Daylight-Responsive Controls 5.

Introduction 5.1.

This chapter for *Daylight-Responsive Lighting Control Systems* is an introduction and adjunct to the *IEA SHC Task 21 Application Guide*. It contains general information on the nature of daylight and electric light and their integration, the application of shading and electric lighting control systems in situations where daylighting systems are being used, and the benefits of controlling daylight and electric lighting. The chapter also includes information on probable occupant behaviour when these systems are used and the importance of taking user awareness into account.

There are at least two dimensions to daylight-responsive controls: the control of the daylight input to the space, and the control of the electric lighting output. The first is critical for providing adequate quantity and quality of daylight in interior spaces. The second saves energy and improves the overall distribution of light when daylight is insufficient. For both of these systems, user satisfaction and acceptance is extremely important. Annoyances caused by the system, such as glare, temporary reductions or sudden changes in brightness, or irritating mechanical noise, will reduce the system's effectiveness.

However, maintaining a constant illumination level or luminance at some reference plane or point in a room by means of controls is not always desirable and is often impossible. The illuminance provided by the sky is variable compared to the illuminance provided by electric lighting. Skylight varies continuously; this variation creates one of the fundamental differences between daylighting and electric lighting design. The sky luminance and resultant illuminances vary with latitude, time of day, and the seasons; random variations in sky luminance also result from the density and movement of clouds. In sidelit rooms, the illuminance at points near windows is rarely more than one-tenth of that outdoors and is often considerably less at points far from the window. Nevertheless, the daylight in an interior space is of sufficient magnitude to be a useful contribution to the lighting of building interiors for much of the year. The introduction of target illuminance or luminance levels and variability about those targets is therefore a practical solution to the lighting of building interiors.

Daylighting and daylighting systems can no longer be considered isolated elements of a building design. It is necessary at an early stage to consider the implications and interactions of daylighting design decisions with other design criteria such as energy consumption (electric lighting, mechanical heating and cooling), heat loss and heat gain, sound transmission, and economics. The *IEA SHC Task 21 Application Guide* classifies and describes types of electric lighting control systems that are currently available, installation and maintenance procedures, methods for predicting energy savings from the use of these control systems, user reaction to the systems, and methods for selecting an appropriate system for a specific situation. The guide also presents an overview of all the systems that have been tested within the IEA SHC Task 21 programme and the methods used to evaluate these systems.

5.2. Daylight and Electric Light

5.2.1. Daylight Variations

Daylight is a dynamic source of lighting. As noted above, the illuminance from the sky is not constant, and the variations in daylight can be quite large depending on season, location or latitude, and cloudiness. As a result, both daylight and electric lighting control systems will be needed from time to time to adapt the lighting systems to changing lighting conditions.

The CIE International Daylight Measurement Programme (IDMP) has undertaken worldwide recording of daylight fluctuations in global and diffuse illuminances. Much has been done in the statistical processing of these data to make them accessible to users [Kittler et al. 1992]. Different skylight levels can be found under the same sunlight conditions, and, even when the sky pattern remains the same, the range of solar illuminances may increase as a result of a momentary turbidity filter or scattering of particles over the sun. In consequence, any prediction system has to be flexible to allow for the multivariate changes that characterise the combination of sunlight and skylight. A proposal for universal sky models of reference daylight conditions based on 15 new sky standards has been introduced [Kittler et al. 1999] and is now being adopted by the CIE. This universal daylight system will enable comparison and characterization of the daylight climate in any location, either by analysing measured data or simulating illuminance conditions using the 15 sky standards.

5.2.2. Electric Light Sources

Electric lighting is a major energy end use in commercial buildings and can affect cooling and heating loads. The internal generation of heat from lighting, equipment, and occupants will often result in a cooling load for most of the year during daytime occupancy hours. It is possible to conserve this energy by increasing the use of daylight and also using daylight-responsive lighting controls, provided that solar heat gain is also controlled [Rubinstein et al. 1991, Lee et al. 1998a].

