The potential of simplified concepts for daylight harvesting

Short Title for Running Head: Simplified concepts for daylight harvesting

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Abstract

Daylighting systems offer tremendous potential for reducing the energy consumption of electric lighting, but their usage has been inhibited by high costs and imperfect performance of current technologies. This paper presents energy savings predictions for two proposed daylighting technologies, a daylight-sensing switch and an automatic blinds system, which employ simple, inexpensive components and designs. Assumptions of solar irradiance, blind position, blind operation behaviour, and light switching behaviour were combined with illuminance data and daylight factors to develop an algorithm for calculating the potential energy usages of six different systems in commercial private offices and open plan offices. Results show the combined usage of the proposed technologies perform with an average annual energy savings of 24% compared with manual switching and blinds operation in Albany, New York. Compared with a photosensor-operated dimming system, the proposed technologies combined show better performance during summer months. Comparisons also were made for the systems in six U.S. climatic regions.

1. Introduction

Daylight harvesting in commercial buildings is experiencing renewed interest in the United States, particularly in light of the environmental consequences of power generation, the desire for sustainable design, and current strains on the nation's power grid. The United States Department of Energy estimates that US commercial businesses use one-quarter of their total energy consumption for lighting.[1] Daylighting and its associated systems, therefore, offer the opportunity to reduce energy consumption and costs.

Commercial buildings in the United States house more than 6 billion m^2 (64 billion $ft.^2$) of lit floor space.[2] Most of these buildings are lit by fluorescent lighting systems. Estimates show between 30% and 50% of the spaces in these buildings have access to daylight either through windows or skylights.[3] The installation of technologies designed to take advantage of available daylight would be an appropriate energy-saving strategy that could potentially turn off millions of light fixtures for some portion of each day.

A number of technologies currently on the market are designed to either reduce energy use from electric lighting or increase the daylight penetration within a building while controlling glare. The energy-reducing systems typically employ a photosensor technology teamed with a dimming fluorescent lighting system, which reduces energy demand by dimming lights proportionally to the amount of daylight received at a reference plane. Unfortunately, most of these systems do not guarantee effective operation because daylight rarely penetrates uniformly into a building's interior. Daylight penetration can vary at adjacent workstations because individuals operate blinds or exterior obstructions block daylight. Additionally, each photosensor typically controls a number of light fixtures in a space, often resulting in areas that are too dark and others that are over-lighted. High initial costs for full dimming ballasts and difficulties with installing and commissioning photosensors also impede the installation of these systems in commercial buildings. Currently, dimming electronic ballasts represent a lackluster 1% share of the US fluorescent lamp ballast market.[4]

Systems that improve daylight penetration include light shelves, light pipes, controlled shades and blinds, and other active sun-tracking daylight delivery systems. Again, most of these technologies involve high initial and maintenance costs.

Problems with current daylighting systems combined with poor sales point to the need for new designs that are simple, low cost, and effective. But before product commercialisation can be considered, manufacturers need proven guarantees of performance; therefore, new daylighting system designs must demonstrate their expected energy savings before they go to market.

This paper presents an evaluation of the performance potential of two simplified daylighting concepts that improve daylight penetration and reduce energy consumption of electric lighting systems. An assumptions model and computer simulation were developed to evaluate and compare the energy savings of these concepts against existing lighting systems, described herein.

2. Simplified daylight harvesting product concepts

To improve upon existing systems, new designs for a simplified, low cost daylight harvesting system should meet the following goals:

- install easily for a retrofit, or incorporate simply into existing fixtures or daylighting-related products (e.g., window blinds)
- be inexpensive to manufacture
- achieve high energy savings
- not annoy occupants
- not incur high design costs.

Two technologies are proposed in this evaluation. The first is a device designed to reduce the energy consumption of electric lighting, called here the daylight switch. This device switches lights on or off in response to the amount of daylight illuminance. The second technology, an automatic blinds system, is a device that opens window blinds once per day, increasing the possibility of a well-lit task plane and thereby increasing the potential for lighting energy savings.

2.1 Description of the daylight switch

The proposed daylight switch is a device similar to a photosensor on a streetlight that will switch on and off the power to the ballast, depending on the availability of daylight.

The device would be programmed to turn the lights on when the illuminance on the photocell drops below a certain value, and turn lights off when the illuminance due to daylight reaches a higher cut-off value. This value could be adjustable depending on the user's needs. The advantages of such a device include:

- lower initial cost because of the integrated installation of the photosensor and a cheaper, non-dimming ballast

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- easy installation
- self-commissioning logic.

2.2 Description of the automatic blinds system

The proposed automatic blinds system is a device that opens window blinds once per day, either overnight or during lunch time. The blind-opening mechanism could either be a simple mechanical device or a solar-powered mini-motor programmed to activate during specific times of the day. The advantages of such a device include:

- complementary operation with other daylight harvesting systems already in use
- a design that makes use of the daylight that would have been lost
- potentially a simple and inexpensive add-on to window blinds technology
- easy installation and automatic operation
- manual operation possible at any time.

Studies have consistently shown that people close their window blinds to control unwanted glare from sunlight. Blind closure often happens at the beginning of the day, in anticipation of direct solar glare later on,[5] and people rarely reopen them once the glare condition has subsided.[6] These findings are further supported by Rea,[7] who found that manually controlled blind positions remain the same through the course of the day, and from one day to the next.

If sufficient daylight is available at the task plane, however, there is an increased probability that people will choose not to switch on their lights,[8] although this probability may be mainly determined by habitual behaviour,[9] daylight distribution,[8] and occupancy patterns,[10] rather than by daylight illuminance on the working plane.

The automatic blinds concept is designed to increase daylight at the task plane automatically, potentially reducing the chance that occupants will turn on electric lighting, yet still allow users the freedom to manually close (or open) the blinds when necessary. In essence, the blinds are designed to automatically open when people wouldn't otherwise think to open them. It is hoped that occupants will appreciate the view and environmental improvements the device offers and not close their blinds unless incident sunlight causes visual or thermal discomfort.

3. Comparative simulations

To quantify the benefits of the daylight switch and the automatic blinds concepts, computer simulations were run to compare the energy consumptions of the described products against existing systems for both open plan offices and private offices. The simulated systems employed various combinations of switching and dimming control and blinds control. The types of switching and dimming control included:

- daylight switch
- manual switching (private offices) and timed switching (open plan offices)
- perfect dimming (currently available daylighting systems that use photosensors and dimming ballasts, theoretically representing maximum energy savings).

The types of blinds control included manual blinds and the automatic blinds concept.

