SynthLight Handbook

Chapter 4: Integration of Electric Lighting-Daylighting

Authors: Aris Tsangrassoulis, Afroditi Synnefa
Revision: 25 February 2004

About

This is chapter 4 of 5 of the handbook for the SynthLight on-line course on lighting:

1. Fundamentals
2. Daylighting
3. Artificial Lighting
4. **Integrating Artificial Lighting and Daylighting**
5. Case Studies

For more material and the other chapters, please visit the SynthLight web site at: http://www.learn.londonmet.ac.uk/packages/synthlight/index.html.

This site also has an on-line test consisting of 15 questions each for each of the four main chapters. If you answer more than 80% of questions correctly, you will be sent a Certificate of Virtual Attendance.

Acknowledgements

SynthLight was part-funded by the European Commission under the SAVE programme. The project number is 4.1031/Z/01-123/2001.

Disclaimer

Although much care has been taken in ensuring that all facts and concepts laid out in this document are correct, the author can not be held liable for any mistakes that might have crept in. If you discover any inconsistencies, please notify <atsagra@cc.uoa.gr>, so future revisions of this document can be corrected.

Table of contents

4.1 INTRODUCTION

As the cost of energy has continued to rise, increasing effort has gone into minimizing the energy consumption of lighting installation. This effort has evolved along three major directions:

1. The development of new energy efficient lighting equipment
2. The utilization of improved lighting design practice
3. The improvement in lighting control systems.

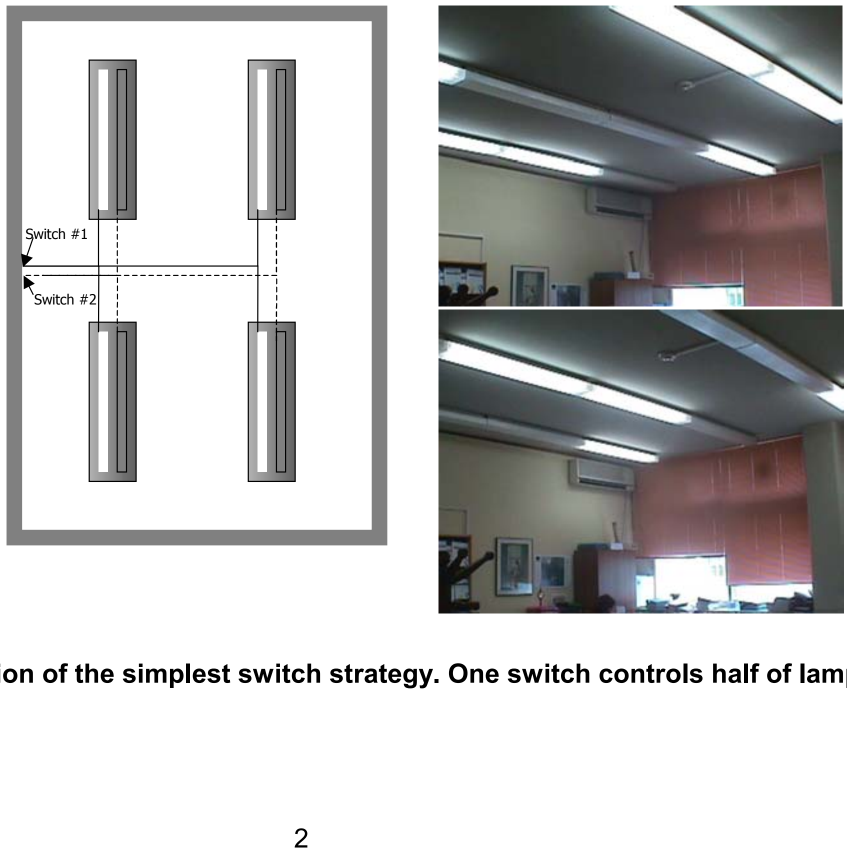
While saving energy is of a great importance, there are some other associated benefits which should be considered. These are productivity and quality. However is quite difficult to quantify their influence. Lighting controls perform functions like on-off, time scheduling, dimming, dimming due to presence of daylighting, lumen depreciation and demand control.

Lighting controls can also be grouped into two general categories: centralized controls and local controls. Centralized controls are used in buildings where it is desirable to control large areas of the building on the same schedule. For example in the morning the system can turn on lights a few minutes before the arrival of the employees. After the end of the working day the system can turn off lights again. During the day the lighting system can be adjusted in order to avoid peak demands (for example during noon at summer months).