Using higher-efficiency lamps and ballasts and improving the effectiveness of fixtures and layout can increase the efficiency of building illumination and reduce adverse environmental impacts of electricity generation. Using daylighting systems with appropriate shading and electric lighting controls can substantially add to those energy and cost savings by reducing lighting energy consumption and moderating peak demand in non-residential buildings. To achieve optimum results, a room or interior space needs to be zoned for optimal placement of luminaires and sensors, with luminaires parallel to the windows. Another essential consideration is how lighting is positioned relative to the work spaces. Both task and ambient lighting need to be considered in this respect.

Some types of electric lighting, e.g., most HID sources, cannot be dimmed or safely switched on/off. Such sources are widely used in industrial buildings, swimming pools, and sports halls. Fluorescent lighting is the light source generally used with electric lighting controls, but consideration should be given to the fluorescent lighting's colour-rendering ability and colour appearance, if it is to be used with daylighting. Fluorescent lamps with a colour temperature within 3,000-4,500°K are most likely to be in agreement with the colour temperature of daylight. Daylight, climate, and individual preferences must be taken into account; in high-latitude countries, which are predominantly cloudy, there is a preference for warm-white lamps whereas in sunny (low-latitude) countries, there is a preference for cold-white sources. The latter colour temperatures may, however, be seen as too cold for night-time use.

When both daylight and electric light are used, care should be taken to minimise luminance differences between the window area and its surroundings to ensure visual comfort. Interior surfaces need to be light in colour to maximise the inter-reflection of light. In addition, particular care should be taken because of specular reflection that results from the shiny or mirrored surfaces that are sometimes used as components of the daylighting system and/or shading device [Zonneveldt and Mallory-Hill 1998].

5.3. Electric Lighting Control Systems

Photoelectric controls can be very effective in reducing lighting, heating, and cooling loads in some types of spaces, such as offices, restaurants, shops, industrial buildings, and schools. Control by switching or dimming is now one standard way to control lighting and allow the energy-saving potential of daylight to be realised in practise. Prediction methods have been developed to assess the potential energy benefits of these controls [Littlefair 1984, Littlefair and Heasman 1998].

During the past ten years, the use of electric lighting controls has shown potential to significantly reduce lighting energy use and to moderate peak demand in commercial buildings compared to conventional systems without controls [Rubinstein et al. 1991]. Lighting control strategies have included automatically dimming the lights in response to daylight, dimming and switching luminaires on or off according to occupancy, and performing lumen maintenance, i.e., automatic compensation for long-term lumen losses. However, these systems have proved in some instances difficult to calibrate and commission in actual practise.

Lighting controls that are now becoming available offer potential solutions to these difficulties: lighting energy monitoring and diagnostics, easily accessible dimming capabilities, and the ability to respond to real-time utility pricing signals. Research using an advanced electric lighting control system has found that daylight-linked control systems can bring about sustainable reductions of 30–41% in electrical energy for an outermost row of lights in a perimeter zone, and 16–22% for the second row of lights [Rubinstein et al. 1998]. However, it should be noted that if the cost of dimming controls is based on the system's ability to produce a cost-effective reduction in lighting energy, the installed cost of the lighting controls should not exceed about 10 Euros per square metre floor area (for a payback period of three to four years).

With the advent of inexpensive handheld remote controls, occupant-controlled dimming is becoming an affordable option and has received a high occupant satisfaction rating [Maniccia et al. 1998]. In a study comparing the energy savings and effectiveness of various control techniques in offices during a period of seven months in a building in San Francisco, controls yielded 23% savings for bi-level switching, 45% savings for occupant sensing with task tuning, 40% savings with occupant sensing and manual dimming, and 44% savings for occupant sensing and automatic dimming. The last figure for savings is low because of the high light levels required by the occupants [Jennings et al. 1999].

