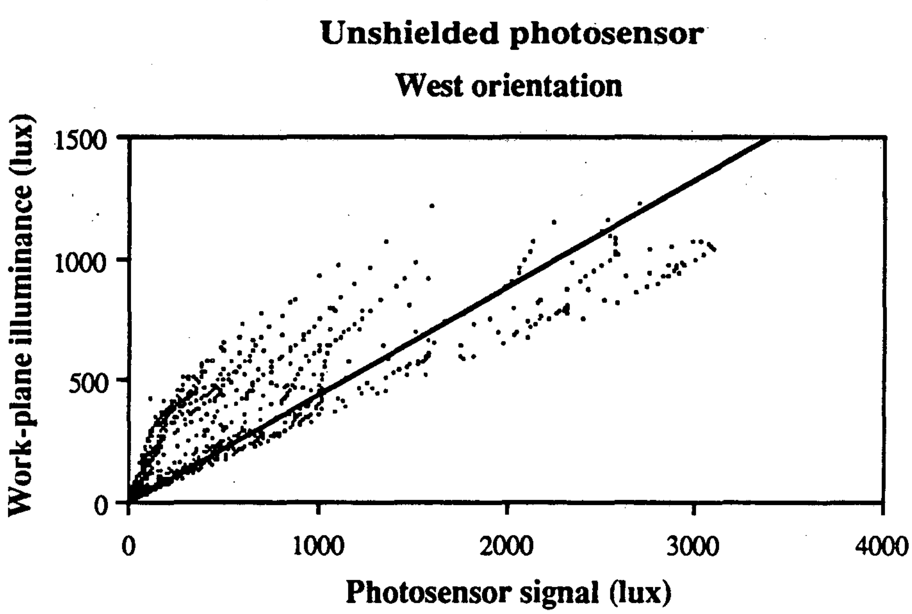

Figure 4. The relationship between the work plane illuminance due to daylighting and the signal from the unshielded photosensor for west orientation with 25% and 75% ground reflectance, considering all slat angles for which no direct sunlight penetrated into the space.

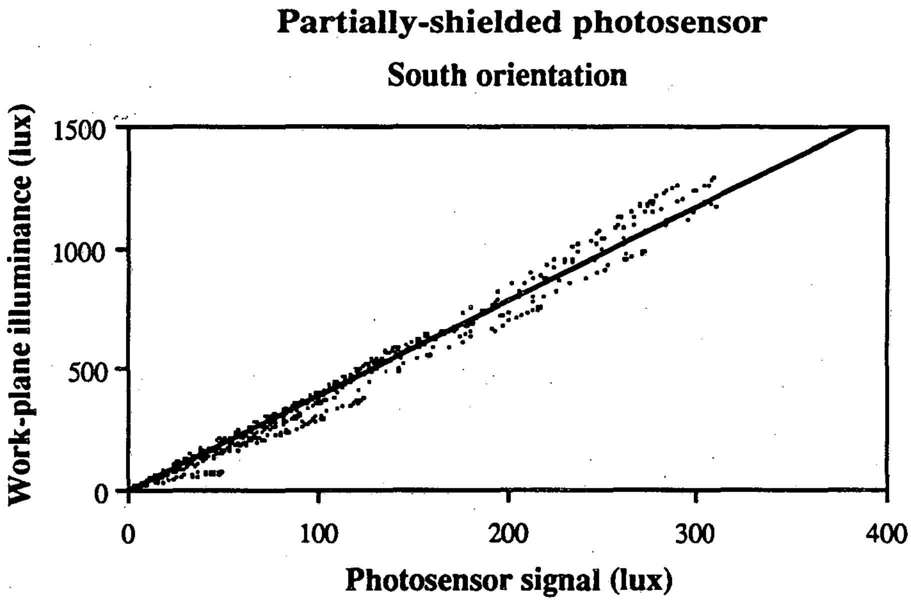

Figure 5. The relationship between the work plane illuminance due to daylighting and the signal from the partially-shielded photosensor for south orientation with 25% and 75% ground reflectance, considering all slat angles for which no direct sunlight penetrated into the space.

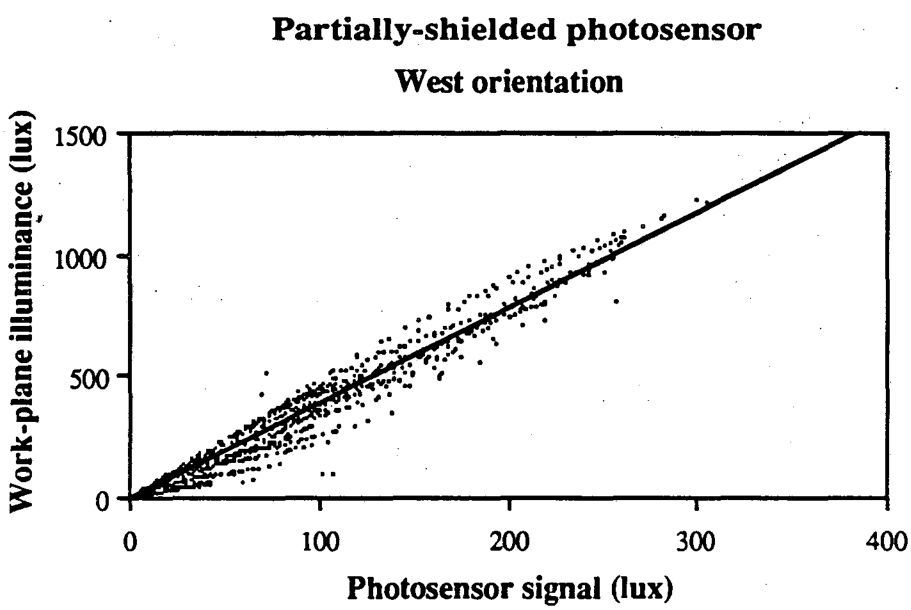

Figure 6. The relationship between the work plane illuminance due to daylighting and the signal from the partially-shielded photosensor for west orientation with 25% and 75% ground reflectance, considering all slat angles for which no direct sunlight penetrated into the space.

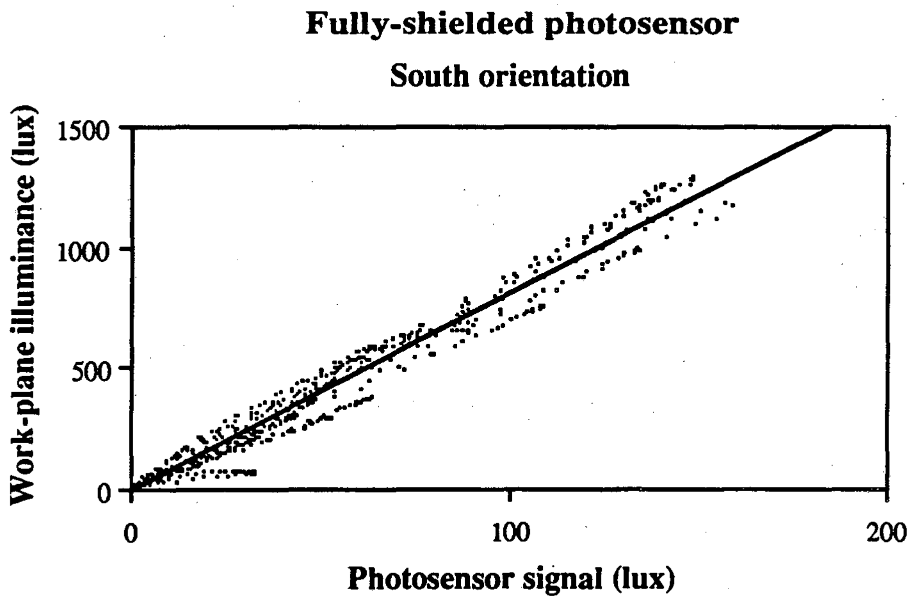

Figure 7. The relationship between the work plane illuminance due to daylighting and the signal from the fully-shielded photosensor for south orientation with 25% and 75% ground reflectance, considering all slat angles for which no direct sunlight penetrated into the space.