Localized controls are designed to affect only specific areas.

4.1.1 On-off controls

These controls turn lights on or off. The simplest form is a wall switch. These switches should encourage deactivation of lighting whenever appropriate. Although a simple device, can perform more complicate functions like the one that is presented in the following figure. There are two lamp luminaires , while one switch can control half of the lamps.



Schematic representation of the simplest switch strategy. One switch controls half of lamps.

Another common application of wall switches is the activation of the luminaries located into the perimeter zone of buildings near the façade (this zone extents ~2.5 times the height of the window) as in the case presented below:

Luminaires near the façade. Their control can be separated from the control applied to the luminaries located at the core of the building.

Other forms of activators include:

- **Timing controls**
  There are different types of time controls. They can be used for direct on-off control of lights or for control of lighting contactors. Sophisticated digital timers offer the possibility to programme their function according to a predefined schedule. Timers can be used in conhunction with photsensors.

- **Sensors**
  1. Photoelectric sensors. Most inexpensive photosensors use cadmium sulfide as the active element for light detection. Over several years the sensitivity of the sensor changes and the photocell turns lights on earlier in the evening and off later in the morning. This drift causes lights to operate for longer period. Electronic photosensors use a light sensitive silicon diode to detect daylight and provide more precise control. Electronic photosensors are more costly than cadmium sulfide cells but savings in energy costs generally justify their installation.
     Occupancy sensors. Occupant sensors are switching devices that respond to the presence and absence of people in the sensor's field of view, a view which should cover the control area. Occupancy sensors serve three basic functions:
     1. To automatically turn lights on when a person enters the room,
     2. To keep the lights on while the controlled space is occupied
     3. To turn the lights off within a predefined time interval after if the room in unoccupied.

Passive infrared (PIR) sensors react to the infrared heat energy emitted by people. PIR sensors are passive devices in that they only detect radiation. They are designed to be maximally sensitive to objects that emit heat energy at a wavelength of around 10microns. PIR sensors are strictly line-of-sight devices.

Ceiling sensor

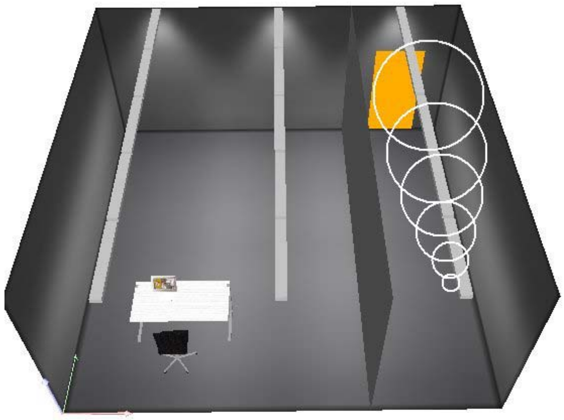
Wall sensor

PIR sensors employ a pyroelectric transducer to detect infrared radiation. The device converts the IR energy into a voltage signal. Most PIR sensors are sensitive to hand movement up to a distance of about 3 m, arm and upper torso movement up to 6m and full body movement up to about 12 m.

Placement of sensors

Ultrasonic sensors activate a quartz crystal that emits ultrasonic waves throughout space. The unit then senses the frequency of the reflected waves. If there is a motion, the reflected wave's frequency will shift slightly (Doppler effect) . Ultrasonic sensors operate at frequencies that are above human sensitivity (20kHz). Typical operating frequencies are 25, 30 and 40 kHz. The ultrasonic sound waves cover the entire area. For this reason ultrasonic sensors are somewhat more sensitive to movement.

Acoustic sensors respond to sounds created as a result of a person's movement in the area. This type of sensor can be used in irregularly shaped room or corridor. Active Infrared sensors emit invisible infrared light beams in a specific pattern and a receiver responds to changes in the light beam patterns caused by a person's movement in the field of view.



Placement of acoustic sensor

According to the US EPA the following energy savings can be realized:

OCCUPANCY AREA	ENERGY SAVINGS
Private Office	13 - 50 %
Classroom	40 - 46 %
Conference Room	22 - 65 %
Restrooms	30 - 90 %
Corridors	30 - 80 %
Storage Areas	45 - 80 %

Typical values of energy savings for various occupancy areas.