Energy savings from occupant sensing versus dimming depend to a large extent on the behaviour of occupants (see Section 5.6). In offices where occupants remain at desks during the day, dimming controls will save more energy. An occupant's immediate lighting requirements will also vary with the type of work being undertaken.

Daylighting controls are being increasingly linked to whole building management systems. As a component of a more comprehensive control system, daylight may be even more cost effective in applications where it would be otherwise difficult to justify on a financial basis.

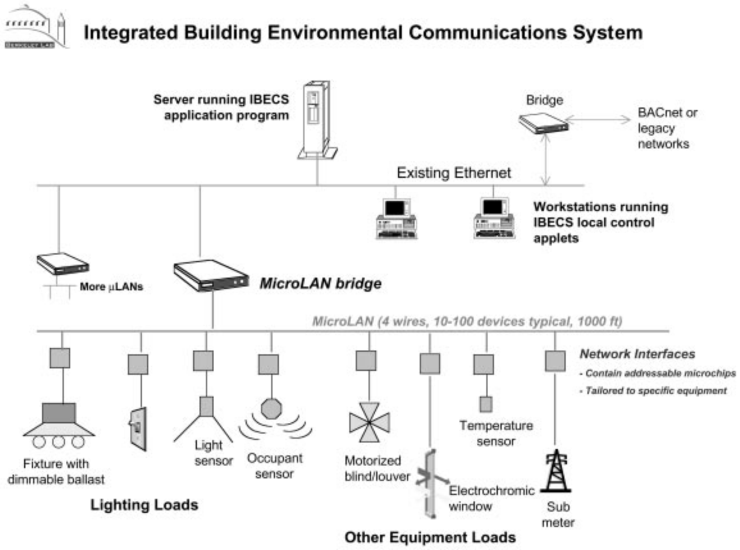


Figure 5-1. Building communications network [Rubinstein et al.1999]

5.3.1. A Building Communications Network

It is now possible to use computer software to programme the response of ballasts through a remote centralized control system. Depending on occupants' needs, a programmable system could save more energy than a directly controlled system. Setting up a programmable system is more costly in wiring and commissioning than a directly controlled system, but with a programmable system, building managers have the ability to adjust lighting levels from a remote location in response to an occupant's request and thus save maintenance staff the time that would be necessary to respond to the complaint. This new area of control technology is now being researched with the aim of providing a low-cost building communication network that will allow individual lighting loads to be controlled via an existing enterprise network (e.g., Ethernet). A building communications network enables both occupant-based and building-wide control of lighting systems and provides the hardware and software infrastructure for controlling and integrating the operations of most electrical loads in a building [Rubinstein et al. 1999]. A currently available system (Ergolight) also addresses the needs of office workers and energy management by offering electronic controls and energy management software in an integrated package.

Figure 5-1 shows a conceptual system that allows the light output from an overhead fluorescent light to be dimmed from a PC via a low-cost building control network. In this concept, the MicroLAN bridge couples an existing Ethernet network to the new MicroLAN, which networks together all lighting and other loads for that building zone.

5.3.2. New Installations and Retrofits

New installations and retrofits require different approaches. With a new installation, performance targets can be set and a light source and shading device can be chosen based on economic, ergonomic, and technical considerations, e.g., an acceptable payback period. With existing installations, choices will be limited by the building constraints and the availability of daylight.

5.3.3. Components of an Electric Lighting System

Apart from saving energy, a lighting control system must also 1) not disturb occupants, 2) be reliable, 3) conform to lighting standards, and 4) have a reasonable payback period.

Various systems for electric lighting control are available; these systems are either centrally or locally controlled. It is possible to control each luminaire or an entire building or floor area by a connected centralised system. Centrally controlled systems usually rely on a single daylight sensor that is often located on the ceiling (or sometimes the wall) of a large area in the centre of a circuit (or with a luminaire) and is calibrated on site within the sensor itself or within the controller to maintain a constant illuminance level. Controls can be adjustable in their preset levels, i.e., the range of light levels, with stepped or continuous ranges of lighting. Different types of controls can be used with different space functions; e.g., in circulation spaces, a simple on/off control may be all that is necessary, whereas in a large office, dimming controls may be the answer.