A base case system was established for energy savings comparisons. The private office base case used a combination of manual blinds operation with manual switching. The open plan office base case used a combination of manual blinds operation with timed switching.

To make a realistic comparison of energy consumptions for the six simulated lighting systems, the simulation model must take into account the amount of daylight available within a space. The level of daylight illuminance on a task plane was used in this model to determine when (and how much, in the case of a perfect dimming system) electric lighting is needed in a space to meet occupant needs, which in turn affects the total energy consumption. Numerous parameters work together to influence daylight availability; therefore, the authors, working from available literature, made assumptions about the key parameters affecting indoor daylight availability. These assumptions were used for the simulation algorithms.

3.1 Assumptions of parameters

Some of the parameters that influence system performance and the human interaction with these systems have been assumed based on data available in previous literature or, in some cases, the authors' logic and common sense. The assumptions in this model fall into three categories:

- daylight factor and solar irradiance data
- conditions under which occupants choose to open and close their blinds
- conditions under which occupants choose to switch their lights on and off.

3.1.1 Daylight factor and solar irradiance data assumptions

For this model, the authors used available sky illuminance data and developed assumptions for daylight factors and solar irradiance, all which influence the level of daylight illuminance on the task plane.

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Illuminance data

Horizontal diffuse illuminance represents the amount of light coming from the sky, excluding the sun, and arriving on a horizontal surface. To determine daylight illuminance on a task plane, this simulation used published data for the monthly average horizontal diffuse illuminance at every hour for both clear and overcast skies in six US cities.[11]

Daylight factor values

Although empirical data for typical daylight factors in offices do not exist, there is some consensus among designers and researchers for typical values. Daylight factor values vary depending on blind position and distance into a space from the window.

The authors assumed that there are two task areas in the daylight zone of open plan offices, one adjacent to the window (the "first row"), and another some distance back into the space (the "second row"). The daylight factors assumed by the authors for the two rows are shown in Table 1. The authors measured daylight factor values in typical offices to ensure that the chosen values were realistic. The daylight factor for private offices is considered the same as that of the first row of open plan offices.

The above daylight factor assumptions also were compared with measured daylight transmittance values. The diffuse daylight transmittance of lowered blinds with horizontal (open) slats under an overcast sky has been measured at 70% by Tregenza (see Appendix A).[12] The transmittance of closed blinds has been measured at 10%[12] and 15%.[13] This ratio of

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approximately 7:1 between open and closed transmittances matches closely with the difference between the “second row” figures ($3:0.4 \approx 7:1$) for blinds open and closed.

However, one may note that the authors’ assumed daylight factor in the first row with horizontal (open) slats (5%) is lower than predicted by Tregenza’s figure of 70% transmittance. This is because Tregenza’s figure is for the transmittance in all directions, whereas the transmittance downward from the blind to the first row desks is likely to be lower because the slats act to reduce the amount of light in this direction. The figure for the second row is as predicted by Tregenza (4% multiplied by 70% is approximately 3%). Hence, the daylight factors given in Table 1, being a combination of assumptions and non-statistically significant experimental data, are reasonable.

Irradiance data

Solar irradiance represents the amount of energy coming from the sun and a small area around the sun, and arriving on a surface inclined at right angles to the incident sunlight. Several researchers have found that solar irradiance correlates with occupants’ decisions to manually close their blinds. These decisions in turn affect the daylight factor and daylight illuminance on the task plane. Irradiance data is important for determining the times of day when blinds are closed by the occupant and times when blinds remain closed. To obtain the actual beam irradiance from the sun on an interior task plane, a number of factors are needed, including building orientation, the azimuth angle of the sun, and hourly irradiance data. After such values are obtained, the threshold value of irradiance—the point at which a person closes the blinds—is needed; however, this value currently is of debate. The most robust findings are those of Inoue et al.[14] corroborated by Reinhart and Voss,[6] who found that the likelihood of manual blind closure was closely related to the distance that unobstructed sunlight penetrates the interior (determined by the elevation and azimuth of the sun). However, it is not clear whether these results would apply to sunlight that is partially obstructed by an open but lowered window blind.

Instead, a much simpler approximation of the direct sun exposure was used. The authors assumed that window blinds on a specific façade would be closed at all times when there was direct solar radiation on that façade. It also was assumed that there would be no direct solar radiation on the north façades. Direct solar radiation would occur:

- at all times on the south façade
- only until 13:00 on the east façade
- only after 13:00 on the west façade.

Data on the hourly percentage likelihood of sunshine[11] were used together with the above assumptions to determine blind position. A summary of the daylight factors and solar irradiance assumptions can be found in Table 2.

3.1.2 Blinds opening and closing assumptions

Unfortunately, occupant use of manual blinds is not well-understood, and occupant responses to automatic blind control systems seem to be very complex.[6] It is conceivable that some occupants may adopt the habit of closing their blinds every day on arrival, and that some may choose to close their blinds preemptively if the sky is clear in the morning.

In considering the proposed automatic blinds design, products installed in west and south façade windows would start the day open, and products installed in east façade windows would start the afternoon open, after the sun has moved off the façade. Again, occupants may close the automatic blinds at any subsequent time. Therefore, the amount of lighting energy that could potentially be saved depends on how long those blinds are likely to remain open during the day compared with manual blind use behaviour.

The authors used the above assumptions about solar irradiance for this model and assumed that occupants would not close their blinds until direct sunlight was incident through their windows. Once the blinds were closed, it was assumed that occupants would not re-open them. Further, occupants would not raise their blinds, but rather they would leave them in the lowered position and only control the slat angle.

This model calculates the hourly blind closure probability for each month based on the above assumptions about solar radiation on the façade. Blind position in turn determines the daylight factor and the daylight illuminance on the task plane. A summary of the blind operation assumptions can be found in Table 2.

3.1.3 Switching and dimming control assumptions

Three types of assumptions are involved with lamp switching and dimming: space type, occupant switching behaviour, and illuminance values used by automated switching and dimming systems.

In this simulation, the authors assumed that manual light switching was applicable only to private offices; open plan offices were assumed to have a timed switch control in the absence of the daylight switch or the perfect dimming systems. A timed switch keeps the lights on all the time when the office is occupied, allowing no manual control.

In the case of private offices, manual control is possible. Consequently, it simply was assumed that occupants with manual control would switch their lights on if the daylight illuminance in their task area were less than 400 lux. It also was assumed that occupants would not switch their lights off again at any time during the working day. However, it was assumed that someone – either individual occupants, a designated person, or a time clock – would switch off the lights at the end of the working day. This model results in a moderate seasonal variation in electric lighting use, determined by daylight levels at the beginning of the working day. Such variations have been found by field studies of manual light switching, including those of Moore et al.[15] who found that summertime electric lighting loads averaged 51% while winter loads averaged 60%.