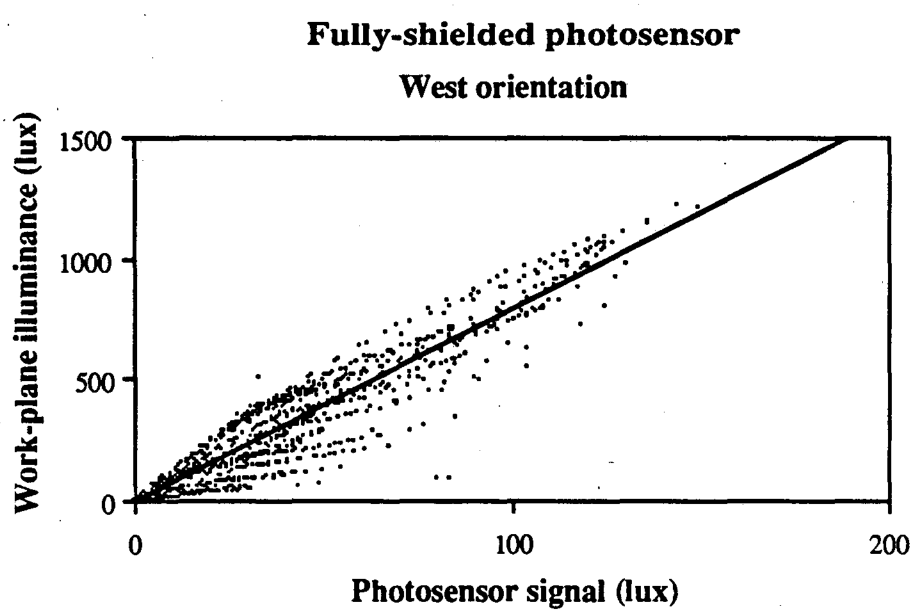

Figure 8. The relationship between the work plane illuminance due to daylighting and the signal from the fully-shielded photosensor for west orientation with 25% and 75% ground reflectance, considering all slat angles for which no direct sunlight penetrated into the space.

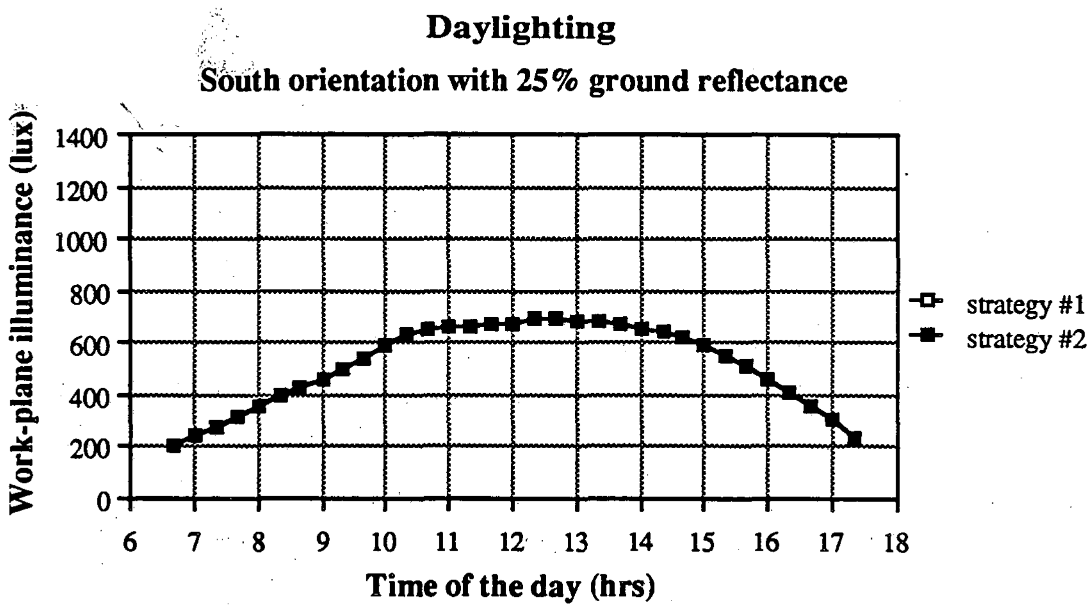

Figure 9. The resulting work plane illuminance due to daylighting under control strategy #1 (maximization of view potential) and control strategy #2 (maximization of work-plane illuminance), for south orientation and 25% ground reflectance.

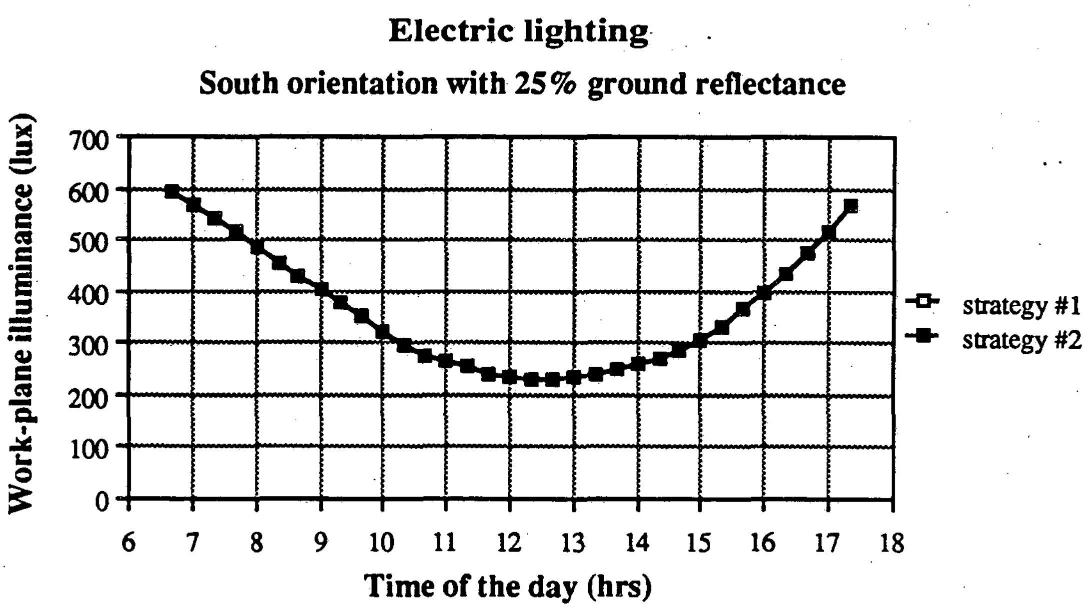

Figure 10. The resulting work plane illuminance due to electric lighting under control strategy #1 (maximization of view potential) and control strategy #2 (maximization of work-plane illuminance), for south orientation and 25% ground reflectance.