In locally controlled systems, a light sensor estimates the luminance on the work surface and adjusts the light output of the lamp to maintain a preset level. In general, localised systems perform better than centralised systems. However, one of the shortcomings of using these sensors is the problem of reflectance factors, e.g., when a large white sheet of paper is spread out on the work surface. This problem can be overcome by proper placement of sensors or can be reduced by using sensors with a large view angle.

Photoelectric Sensors

A key element of all types of photoelectric control is the sensor, which detects the presence or absence of daylight and sends a signal to a controller that will adjust the lighting accordingly. The location of the sensor is important because it influences the type of control algorithm used.

The photoelectric cell or sensor is often located on the ceiling and is calibrated on site to maintain a constant illuminance level. A single sensor that dims large areas can cause problems if some parts of the interior space are overshadowed by buildings or trees. It has been found that with innovative daylighting systems such as light shelves, a partially shielded sensor (shielded from the window only) is not susceptible to sky conditions and direct light from the window [Littlefair and Lynes 1999].

Controllers

A controller is located at the beginning of a circuit (normally the distribution board or the ceiling space) and incorporates an algorithm to process the signal from the photosensor and convert it into a command signal that is received by the dimming or switching unit.

Dimming and Switching Units

A dimming unit smoothly varies the light output of electric lights by altering the amount of power flowing to the lamps. If daylight is less than the target illuminance, the control tops up the lighting to provide the right amount on the work plane. Dimming controls can save more energy than switching if they are linked to daylight and if lamps are dimmed at the start of their lifetimes to compensate for their increased output. Dimming controls are also less obtrusive to occupants than switching, but a manual override is recommended in areas where occupants expect to have control [Slater et al. 1996]. Switches can also be used instead of dimmers, but this is not recommended except for limited applications because they are more obtrusive and may use more energy than dimming switches. High-frequency dimming produces the greatest savings in all but the most well daylit rooms.

A problem with photoelectric switches is rapid switching on and off when daylight levels fluctuate around the switching illuminance. This can annoy occupants and reduce lamp life. Various techniques have been developed to reduce the amount of switching. Differential switching control uses two switching illuminances, one at which the lights are switched off and another, lower illuminance level at which the lights are switched on. Photoelectric switching with a time delay can also introduce a delay in the switching process.

Occupancy Sensors

Recent studies have shown that workers are out of their offices 30–70% of the time during working hours [Newsham et al. 1995, Opdal and Brekke 1995, Love 1998]. A conservative estimate of savings possible from controls is about 30%, once time delays on occupancy control systems are taken into account. The actual savings will depend on the nature of the organisation using the space and the number of occupants in an office. Occupancy sensors are well suited to buildings where people are often away from their offices for a longer time than a few minutes. A weak point in this system is that the switching off of a certain zone, in a room where other people remain working, is generally experienced as disturbing. Recently developed systems allow a very smooth dimming down (or up after the return of the occupant) instead of sudden switching, which can help overcome this problem in group offices and thus increase user acceptance.

5.3.4. Types of Control Strategies

The general classification of control systems includes: closed loop systems (individual or with a limited number of luminaires) and open loop systems (central systems). Open and closed loop systems can also be stepped or continuous dimming systems. The calibration and the photosensor locations are quite different for these two systems because each system's algorithm expresses a different relationship between the photosensor signal and the output of the electric lights.

A control system is considered to be closed loop when the photosensor is located so that it is able to detect both the electric light that the system controls and the available daylight. In this case, the sensor needs to allow for the output of the lighting system that it controls. In contrast, an open loop control system's photosensor is designed and located so that it detects only daylight and is insensitive to the electric light that it controls. Although a lighting control system focuses on sensor placement and zoning, both of which are critical, other factors should be considered, including occupant override of controls, integration of controls with task and ambient systems, and design of the control system to accommodate skylights or light shelves.