The daylight switch system employed in this model operates on a simple logic that turns the lights on when task daylight illuminance is less than 400 lux and turns the lights off when the task daylight illuminance is greater than 600 lux. With the perfect dimming system, the electric light dims in response to the task illuminance level, maintaining it at a minimum of 400 lux. Studies show that most dimming ballasts can dim lamps to less than 20% of maximum light output.[16] Hence, it was assumed that even if the daylight illuminance were greater than 400 lux, the dimming system would use a minimum (15%) of energy at all times it is on.

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A summary of the switching and dimming control assumptions can be found in Table 2.

3.2 Occupancy times

In most organizations, employees no longer all arrive and leave at the same time of day; some latitude is to be expected, due to variations in workload, personal preference, and non-work commitments. Consequently, most buildings are partially occupied for a long period, as opposed to being fully occupied for a shorter period, as would have been the case in the past. The decline in the proportion of workers conducting purely clerical tasks also means that many people work longer hours than in previous decades. This model, therefore, assumes that a building will be occupied between 08:00 and 18:00.

3.3 Calculation process

The authors used the data and assumptions described to calculate and compare the energy consumptions of six systems: manual blinds and manual or timed switching (base case); the daylight switch; the automatic blinds system; the daylight switch plus the automatic blinds; perfect dimming; and perfect dimming plus the automatic blinds. The comparison simulation used algorithms (Appendix C) developed in Microsoft Excel using "IF" and "THEN" statements. The calculation was completed in Excel in the following three steps:

1) Determination of blinds position:

The monthly average probability of blinds being open at every occupied hour was calculated using the assumptions of irradiance data, manual blinds operation, and automatic blinds operation. (See Appendix B for details.)

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2) Determination of lamp switching and dimming states:

The monthly average horizontal diffuse illuminance data at every occupied hour for clear and overcast skies,[11] the assumptions on daylight factor, and the type of switching system were used to calculate the switching or dimming state of the lights for fully closed and fully open blinds. (See Appendix C for details.)

3) Determination of energy consumption:

The monthly average energy consumption value for every occupied hour was calculated based on the respective hour's "open blind" probability and the switching or dimming state. This could be any value between 0, representing no energy consumption, and 1, representing the maximum energy consumption of the installed electric lighting capacity. (See Appendix D for details.)

4. Results

The results in Table 3 indicate the predicted annual lighting energy consumption for each simulated system, as a proportion of the installed lighting capacity. These consumption values are based on horizontal daylight illuminance data for Albany, New York. To estimate energy savings, compare the energy consumption for each scenario with the energy usage for the base case.

Figure 1 shows the average annual lighting energy consumption of each system for both open plan offices (first and second rows averaged) and private offices (represented by first row data only) for Albany, New York. The proposed automatic blinds system shows considerable savings in private offices but no savings with open plan offices, because lights turn off with a timed switch in these spaces, not in response to daylight. The perfect dimming system with the automatic blinds shows the most savings, followed by the perfect dimming system alone. The combination of the daylight switch and the automatic blinds shows considerable savings over the base case, compared with the use of either one of these technologies alone.

Figure 2 shows the average monthly lighting energy consumption values using the different combination of systems for a private office in Albany, New York. All systems seem to perform better in the summer months, as expected, because of the increased availability of daylight. The use of the daylight switch, the automatic blinds, and the combination of both offer no significant savings over the base case in the winter months, while in summer they provide significant savings. The use of the automatic blinds with a perfect dimming system shows consistent savings throughout the year compared with the use of a perfect dimming system alone.

Figures 3 and 4 show that the automatic blinds system by itself offers no lighting energy savings in the north façade for private offices or for any façade in an open plan office. However, it does show a considerable energy-savings potential in the east and west façades for private offices. The daylight switch by itself does not show much energy savings in any façade, except for the north façade in an open plan office. When the automatic blind system is used with the daylight switch, considerable energy-savings is possible in the east and west façades of both open plan and private offices.

An extension of the model for different climatic zones in the United States was also completed to further understand the benefits of the daylight switch and the automatic blinds systems. The lighting energy savings using these devices compared with one another is almost in the same proportion for all the cities evaluated, as shown in Figure 5. The highest energy savings for all devices is in Charleston, South Carolina because of higher horizontal diffuse illuminance availability in both clear and overcast sky conditions. A southern city with the most cloudy sky seems to have the highest energy savings using these devices. One should bear in mind that the changes in lighting energy consumption will affect annual whole-building energy consumption (including heating and air conditioning) in ways that depend on that region's climate.

5. Discussion

The relative magnitude of each result compared with the other systems is as would be expected; the different scenarios seem to be in the correct order of energy savings. This suggests that the model is internally valid, and that the relative magnitudes can be taken as indicative. However, the absolute magnitude of the energy savings must be compared with values found in real buildings and by other researchers in order to be validated.

No field studies of annual energy consumption from different combinations of switching systems and blind mechanisms have been found. Therefore, it is only possible to compare the results of this model with the results of similar algorithmic models of lighting energy consumption. However, the large number of assumptions made in any model, and the slim chance of other models sharing those same assumptions, makes comparisons between models very loose. Two existing daylighting models were chosen for a comparison of results.

5.1 Comparison with Reinhart (2002) model

Reinhart's study[17] uses a radiance-based model in conjunction with real hourly beam and diffuse irradiances to determine daylight levels throughout the year in a simulated office. Reinhart's main intention was to investigate the effect of variables such as partition height, ceiling height, and surface reflectances, although four different blind control strategies were incorporated into the model, as follows:

1. Blinds permanently raised (i.e., as if no blind were present), unlike the authors' model in which "open" blinds are lowered with slats horizontal.
2. Fully automatic blinds, normally kept in the raised position, but lowered with a slat angle of 45° if beam irradiance exceeds 50 W/m^2.
3. Manual blinds lowered with a slat angle of 45° if beam irradiance exceeds 50 W/m^2. Once lowered, blinds remain lowered until raised the following morning.
4. Blinds permanently lowered with a slat angle of 45°.

Reinhart does not state the blind transmission values or daylight factors used in the model.

5.2 Comparison with Newsham (1994) model

Newsham used an ad-hoc model, probably based on daylight factors, to predict interior lighting levels.[18] Newsham assumed that occupants would switch their lights on if the interior light level were less than 150 lux, but he did not state what type of daylight data were used in the model.