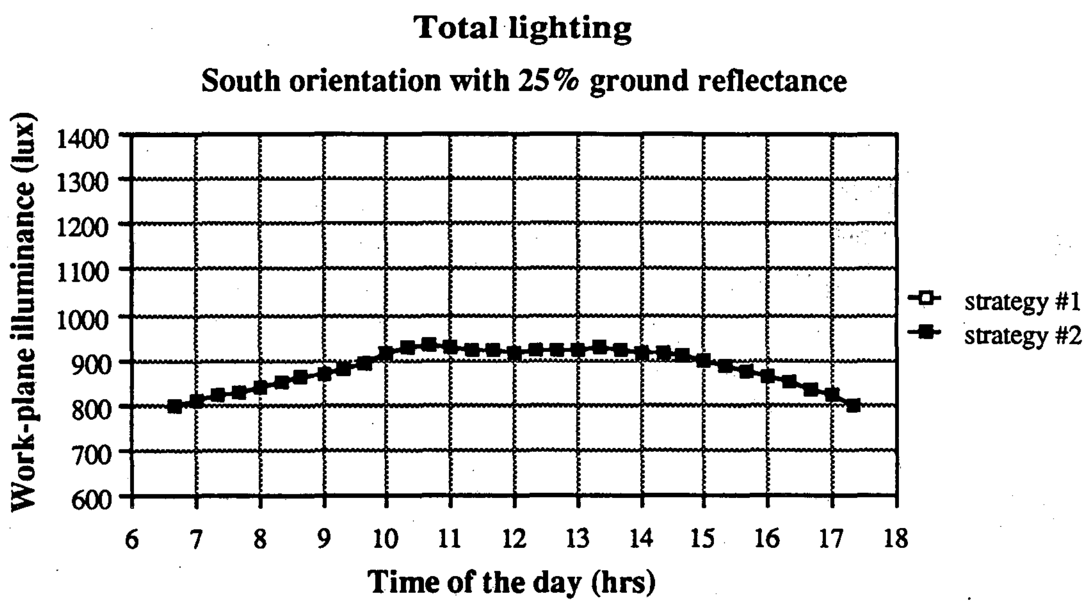

Figure 11. The resulting work plane illuminance due to daylighting and electric lighting under control strategy #1 (maximization of view potential) and control strategy #2 (maximization of work-plane illuminance), for south orientation and 25% ground reflectance.

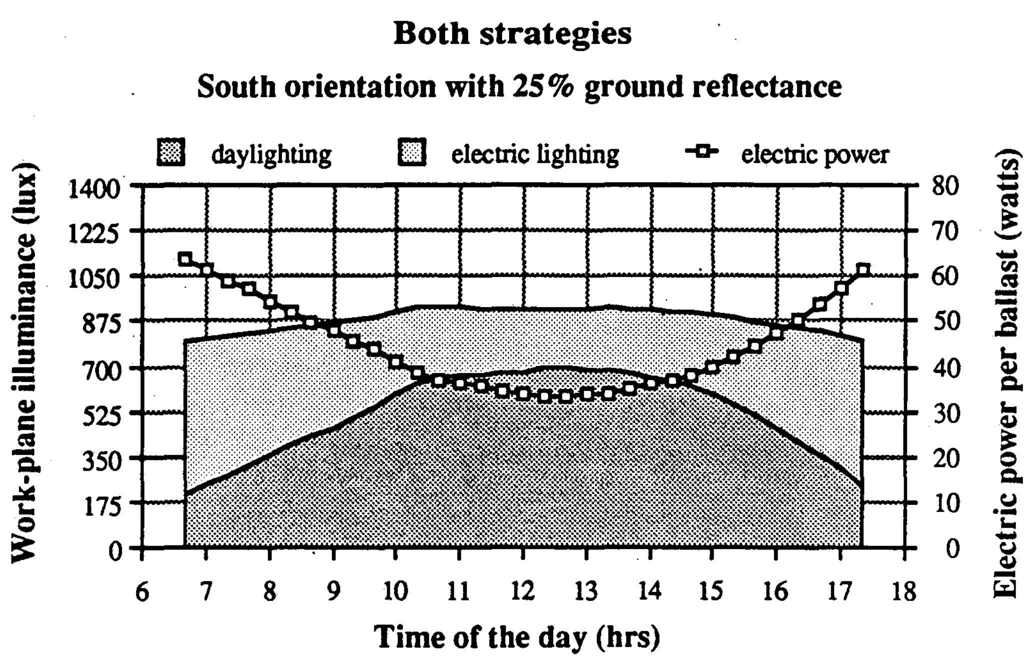

Figure 12. The resulting work plane illuminance and the input power to the electric lighting system for both control strategies, for south orientation and 25% ground reflectance.

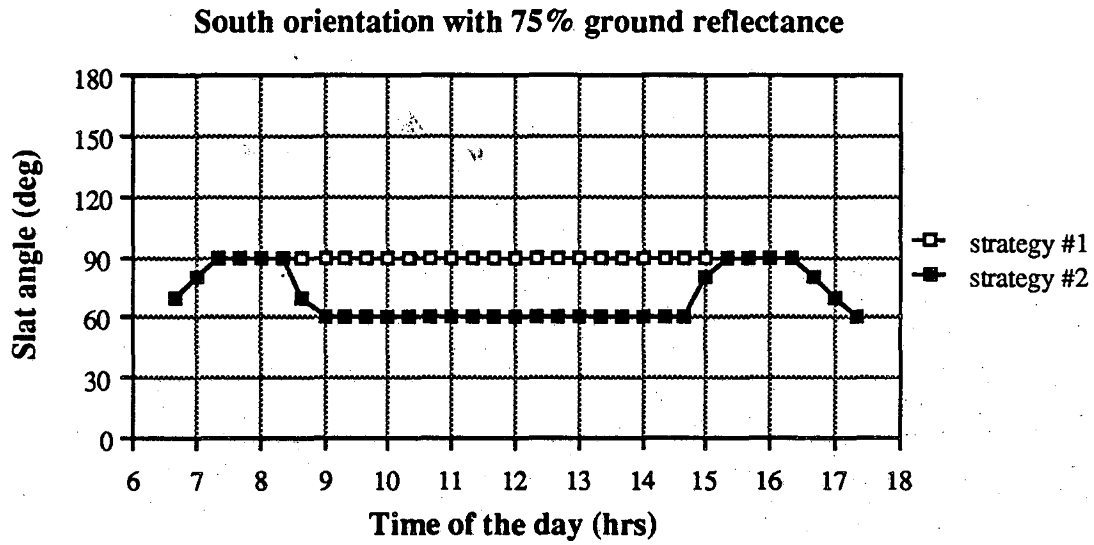

Figure 13. The resulting slat angles under control strategy #1 (maximization of view potential) and control strategy #2 (maximization of work-plane illuminance), for south orientation and 75% ground reflectance.

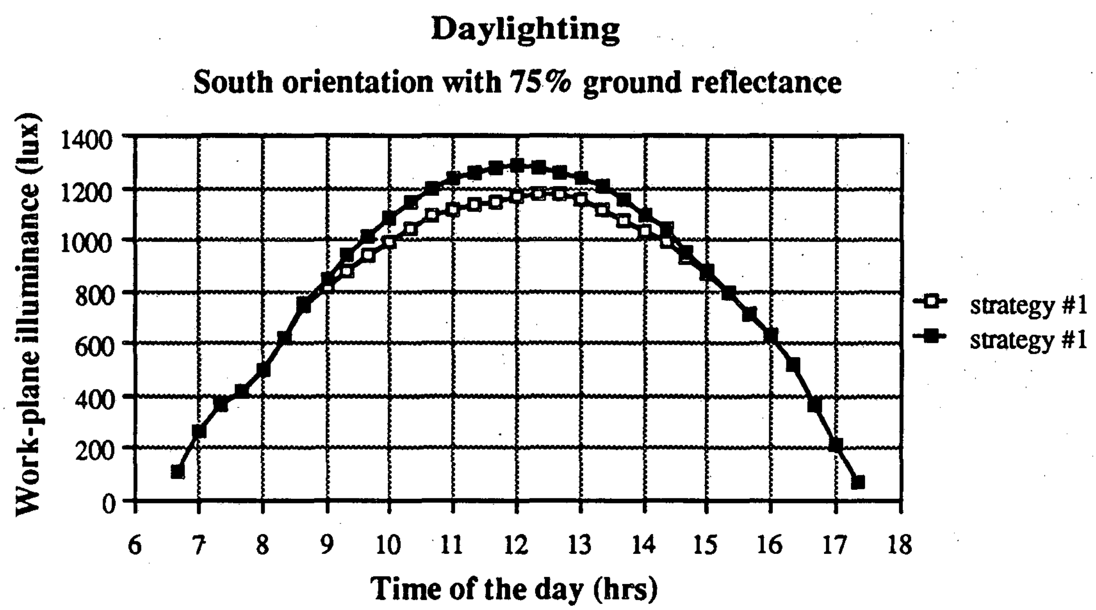

Figure 14. The resulting work plane illuminance due to daylighting under control strategy #1 (maximization of view potential) and control strategy #2 (maximization of work-plane illuminance), for south orientation and 75% ground reflectance.