5.4. Shading Controls

Shading can be used to control glare caused by the sun and/or high sky luminances as well as to control heat gain. Some shading systems can operate independently of a daylighting system; others, such as the transparent sun-excluding system (Figure 5-2), can be included in the daylighting system. In Chapter 4, daylighting systems are described as either shading systems (i.e., these are designed to provide both shading and daylighting) or as unshaded systems. In the latter classification, shading systems may need to be added, particularly in the tropics and in the summer season, to restrict solar heat gain and glare from direct sunlight.

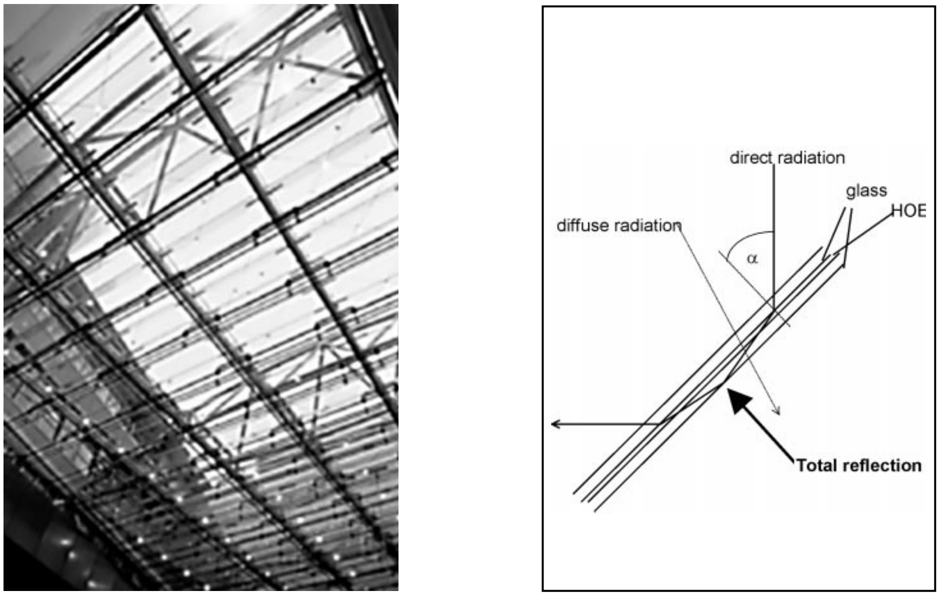


Figure 5-2: This transparent sun-excluding system consists of holographic optical elements (HOE) laminated between glass. The HOE redirects incident sunlight at the angle of total reflection, and only diffuse light penetrates the glass

A variety of strategies can be used to control a shading system automatically. Most current shading devices are manually controlled. However, when occupants are given only manual control of shading systems, the systems are often left closed, which eliminates all potential benefits from daylighting. External shading systems can be automatically controlled through a centrally controlled master switch that opens, tilts, or closes all shading devices at once. It is also possible to gauge the amount of light available to determine when shading is required. See Section 5.5.1 for a description of integrated shading controls.

An Integrated Approach 5.5.

Daylight, electric lighting, and shading systems cannot be considered separately because daylighting affects electric lighting use and introduces direct sunlight and glare that may be uncomfortable for building occupants. In fact, daylighting is fundamentally a systems integration challenge involving the building siting and orientation, window and/or skylight design, and lighting and shading control systems design, as well as ongoing maintenance. This requires cooperation between architects and lighting engineers. The deficiencies of both daylight and electric light are seldom optimally addressed unless they are seen as an integral part of the overall energy optimisation program.

5.5.1. Integrated Systems

The potential of an integrated dynamic envelope/lighting control system with automatic control of daylight and electric lighting was demonstrated in experimental studies at the Lawrence Berkeley National Laboratory (LBNL) in California, USA [Lee et al. 1998b] and at the École Polytechnique Fédérale de Lausanne, Switzerland [LESO-PB/EPFL 1996, Guillernin and Morel 1999].