Newsham, following Inoue and colleagues[14] to some degree, assumed that occupants would close their blinds if the beam irradiance exceeded 233 W/m^2. Newsham used four blind control strategies, similar to Reinhart's study:

1. Blinds permanently raised.

2. Manual blinds – Occupants opens their blinds in the morning and close them during the day if beam irradiance exceeds 233 W/m^2. Once closed, blinds remain closed.

3. Blinds permanently open November through March and permanently closed April through October (the "seven month strategy").

4. Blinds permanently closed.

Newsham does not state the daylight factors used in the model. A summary of the assumptions from Reinhart, Newsham, and the authors' model can be found in Table 4.

5.3 Comparison of predicted energy savings

Table 5 shows the predicted energy savings comparisons for Reinhart's model and the authors' model. Reinhart's values for the first row seem to match closely with the values from the model described in this paper. There are some differences between this model and Reinhart's that account for the minor differences in the first row and some major differences in the second row predictions: Reinhart's dimming system maintains 500 lux rather than 400 lux; Reinhart allows a 1.22 m (4 ft.) aisle between the first and second rows of workstations, includes 1.63 m (64 in.) solid office partitions, and assumes that second row desks are at the corner of the work area furthest from the window. Hence, Reinhart's second row desks are typically 6.10 m (20 ft.) from the window. This would yield a much lower daylight factor than the 3% assumed in this model. The difference in daylight factor accounts for the proportionately large difference between the figures for first and second row energy savings.

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Table 6 shows the predicted energy savings comparisons for Newsham's model and the authors' model. Newsham does not state any assumptions regarding daylight factor, but because the values are slightly higher, it seems likely that he assumes a figure slightly higher than 4%.

The comparison with Reinhart's and Newsham's models seems to validate the approach used in the authors' model. Hence, the predictions from the model described in this paper can be used as a hypothesis for a field evaluation.

6. Conclusions

The predictions offered here illustrate that simplified daylight harvesting systems, such as the proposed daylight switch and automatic blinds systems, have the potential to provide energy savings, if installation and potential for a given space are considered carefully. At times, the daylight switch and the automatic blinds may serve as a replacement to the existing, more expensive perfect dimming system, or as a complement to the existing system to increase efficiency. For example, the combined use of the daylight switch and the automatic blinds shows greater energy savings during some summer months than the perfect dimming system alone. The use of the automatic blinds with the perfect dimming system gives more than a 15% increase in energy savings compared with the use of just the perfect dimming system. The numbers in Table 3, however, show that the use of the automatic blinds system in the north façade does not improve energy savings, even when combined with other switching systems. Hence, the results from this model should be interpreted differently for different cases or applications. If the performance of the daylight switch and the automatic blinds systems in reality is as predicted in this model, it is likely that the energy savings of these systems compared with the perfect dimming system will be better than this model's calculations. This model assumes a perfect dimming system with flawless operation, which rarely exists in reality. The success of these systems also depends greatly on how inexpensively they can be manufactured, sold, and installed. It is expected that the combined cost, installation, and maintenance of the daylight switch and the automatic blinds will be significantly less than that of the perfect dimming system because of their simplified technology.

The model described here has been developed based on a certain set of assumptions on daylight values, responsive occupant behaviour, and dimming and switching settings. The idea of these assumptions is to simplify the complex daylight calculations. Hence, specific cases will have differences from the model assumptions, and these have to be accounted for in the field. The numbers generated by this model are indicative of the relative energy-saving potential of the two systems. The absolute magnitude of savings will depend to a great degree on how the systems are used and accepted by occupants, and on the baseline energy consumption of manual systems in real buildings, which remain largely unquantified and unpredictable. Both of these factors can be expected to vary significantly from one building to another. Further understanding of behavioural factors is a prerequisite for predicting lighting energy savings at the design stage.

7. References

1. EIA. Annual energy outlook 2001 with projections to 2020. DOE/EIA-0383. Washington, DC: Energy Information Administration, 2001.
2. EIA. 1999 Commercial buildings energy consumption survey: Building characteristics tables. Washington, DC: Energy Information Administration, 2002. (Retrieved from http://www.eia.doe.gov/emeu/cbecs/pdf/alltables.pdf. Accessed January 22, 2004.)
3. Bierman A, Conway KM. Characterizing daylight photosensor system performance to help overcome market barriers. *Journal of IES* 2000; 29(1): 101-115.
4. US Census Bureau. Fluorescent lamp ballasts: Third quarter 2003. Current Industrial Reports, MQ335C(03)-3, 2003.
5. Lindsay CRT, Littlefair PJ. Occupant use of venetian blinds in offices. 1993: PD 233/92. Watford, Building Research Establishment.
6. Reinhart CF, Voss K. Monitoring manual control of electric lighting and blinds. *Lighting Res. Technol.* 2003 ; 35(3): 243–260
7. Rea MS. Window blind occlusion: A pilot study. *Building and Environment* 1984; 19(2): 133-137.
8. Hunt DRG. Predicting artificial lighting use: a method based upon observed patterns of behaviour. *Lighting Res. Technol.* 1980; 12: 7–14.
9. Love JA. Manual switching patterns observed in private offices. *Lighting Res. Technol.* 1998; 30: 45–50.
10. Pigg S, Eilers M, Reed J. Behavioural aspects of lighting and occupancy sensors in private offices: a case study of a university office building. *Proceedings of the 1996 ACEEE Summer Study on Energy Efficiency in Buildings* 1999; 8: 8.161–8.171

11. Robbins CL. *Daylighting: Design and analysis*. New York: Van Nostrand Reinhold, 1986.

12. Tregenza PR. Personal communication with author O Howlett. 17 June 2003.

13. Fusco G, Macrelli G, Polato A, Rossi G. Variable angle photometric characterization of a laminated glass embedding a lamellae system. *Solar Energy* 1999; 66(6): 423-438.

14. Inoue T, Kawase T, Ibamoto T, Takakusa S, Matsuo Y. The development of an optimal control system for window shading devices based on investigations in office buildings. *ASHRAE Transaction* 1988; 94: 1034-1049.

15. Moore T, Carter DJ, Slater AI. A field study of occupant controlled lighting in offices. *Lighting Res. Technol.* 2002: 34(3): 191–205.

16. National Lighting Product Information Program. *Specifier reports: Dimming electronic ballasts.* Troy, NY: Lighting Research Center, 1999.

17. Reinhart CF. Effects of interior design on the daylight availability in open-plan offices. National Research Council Canada, Internal Report NRCC-45374. Ottawa: National Research Council Canada, 2002. (Retrieved from http://irc.nrc-cnrc.gc.ca/fulltext/nrcc45374/. Accessed October 28, 2003.)