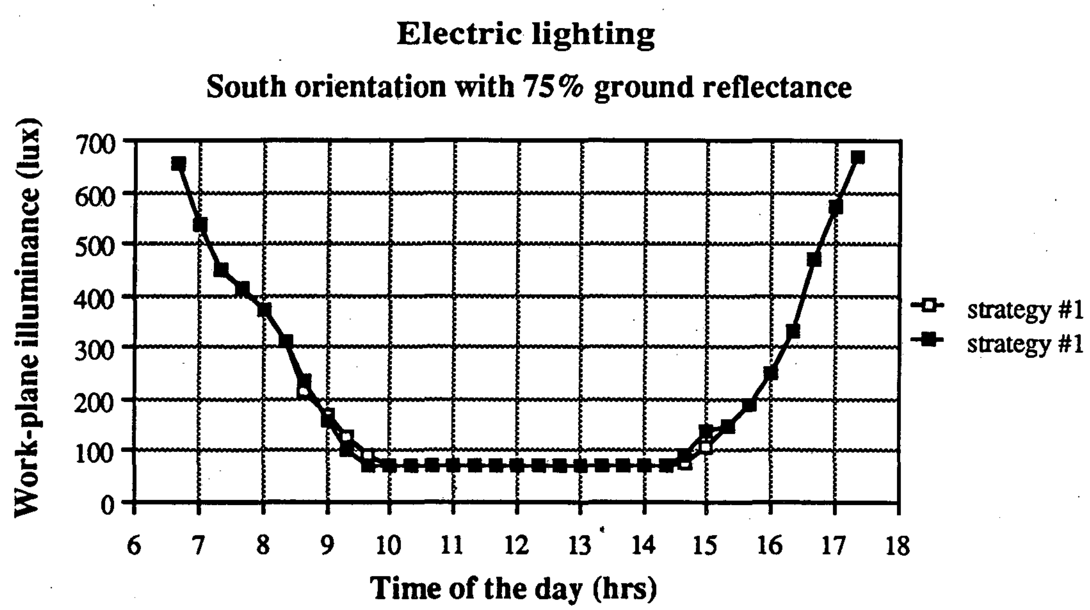

Figure 15. The resulting work plane illuminance due to electric lighting under control strategy #1 (maximization of view potential) and control strategy #2 (maximization of work-plane illuminance), for south orientation and 75% ground reflectance.

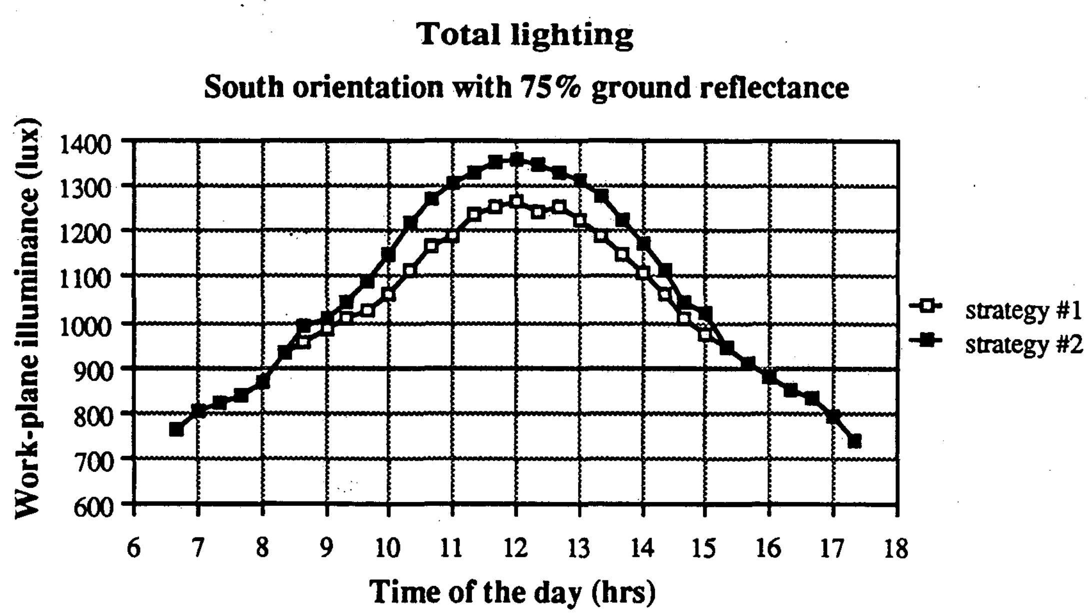

Figure 16. The resulting work plane illuminance due to daylighting and electric lighting under control strategy #1 (maximization of view potential) and control strategy #2 (maximization of work-plane illuminance), for south orientation and 75% ground reflectance.

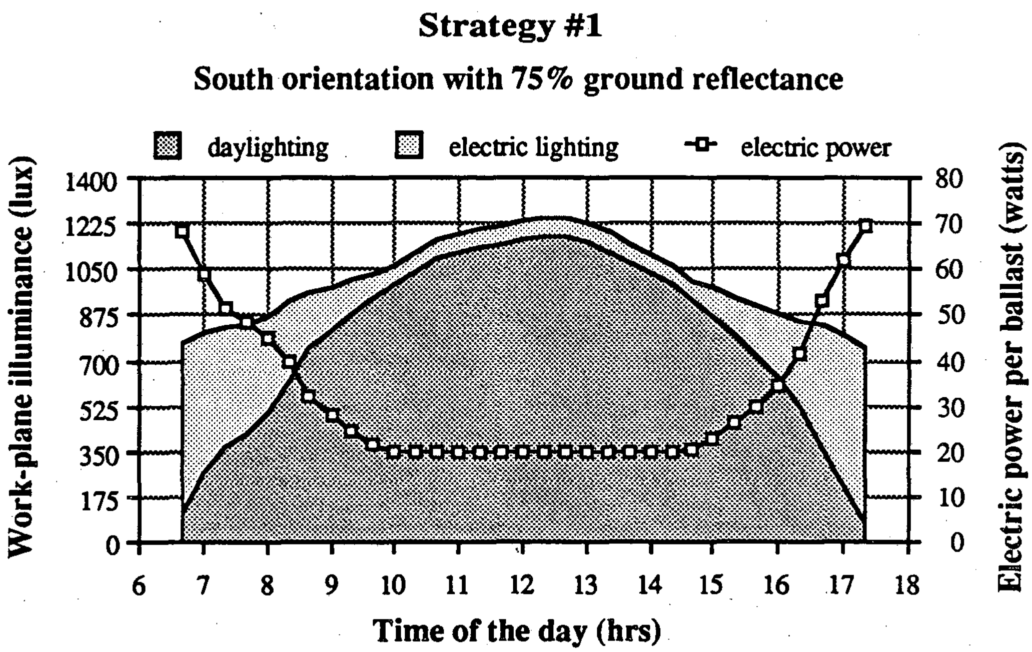

Figure 17. The resulting work plane illuminance and the input power to the electric lighting system under control strategy #1 (maximization of view potential), for south orientation and 75% ground reflectance.