Integrated control systems for blinds and electric lighting systems are characterized by: 1) their capacity to optimise the use of daylight under changing conditions, 2) their consideration of other factors such as avoiding solar gain, and 3) their continuous adaptation to user wishes with override priority granted to the user.

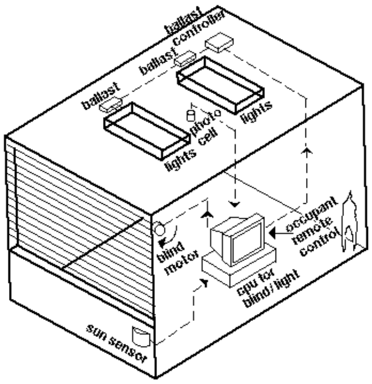
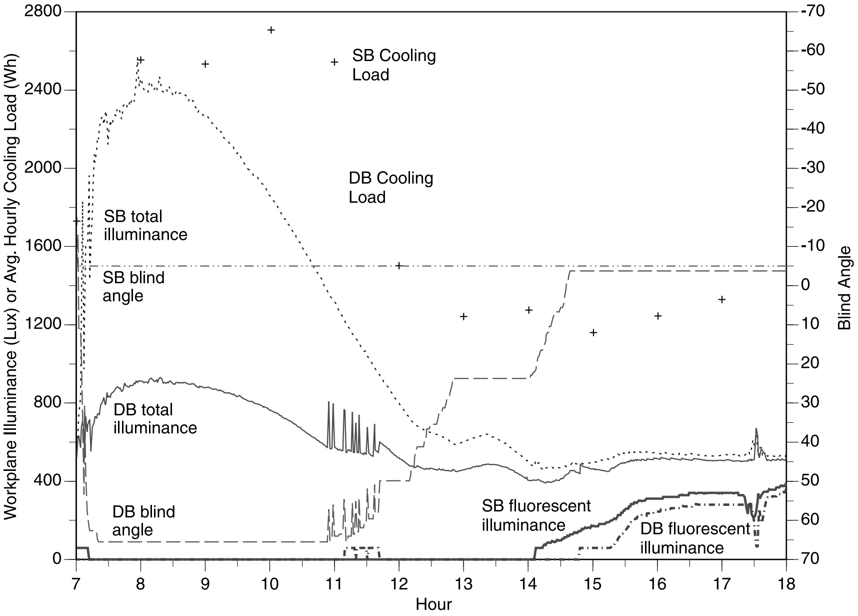


Figure 5-3: Schematic view of integrated venetian blind/electric lighting system

In the preliminary experimental work carried out at LBNL, daylight–responsive dimming of fluorescent lamps was coupled with automatically controlled venetian blind slats that exclude sunlight by automatically varying the slat angle. This system was designed to balance cooling loads and daylight admission by preventing direct sun penetration, actively

Figure 5-4:

Monitored total work plane illuminance, electric lighting illuminance, angle of blinds of the static horizontal blind (SB) and the dynamic venetian blind (DB) on a clear day in California, USA.



managing daylight and electric light to provide 500–700 lux on the work plane, and permitting view when possible. The venetian blinds were polled by the system and activated every 30 seconds, if necessary, to block direct sun and maintain the target daylight illuminance at the work plane if daylight was available. A schematic diagram of the system is shown in Figure 5-3.

Energy, control, and illuminance data were collected for one year. Sample performance is shown in Figure 5-4; for this clear day, daily cooling load savings were 2,917 W (21%), peak cooling load reductions were 332 W (13%), and daily lighting energy savings were 127 Wh (21%) compared to a static horizontal blind with the same dimmable lighting system.