18. Newsham GR. Manual control of window blinds and electric lighting: Implications for comfort and energy consumption. National Research Council Canada, Internal Report NRCC-37021. Ottawa: National Research Council Canada, 1994. (Retrieved from http://irc.nrc-cnrc.gc.ca/fulltext/nrcc37021/nrcc37021.pdf. Accessed October 30, 2003.)

8. Appendices

Appendix A – Measured transmittance values

Table 7 shows the measured transmittance values (daylight factor) for different slat angles of blinds, as measured by PR Tregenza.[12] Total flux transmittance is for white Venetian blinds.

Values were measured in Sheffield, UK, under non-sunny conditions. A full-size test window with various types of blinds and an identical control window without blinds were covered internally with matte white rectilinear boxes. The light reflected from these interior surfaces was recorded using an array of photocells. Continuous measurements were made over periods of several weeks, April through June 2000.

The asymmetric distribution of transmittance occurs because the flux falling on the window is asymmetric. The effective transmittance of a blind varies with ground reflectance and many other factors. The values in the table are typical of windows with small external obstruction and 0.2 ground reflectance. With high external obstruction, the asymmetry would increase.

(Details obtained by direct correspondence with PR Tregenza by O Howlett, 17 June 2003.)

Appendix B – Determination of blinds position

The blind positions were determined based on the assumptions in 3.1.1 and 3.1.2 regarding direct solar radiation on the façade and the manner in which manual and automatic blinds operation responds to those assumptions. A summary of the blind assumptions is in Table 2. Based on these assumptions, the probability of the blinds being open was determined separately for sunny, clear days (C) and overcast days (O). The probability of blinds being open at a given hour (PC) on any day for a specific month was calculated using the monthly average sun availability data (Sp) for every occupied hour,[11] as shown in Eq. 1:

$$Pc = (C * Sp) + (O * (1 - Sp)) \qquad \text{(Eq. 1)}$$

where:

Sp = percentage availability of sun (clear sky) at that hour

C = probability of "open blinds" at a clear sky hour

O = probability of "open blinds" at an overcast hour

Pc = combined probability of "open blinds" at any given hour

The value of 1 represents a 100% probability that the blinds are open, and 0 represents a 0% probability that the blinds are open, as in the example given in Table 8. The combined "open blind" probability value for every hour was determined for both manual blinds and automatic blinds calculations, and that value was used to calculate the daylight illuminance at the task plane for that hour.

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Appendix C – Determination of lamp switching and dimming states

The monthly average switching and dimming states for every occupied hour were determined separately for completely open and completely closed blinds for three types of control systems: manual switching, the daylight switch, and the perfect dimming system. In the case of timed switching, the lights are always on during the occupied hour. This calculation was completed for a private office or first row of an open plan office (same value used for each) and for the second row of an open plan office.

The calculation process used conditional "if" statements based on the horizontal diffuse illuminance data outdoors (separately for clear and cloudy skies)[11] and the task area daylight factor for a given blind position. The calculated value for clear and cloudy sky data was then averaged based on the hourly sun availability data. The switching state value would be 0 for "off" and 1 for "on." The dimming state could be a fraction between 0.15 (minimum energy consumed with the dimming ballast) and 1, representing fully "on." The algorithms for the three control systems are described in Figures 6 – 8 . The algorithm variables include:

E_{task} = daylight illuminance on the task area

Ed = diffuse horizontal illuminance from daylight, outdoors

DF_{open} = daylight factor for the task area when blinds are open

DF_{closed} = daylight factor for the task area when blinds are closed

$E_{mswitch}$ = task illuminance at which occupants manually switch their lights on

$E_{switch\text{-}on}$ = task illuminance at which the system switches lights on (400 lx)

$E_{switch\text{-}off}$ = task illuminance at which the system switches lights off (600 lx)

P = proportion of installed power required by the ballast

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Em = maintained illuminance

Manual switching

Figure 6 describes the calculation process to determine the switching state with manual switching when the blinds are open. This algorithm is repeated for the “blinds closed” state separately for every occupied hour.

Daylight switch

Figure 7 describes the calculation process to determine the switching state with the daylight switch when the blinds are open. This algorithm is repeated for the “blinds closed” state separately for every occupied hour.

Perfect dimming system

Figure 8 describes the calculation process to determine the dimming state with a perfect dimming system when the blinds are open. This algorithm is repeated for the “blinds closed” state separately for every occupied hour.

Appendix D – Determination of energy consumption

Once the switching or dimming state for every hour has been determined, it is possible to calculate the hypothetical lighting energy consumption figures for every façade orientation using the “open blind” probability value for that façade in that hour. The switching or dimming state value for a private office is considered the same as that of the first row in an open plan office.

The predicted lighting energy consumption for a particular façade and row is given by Eq. 2:

$$\text{Total energy consumption} = (Pc * S_{open}) + ((1-Pc) * S_{closed}) \qquad \text{(Eq. 2)}$$

where:

Pc = “open blind” probability

S_{open} = Switching or dimming state for that façade with open blinds

S_{closed} = Switching or dimming state for that façade with closed blinds

Thus, the monthly average energy consumption was calculated for every occupied hour and for all months in a year. This value was then used to determine the overall average monthly energy consumption for all months (Figure 2) and the average yearly energy consumption with the combination of systems (Figure 1).

9. Tables

Table 1 Daylight factors for open plan offices.

Task Area Daylight Factors	First Row	Second Row
Blinds open, lowered, slats horizontal	5%	3%
Blinds closed, lowered, slats vertical	1%	0.4%
Unobstructed window	10%	4%

Table 2 Summary of values and assumptions used in this simulation model.

Irradiance and Illuminance Data		
Daylight factors	First Row and Private Office	Second Row
Blinds lowered, slats horizontal (open)	5%	3%
Blinds lowered, slats angled (closed)	1%	0.4%
Direct solar radiation on a clear sunny day		
North façade	At no time	
East façade	Morning until 13:00	
West façade	From 13:00 until evening	
South façade	At all times	

Blinds Opening and Closing

Manual blinds
- North blinds are always open
- South, east, and west blinds start the day open on 50% of the days when the sun is not on the façade
- Once blinds are open, they stay open for the day unless the sun comes on the façade
- Blinds are closed whenever the sun is on the façade
- Once blinds are closed, they stay closed for the day

Automatic blinds
- North blinds are always open
- South and west blinds start the day open
- East blinds start the day open on 100% of the days when the sun is not on the façade, and are always open in the afternoon
- Once blinds are open, they stay open for the day unless the sun comes on the façade
- Blinds are closed whenever the sun is on the façade.
- Once blinds are closed, they stay closed for the day, except on the east side where they open in the afternoon