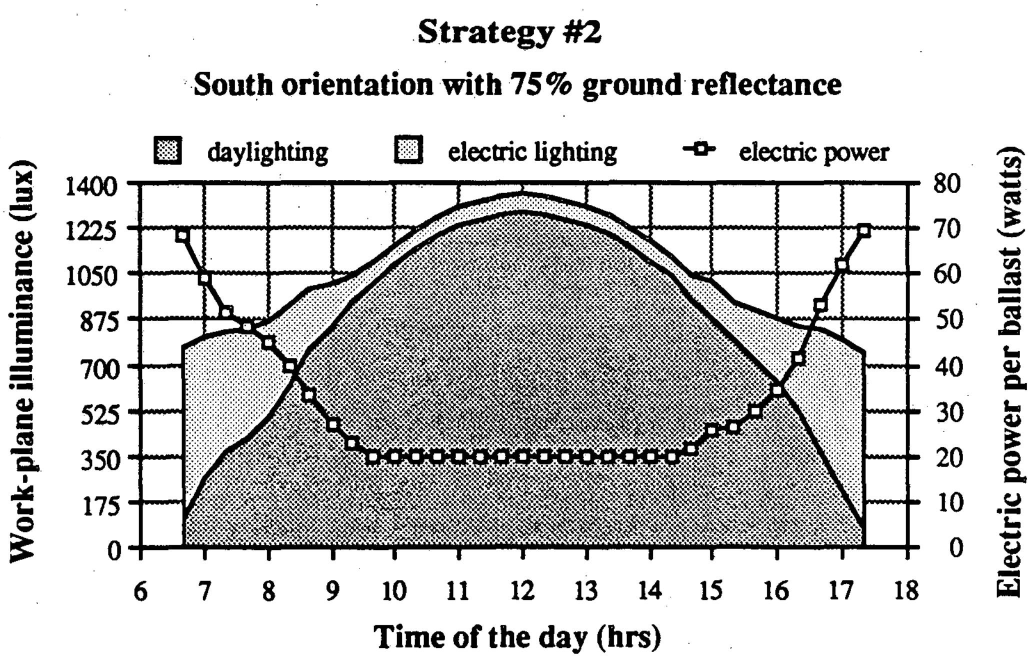

Figure 18. The resulting work plane illuminance and the input power to the electric lighting system under control strategy #2 (maximization of work-plane illuminance), for south orientation and 75% ground reflectance.

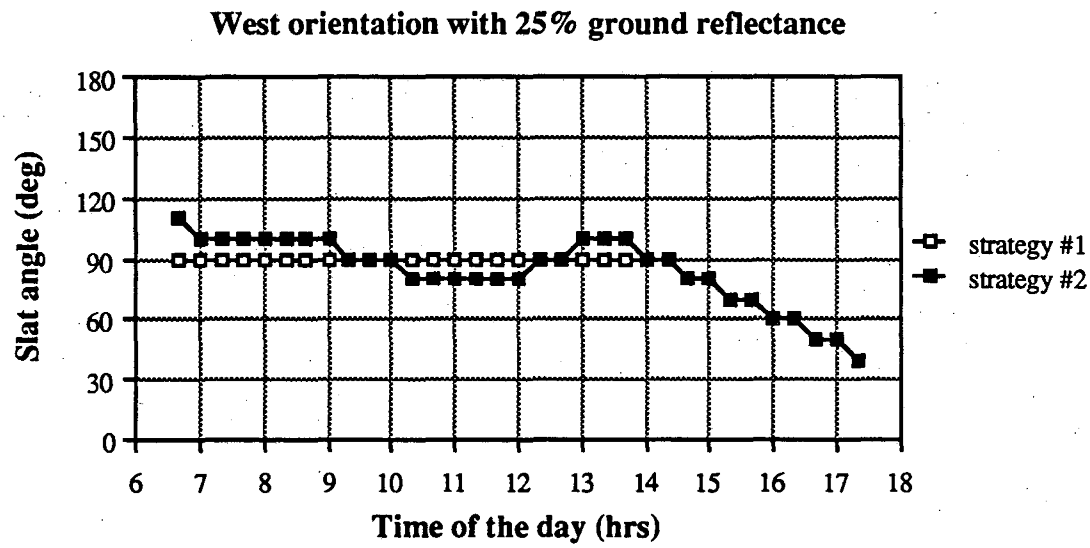

Figure 19. The resulting slat angles under control strategy #1 (maximization of view potential) and control strategy #2 (maximization of work-plane illuminance), for west orientation and 25% ground reflectance.

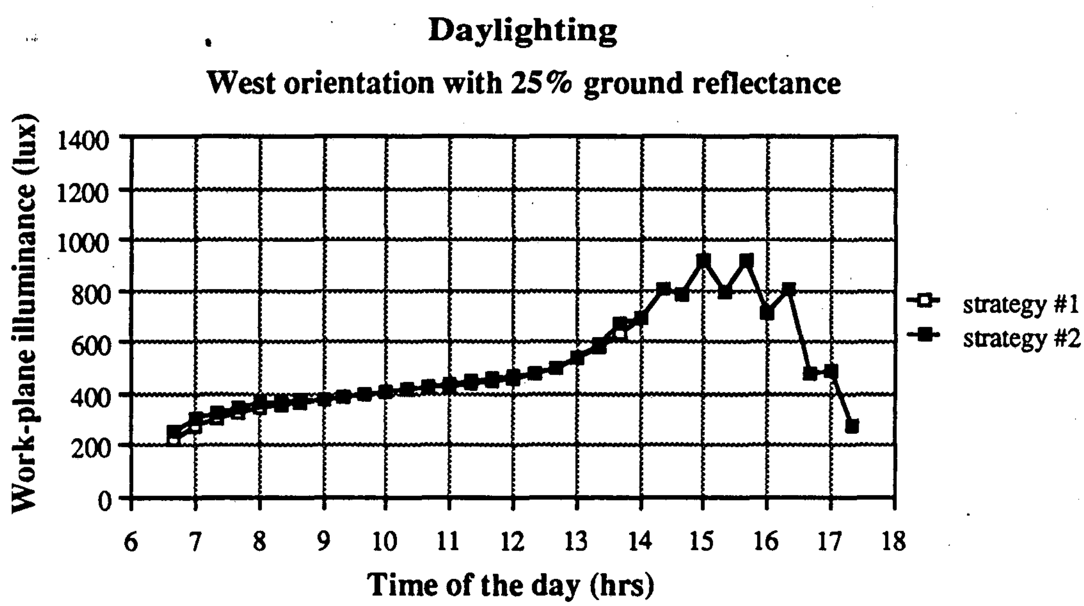

Figure 20. The resulting work plane illuminance due to daylighting under control strategy #1 (maximization of view potential) and control strategy #2 (maximization of work-plane illuminance), for west orientation and 25% ground reflectance.