In LESO-PB/EPFL experiments in Switzerland, a venetian blind controller using fuzzy logic was developed, simulated, and measured [LESO-PB/EPFL 1996]. Fuzzy logic allows the formulation of operation rules that take into account various environmental factors. The EDIFICIO project [Guillemin and Morel 2001], which is currently being carried out under the EU Joule-Thermie Programme, tests a more elaborate integrated controller for heating and cooling, ventilation, blinds, and electric lighting in a room.

5.6. Occupant Behaviour

Experience has shown that manual controls are not used effectively. Many occupants leave electric lighting on once it is switched on even if the illumination from daylight is at a level that would be considered adequate if the occupant were entering the space [Hunt 1980, Andersson et al. 1987]. Although most case studies of lighting controls have focused on energy savings, a major factor in choosing lighting controls should be the improvement of visual comfort. A pilot study of human factors has indicated that satisfaction with lighting controls increases if users can alter settings using a remote-control device. In a study using a remotely controlled dimmable lighting system, the lights were dimmed more frequently than switched off in winter, switching decisions seemed to be mostly related to the amount of daylight available, and occupants seemed to have different personal preferences regarding settings. A recent post-occupancy evaluation of offices in Denmark by Statens Byggeforskningsinstitut (SBI) was based on a comprehensive questionnaire focusing on daylight, sunlight, and electric lighting. This study determined that the use of electric lighting depended on the time of year and the number of persons in the office [Christoffersen et al. 1999]. Post-occupancy evaluations were also conducted within this IEA Task 21 [Hygge and Löfberg 1999].

User-controlled systems enable occupants to set workplace conditions according to performance, activity, and location. A range of devices is available to allow users to control their lighting levels. These typically consist of a hand-held or wall-mounted controller that communicates to a dimming ballast by hard wire or by infrared signals.

The advantages of human and automatic (occupancy) controls could be exploited in a combined system that would build on the advantages of each [Crisp 1984]. Empirical studies [Hunt 1980, Andersson et al. 1987] have shown that, for much of the time, occupants in spaces with relatively glare-free daylighting are satisfied with lower work plane illuminances than are stipulated for automatic control systems. A combined system could be taken a step further to include manually controlled blinds designed to improve the combination of daylight admission and glare control; the device could cost less than a motorised blind. The system would switch off or dim the lights using occupancy-linked controls, reactivating them on a manual signal, and leaving the judgement of lighting adequacy to the user [Love 1998]. This type of combination is directed at providing quality daylight and encouraging the occupant to assess the need for supplementary lighting when entering an interior space.

Benefits 5.7.

5.7.1. Savings Parameters

Energy savings cannot be realised in daylit buildings unless the electric lights are dimmed or switched in response to the amount of available daylight. The energy savings achieved with daylight-responsive lighting controls will depend on the daylight climate, the sophistication of the controls, and the size of the control zones. An evaluation of currently available responsive control systems is presented in the *IEA SHC Application Guide*. This evaluation has shown that daylight-responsive systems used up 40% less than non-controlled systems (Figure 5-5). Cooling load reductions have also been noted, which can save an additional 2–3% of electrical energy consumption. Savings can be larger than 40% especially in toplighted spaces. In hot climates, the cooling savings can also be larger.

Figure 5-5: Lighting power for first row of lighting fixtures in the south zone versus time of day for clear (CLR) and overcast (OC) days in July, September, and December in San Francisco [Rubinstein et al. 1999]

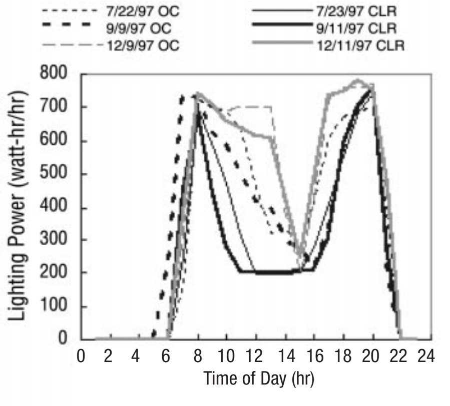


Figure 5-5 shows a graph for the south side of a building in San Francisco with lighting power as a function of time of day. The first row of lights in the perimeter zone shows significant dimming during daylit hours, dropping from 780 Watts to 200 Watts for several hours each day. Even on an overcast day, there is a significant reduction for a few hours.