Switching and Dimming Control

Manual switch control in private offices
- Occupant turns on the lights when daylight illuminance is <400 lux on the task plane at any hour
- Occupant does not turn on lights when daylight illuminance >400 lux on the task plane in the morning
- Occupant never turns lights off
- Lights are automatically turned off at 18:00 every day

Timed switch control in open plan offices
- Lights are on all the time (08:00 to 18:00)

Daylight switch
- Turns on lights when daylight illuminance <400lux on the task plane
- Turns off lights when daylight illuminance >600 lux on the task plane
- Lights are automatically turned off at 18:00 every day

Dimming systems
- Dims light level up and down to maintain 400 lux at the task plane
- Minimum power consumption is at least 15% of full power
- Lights are automatically turned off at 18:00 every day

Table 3 Predicted annual energy consumption values for the different systems in Albany, New York. (1 = highest level of possible energy consumption)

	Private office					Open plan (average of first and second rows)				
Façade	East	South	West	North	Average of all facades	East	South	West	North	Average of all facades
Manual blinds + Manual switching	0.95	0.95	0.86	0.54	0.82	1.00	1.00	1.00	1.00	1.00
Automatic blinds	0.71	0.89	0.71	0.54	0.71	1.00	1.00	1.00	1.00	1.00
Daylight switch	0.92	0.92	0.83	0.49	0.79	0.95	0.95	0.88	0.63	0.85
Daylight switch + Automatic blinds	0.67	0.84	0.66	0.49	0.66	0.76	0.89	0.76	0.63	0.76
Perfect dimming	0.69	0.69	0.60	0.25	0.56	0.76	0.76	0.67	0.32	0.63
Perfect dimming + Automatic blinds	0.43	0.61	0.42	0.25	0.43	0.50	0.68	0.49	0.32	0.50

Table 4 Summary of assumptions for this model and comparison models.

	This model	Reinhart	Newsham
Working hours	08:00-18:00	08:00-18:00	08:00-17:00
Automatic blind operation	• North blinds always open • South and west blinds start the day open. • East blinds start the day open on 100% of days when the sun is not on the façade, and are always open in the afternoon • Once blinds are open, they stay open for the day unless the sun comes on the façade • Blinds are closed whenever the sun is on the façade. • Once blinds are closed, they stay closed for the day, except on the east side where they are open in the afternoon	Automatic system raises and lowers blinds when sun shines	Not considered
Manual blind operation	• North blinds always open. • South, east, and west blinds start the day open on 50% of the days when the sun is not on the façade • Once blinds are open, they stay open for the day unless the sun comes on the façade • Blinds are closed whenever the sun is on the façade. • Once blinds are closed, they stay closed for the day	"Manual" control assumes that users open their blinds at the beginning of the day and close them for the rest of the day when the sun shines	"Manual" control assumes that users open their blinds at the beginning of the day and close them for the rest of the day when the sun shines
Automatic lighting controls	*Daylight switch* • Turns on lights when daylight illuminance <400lux on task • Turns off lights when daylight illuminance >600 lux on task *Perfect dimming* • Dims light level up and down to maintain 400 lux at task • Minimum power consumption is at least 15% of full power	The dimming system maintains 500 lux on the task area	Not considered
Manual switching control	• Occupant turns on the lights when light daylight illuminance <400lux on task at any hour • Occupant does not turn on lights when daylight illuminance >400 lux on task in the morning. • Occupant never turns lights off • Lights are automatically turned off at 18:00 every day	Not considered	• Only one user in the space, who may sit 1.25 m to 6.25 m from the window • At 08:00 and 13:00, user switches lights on if DL<150 lux, and off if DL>150 lux.
Timed switching control	Keeps the lights on from 08:00 to 18:00	Keeps the lights on from 08:00 to 18:00	Keeps the lights on from 08:00 to 17:00

Blinds	• Transmittance 10% when fully closed • Blinds are assumed always to be in the lowered rather than the raised position	• Transmittance 15% when closed. • Blinds raised up and down; when down, slats are angled at 45°	Transmittance 20% when closed
Daylight factor	• 5% in the first row with blinds open; 1% with blinds closed • 3% in second row with blinds open; 0.4% with blinds closed	15% first row; unspecified second row	Overall space 2.7% average daylight factor; no specific DFs mentioned

Table 5 Comparison of energy savings for automatic and manual blinds in conjunction with a perfect dimming system, using Reinhart's model and the authors' model.

Comparison of savings	Reinhart's algorithm with perfect dimming	This model, with perfect dimming
Automatic blinds 1st row	57%	57%
Automatic blinds 2nd row	27%	43%
Manual blinds 1st row	48%	44%
Manual blinds 2nd row	23%	30%

Table 6 Comparison of energy savings for manual blinds in conjunction with a manual switching system, using Newsham's model and the authors' model.

Comparison of savings	Newsham's "manual" blind algorithm with manual light switching	This model, manual blind opening, manual switching
1st row	23%	18%
2nd row	9%	6%

Table 7 Measured transmittance values (daylight factor) for different slat angles of white Venetian blinds, as measured by PR Tregenza.[12]

Louvre angle, degrees *(-ve when louvres slope upwards to outside)*	Transmittance *(flux through window with blind)*
fully closed	.10
-75	.24
-60	.47
-45	.68
-30	.77
-25	.78
-15	.77
0	.70
15	.51
30	.31
45	.20
60	.12
75	.07
fully closed	.05

Table 8 Hourly “open blind” probability calculation for Albany, New York. (1 = 100% probable open position [fully open], 0 = 0% probable open position [fully closed].)

	Clear				Overcast					Combined			
Hour	North	East	South	West	North	East	South	West	sun%	North	East	South	West
8	1	0	0	1	1	1	1	1	0.59	1	0.41	0.41	1
9	1	0	0	1	1	1	1	1	0.59	1	0.41	0.41	1
10	1	0	0	1	1	1	1	1	0.64	1	0.36	0.36	1
11	1	0	0	1	1	1	1	1	0.66	1	0.34	0.34	1
12	1	0	0	1	1	1	1	1	0.66	1	0.34	0.34	1
13	1	1	0	0	1	1	1	1	0.66	1	1	0.34	0.34
14	1	1	0	0	1	1	1	1	0.66	1	1	0.34	0.34
15	1	1	0	0	1	1	1	1	0.66	1	1	0.34	0.34
16	1	1	0	0	1	1	1	1	0.66	1	1	0.34	0.34
17	1	1	0	0	1	1	1	1	0.66	1	1	0.34	0.34

10. Figures

Fig. 1: Annual energy consumption using different systems for open plan and private offices in Albany, New York.