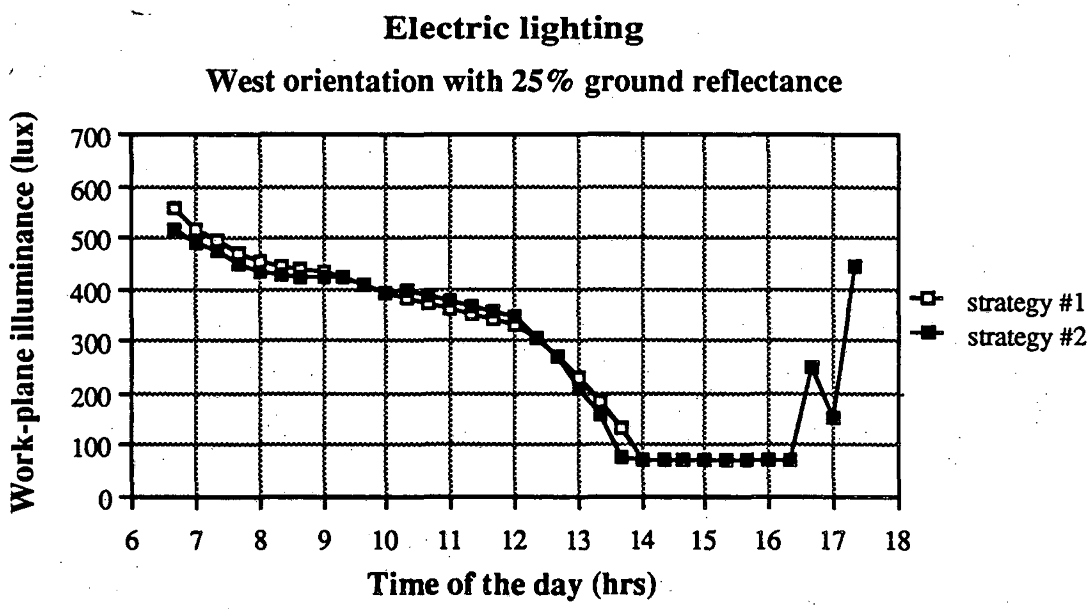

Figure 21. The resulting work plane illuminance due to electric lighting under control strategy #1 (maximization of view potential) and control strategy #2 (maximization of work-plane illuminance), for west orientation and 25% ground reflectance.

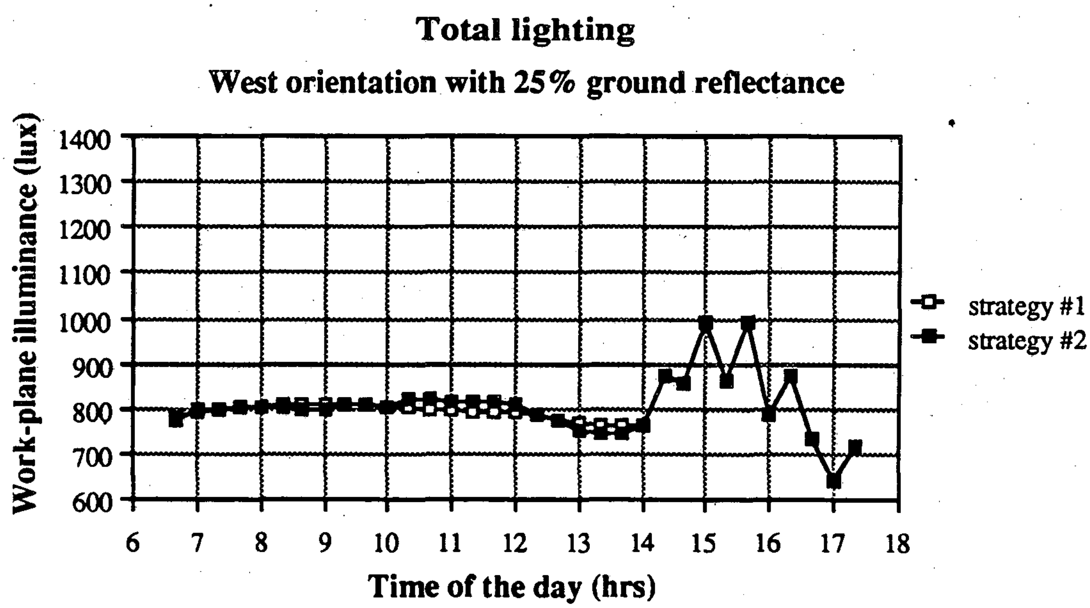

Figure 22. The resulting work plane illuminance due to daylighting and electric lighting under control strategy #1 (maximization of view potential) and control strategy #2 (maximization of work-plane illuminance), for west orientation and 25% ground reflectance.

Strategy #1

West orientation with 25% ground reflectance

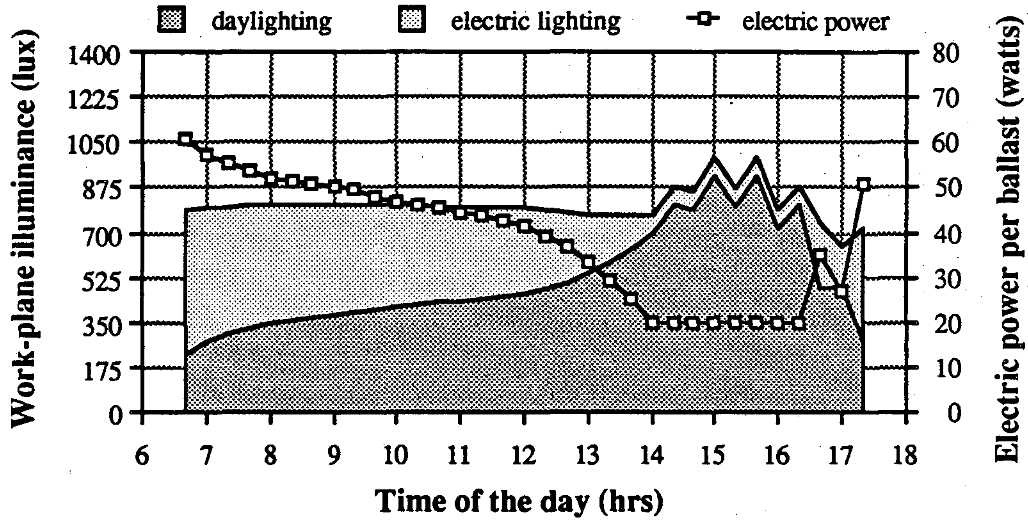

Figure 23. The resulting work plane illuminance and the input power to the electric lighting system under control strategy #1 (maximization of view potential), for west orientation and 25% ground reflectance.

Strategy #2

West orientation with 25% ground reflectance

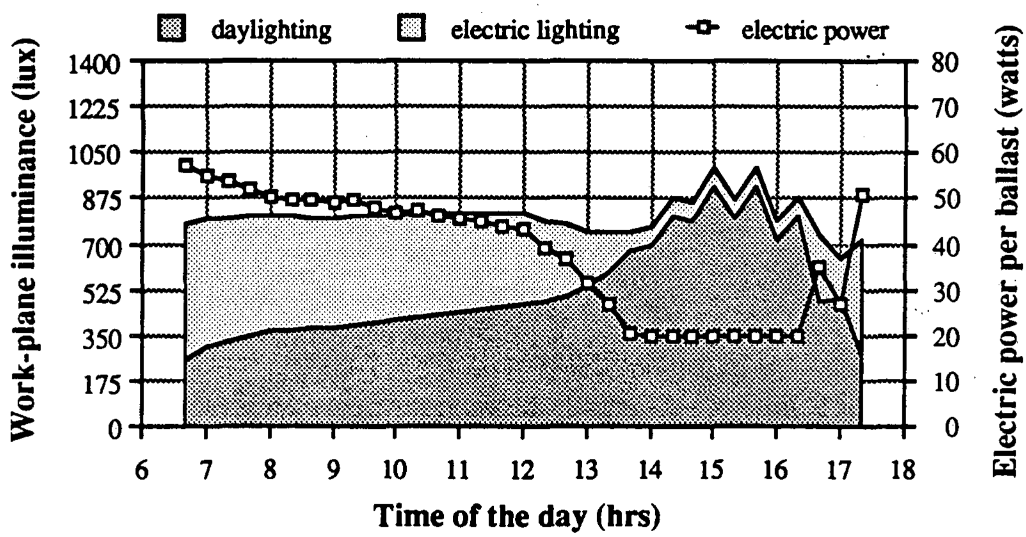

Figure 24. The resulting work plane illuminance and the input power to the electric lighting system under control strategy #2 (maximization of work-plane illuminance), for west orientation and 25% ground reflectance.