5.7.2. Energy and Cost Estimates

The prediction of energy savings from the use of daylight-responsive controls is complex. An accurate estimate requires much information and detailed calculations (see Chapter 3). A simplified method demonstrated in the *IEA SHC Task 21 Application Guide* calculates savings omitting the complex factors such as the reduction of cooling loads. A computer can perform the calculation, which can be split into several factors that permit the user to understand the factors influencing the energy consumption. In this simplified method, the control characteristics of systems are evaluated under a number of sky conditions, and the results are extrapolated to estimate yearly savings. The validity of the extrapolation depends strongly on the type of control.

5.8. User Awareness

Researchers have found that physical and perceived performance of a daylight control system can differ quite remarkably. If the user finds the environment created by the system to be uncomfortable or disturbing in any way (noisy or too abrupt in its on-off switching), the system is likely to be rejected or an attempt will be made to compromise it. Energy savings are therefore directly related to a system's acceptance and proper operation by the user. Noisy or hard-to-operate systems are likely to be compromised. In addition, inappropriate ambience can result in rejection of the system. View aesthetics are also an important consideration. Users often do not accept daylight without view. In addition, the quality of light is important as is the avoidance of high contrasts and absolutely uniform lighting.

System Awareness 5.9.

An important but often overlooked aspect of control installations is the training of maintenance personnel and building occupants in the operation and purpose of a daylight-responsive control system. Although most manufacturers provide technical support during and for a period following installation of their systems, it is easier and more economical if those managing and occupying the building can address most problems.

Building and facility managers need to be aware of how to operate the system and adjust it. They need to understand the system's performance. Building occupants should receive information about the purpose of the system.

Installation and Maintenance 5.10.

5.10.1. Calibration of Sensors

The installation of luminaires with factory-installed sensors does not differ greatly from the installation of conventional luminaires. At the installation site, installers need only measure the illuminance on the work surface at night and during the daytime under each luminaire and to adjust the sensor until the desired lighting level is achieved. When there is one daylight level sensor controlling multiple luminaires in a single zone or room, then the placement of the sensor is critical. Generally, the sensor should view a representative luminance on a work surface, should not be able to "look outside," and should be located where it will not receive light from upward-directed lamps when indirect lighting is used. The most appropriate location for a sensor in small spaces (private offices) is usually on the ceiling near the primary work area. Calibrating an occupant sensor means setting the sensitivity and time delay for appropriate operation in the particular space where the unit is installed [Rubinstein et al. 1997].

In more sophisticated systems, calibration may be accomplished by software. Further details on the installation of luminaires with built-in sensors, room-based systems, and calibration of sensors can be found in the *IEA SHC Task 21 Application Guide*.

5.10.2. Maintenance

The need for maintenance depends on many factors. The most obvious is lamp life, i.e., the number of hours that a lamp is expected to burn. If as a result of switching or dimming a lamp burns fewer hours per day than normal, lamp life increases in terms of the number of days between relamping but decreases in terms of the total number of lamp hours. Aging of sensors can also influence system performance. In some cases, systems may require recalibration to account for degradation of the sensors. Photodiodes are known to be very stable, but certain types of plastic used in the white-diffusing covers of photosensors may degrade.

When lamps are replaced or cleaned as part of normal maintenance, the sensors can also be cleaned. Whenever extensive relamping takes place, luminance measurements should be taken and sensors recalibrated.

The daily control, management, and behaviour of shading systems also needs to be considered in case of failure, such as the short-circuiting of sensors. These issues are discussed in more detail in the *IEA SHC Task 21 Application Guide*.