Fig. 2: Average monthly energy consumption for a private office in Albany, New York.

Fig. 3: Percentage of energy savings for different systems over the base case for each façade in a private office (Albany, New York).

Fig. 4: Percentage of energy savings for different systems over the base case for each façade in an open plan office (Albany, New York).

Fig. 5. Energy savings of different systems in an open plan office over the base case for six US cities.

Fig. 6. Calculation process used to determine the manual switching state for every hour on any façade.

Fig. 7. Calculation process used to determine the switching state of the daylight switch for every hour on any façade.

Fig. 8. Calculation process used to determine the perfect dimming state for every hour on any façade.

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Figure 1

Annual energy consumption using different systems for open plan and private offices in Albany, New York.

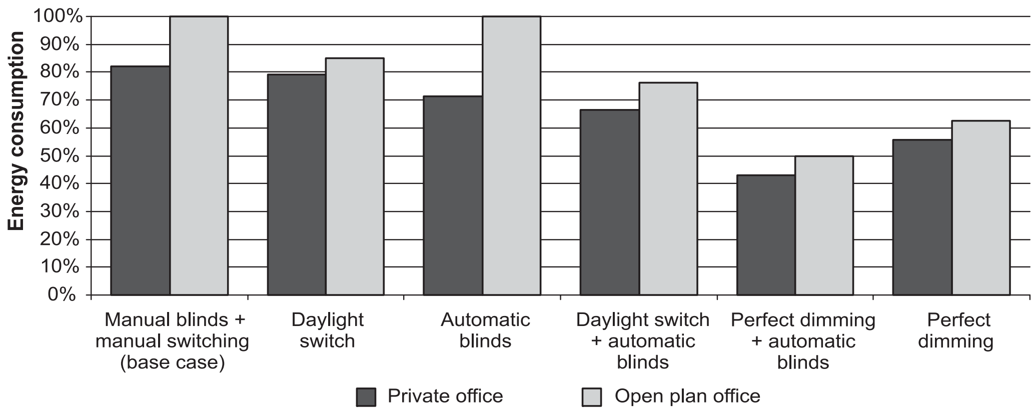

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Figure 2

Average monthly energy consumption for a private office in Albany, New York.

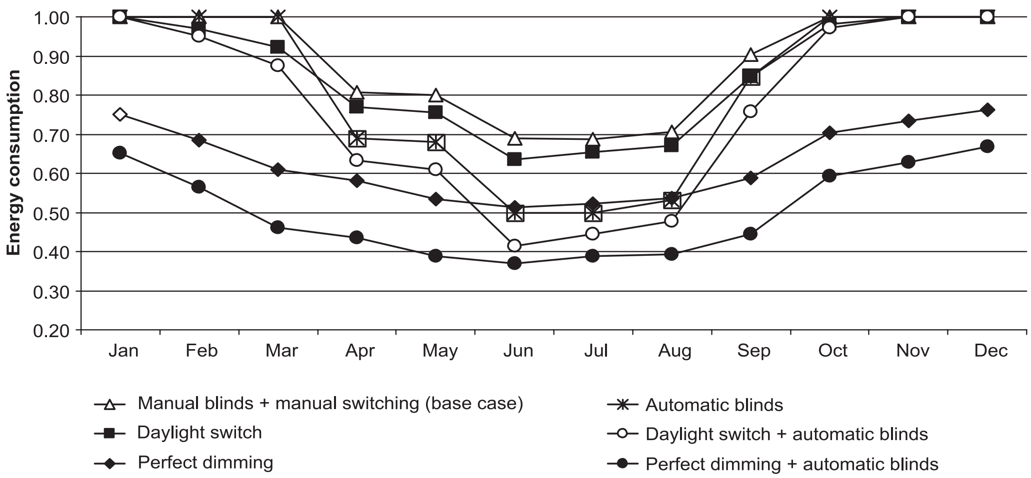

Figure 3

Percentage of energy savings for different systems over the base case for each façade in a private office (Albany, New York).

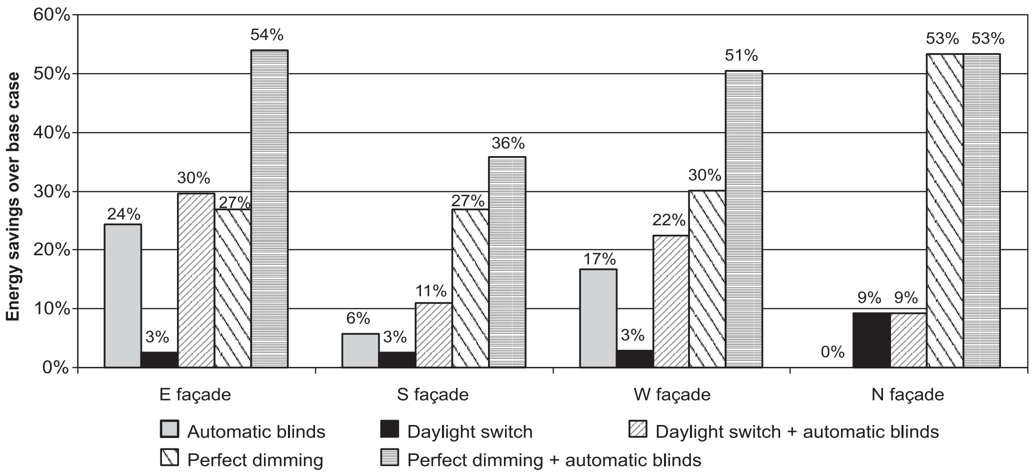

Figure 4

Percentage of energy savings for different systems over the base case for each façade in an open plan office (Albany, New York).

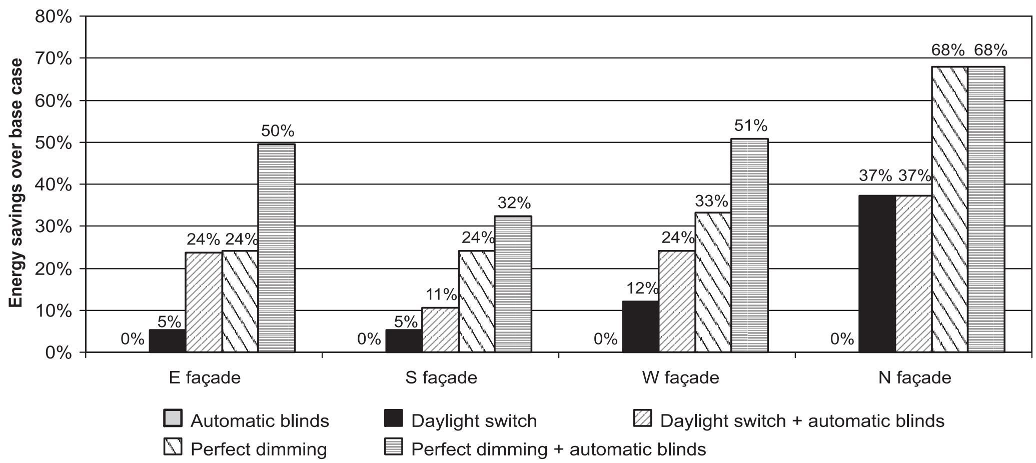

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Figure 5

Energy savings of different systems in an open plan office over the base case for six US cities.