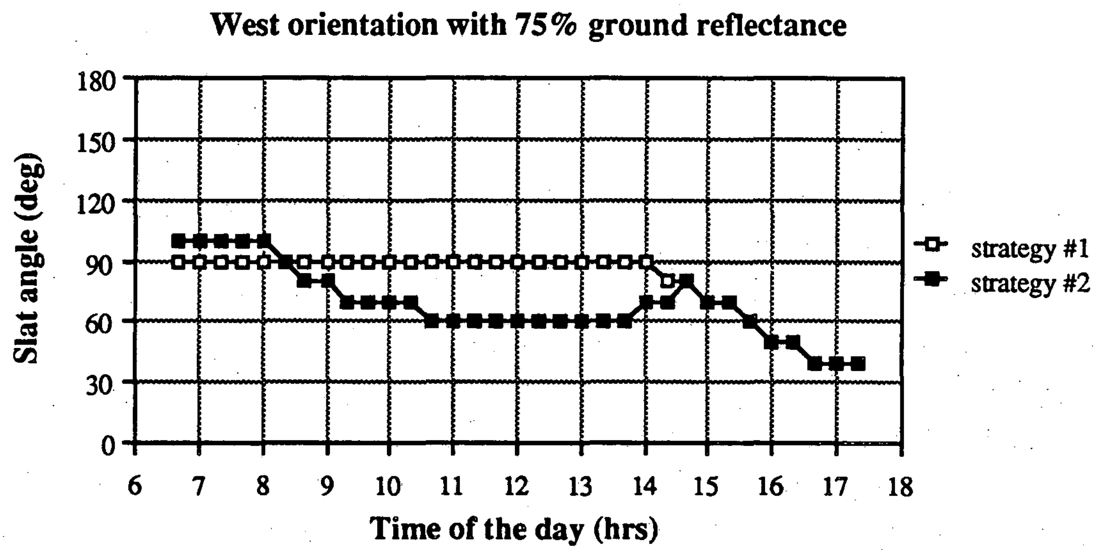

Figure 25. The resulting slat angles under control strategy #1 (maximization of view potential) and control strategy #2 (maximization of work-plane illuminance), for west orientation and 75% ground reflectance.

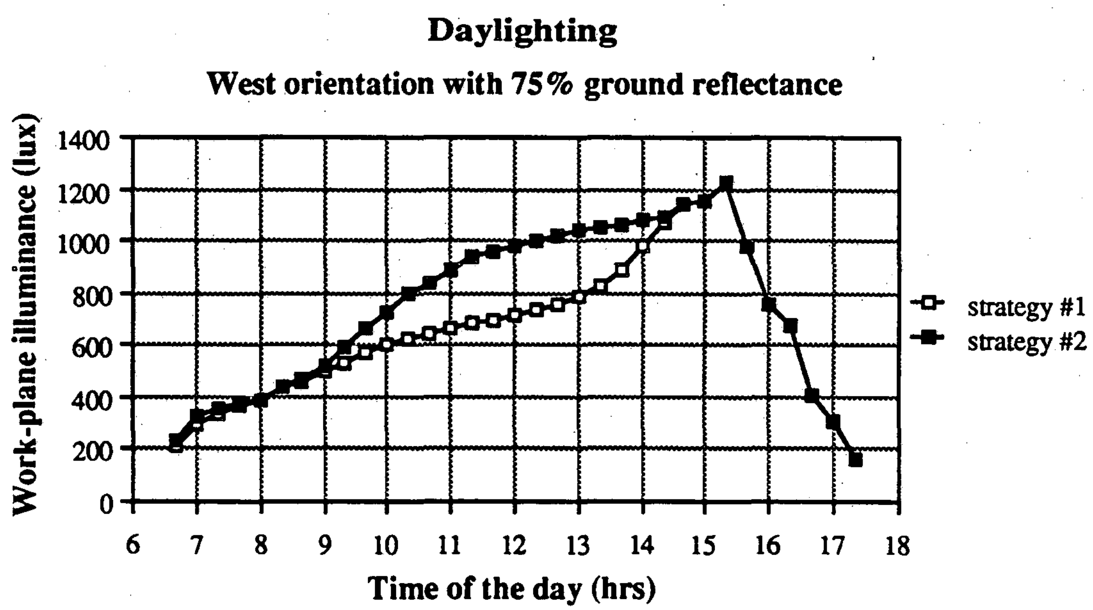

Figure 26. The resulting work plane illuminance due to daylighting under control strategy #1 (maximization of view potential) and control strategy #2 (maximization of work-plane illuminance), for west orientation and 75% ground reflectance.

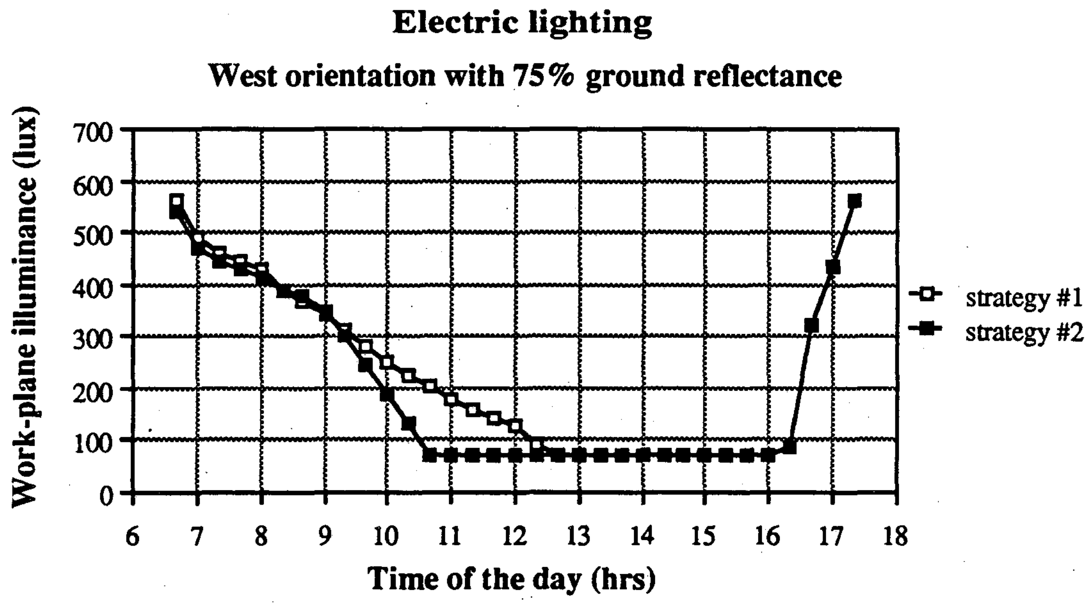

Figure 27. The resulting work plane illuminance due to electric lighting under control strategy #1 (maximization of view potential) and control strategy #2 (maximization of work-plane illuminance), for west orientation and 75% ground reflectance.