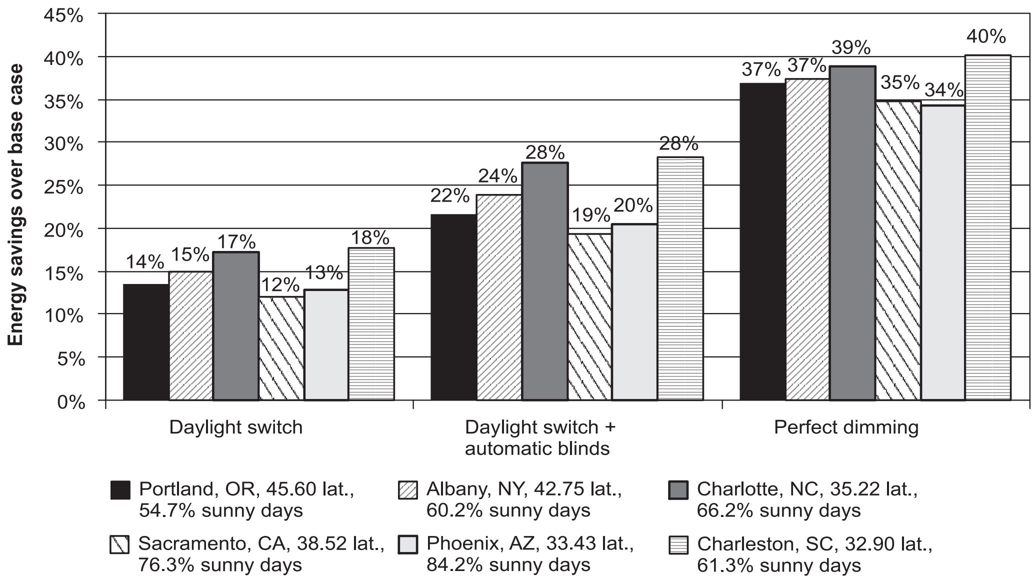

Figure 6

Calculation process used to determine the manual switching state for every hour on any façade.

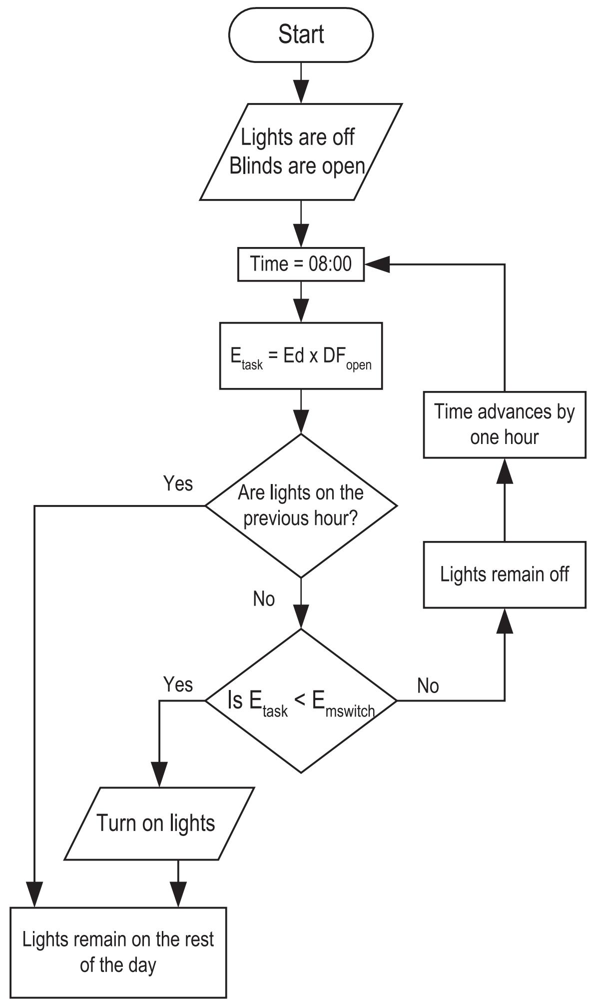

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Figure 7

Calculation process used to determine the switching state of the daylight switch for every hour on any façade.

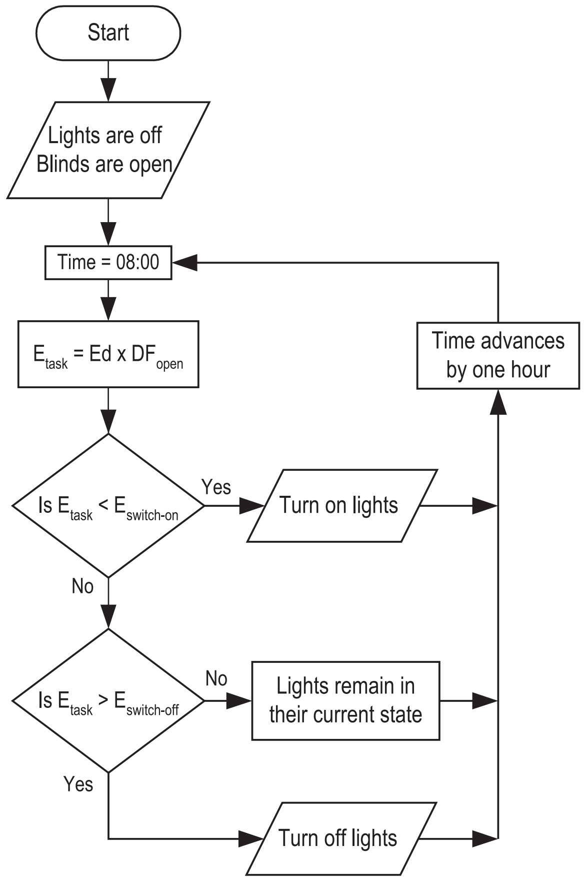

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Figure 8

Calculation process used to determine the perfect dimming state for every hour on any façade.