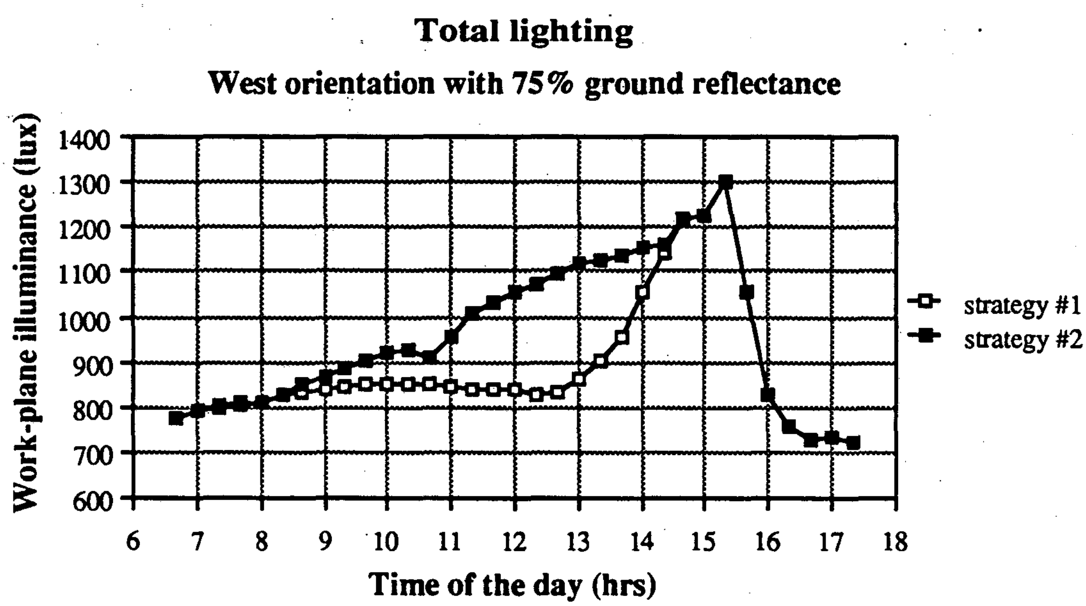

Figure 28. The resulting work plane illuminance due to daylighting and electric lighting under control strategy #1 (maximization of view potential) and control strategy #2 (maximization of work-plane illuminance), for west orientation and 75% ground reflectance.

Strategy #1

West orientation with 75% ground reflectance

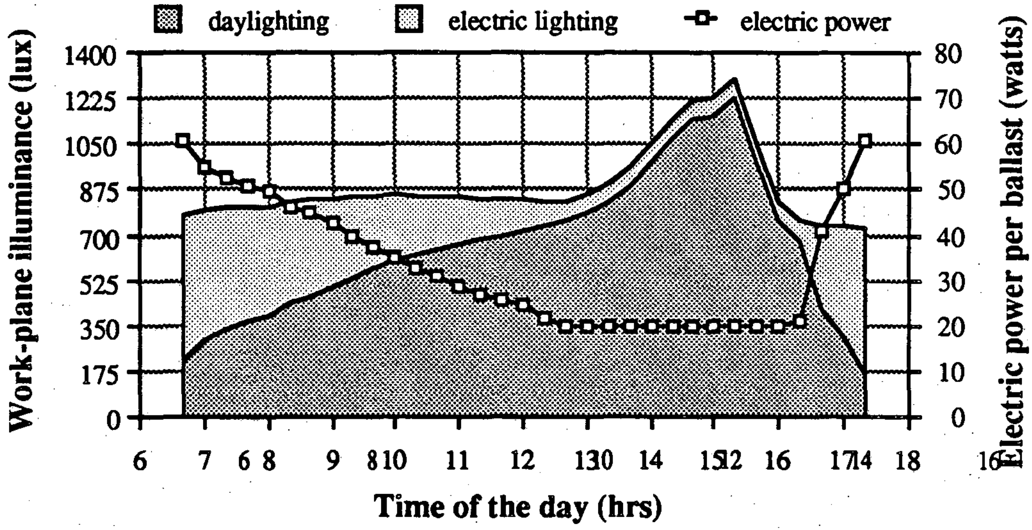

Figure 29. The resulting work plane illuminance and the input power to the electric lighting system under control strategy #1 (maximization of view potential), for west orientation and 75% ground reflectance.

Strategy #2

West orientation with 75% ground reflectance

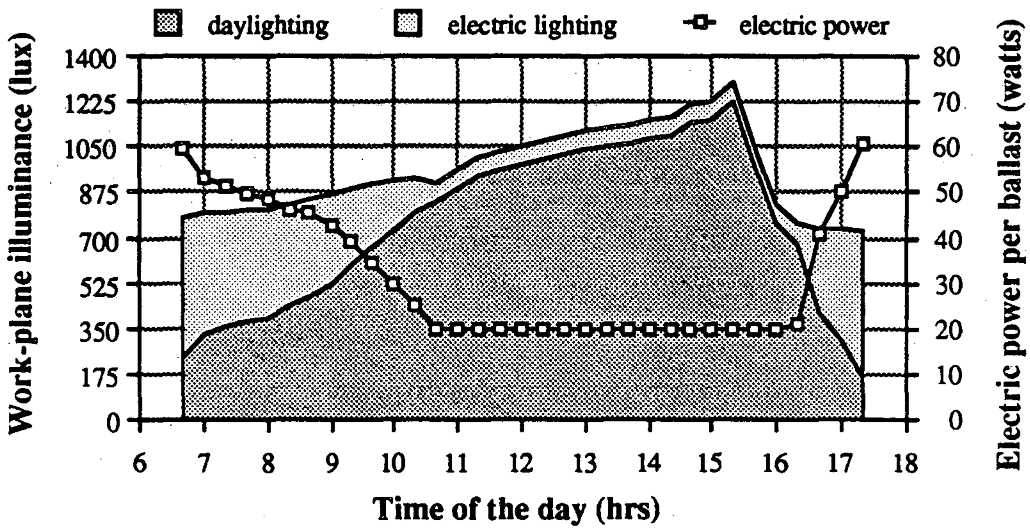

Figure 30. The resulting work plane illuminance and the input power to the electric lighting system under control strategy #2 (maximization of work-plane illuminance), for west orientation and 75% ground reflectance.

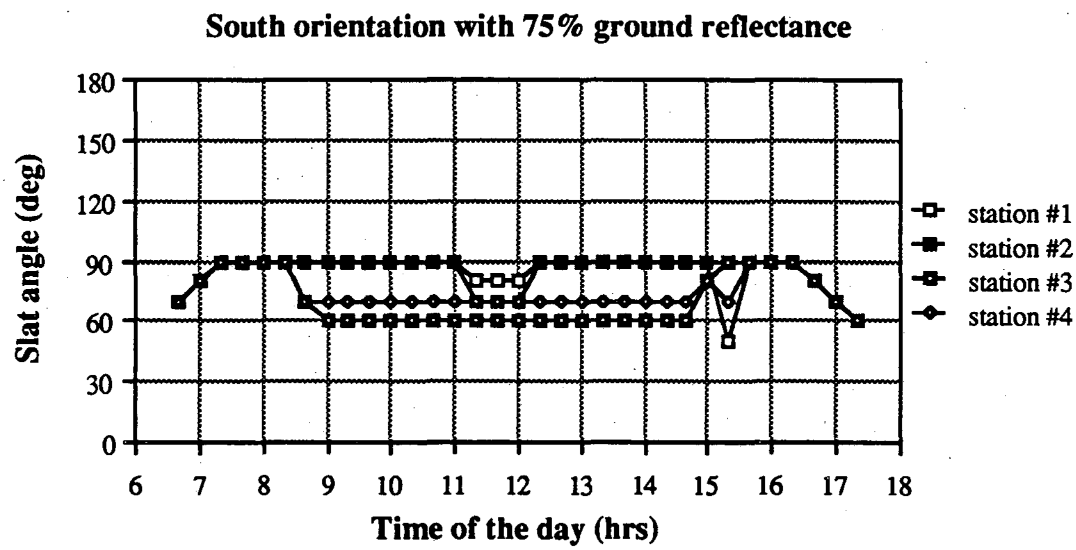

Figure 31. The resulting slat angles from control strategy #2, considering the different station points #1, #2, #3 and #4, at 4, 8, 12 and 16 ft away from the window.