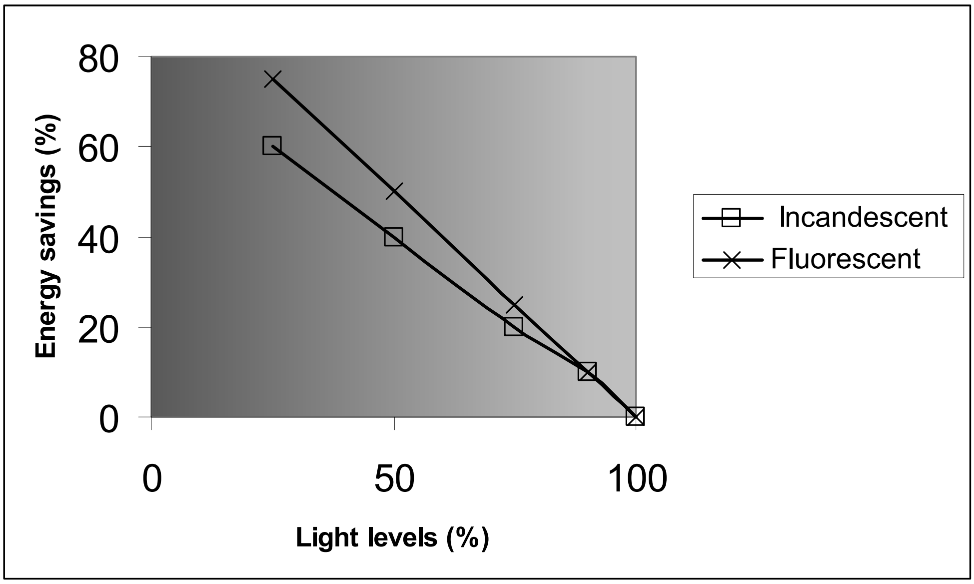
4.1.2 Level controls

- Dimmers

  Dimming can be performed in various ways. The type of dimming is depended on the lamp type and the control strategy. In more details, for incandescent lamps electronic dimmers contain a small semi-conductor device called a triac. This device is turning the power to the lamp off for a portion of each cycle. The disadvantage of this is a rapid filament vibration producing audible noise.

  The other way of dimming is the use of variable transformer. This device simply reduce the magnitude of the voltage supplied to the lamp.

Fluorescent lamps may be dimmed by the use of ballasts, dimming transformers or electronic devices.



Indicative energy savings against light levels for incandescent and fluorescent light sources

In the last decade solid state dimmers have taken over 90 % of the market. By means of an electronic switch, the electronic dimmers turn off the current to the load for a portion of the cycle, thus delivering less power to the load.
In the old days fluorescent fixtures had a starter or a power switch with a 'start' position which is in essence a manual starter. Some cheap ones still do use this technology.
The starter is a time delay switch which when first powered, allows the filaments at each end of the tube to warm up and then interrupts this part of the circuit.
It may be noticed that a few iterations are sometimes needed to get the tube to light. The starter may keep cycling indefinitely if either it or one of the tubes is faulty. While the lamp is on, a preheat ballast is just an inductor which at 60 Hz (or 50 Hz) has the appropriate impedance to limit the current to the tube(s) to the proper value. Ballasts must generally be fairly closely matched to the lamp in terms tube wattage, length, and diameter [3].
Electronic ballasts are devices are basically switching power supplies that eliminate the large, heavy, 'iron' ballast and replace it with an integrated high frequency inverter/switcher. Properly designed electronic ballasts should be very reliable. Whether they actual are reliable in practice depends on their location with respect to the heat produced by the lamps as well as many other factors. Since these ballasts include rectification, filtering, and operate the tubes at a high frequency, they also usually eliminate or greatly reduce the flicker associated with iron ballasted systems. Electronic ballasts have replaced magnetic ballasts as the industry's standard. Electronic ballasts are 10% to 20% more efficient than the best "energy saving" magnetic ballasts. Replacing magnetic ballasts with electronic ballasts provides a quick payback. And, the frequency of electronic ballasts is much higher than for magnetic ballasts, eliminating the annoying hum and flicker sometimes caused by magnetic ballasts.
Some electronic ballasts draw odd current waveforms with high peak currents.
Because of the high peak currents drawn by some electronic ballasts, it is often important to size wiring properly for these high peak currents.

It should be noted here that during the design process the designer must be very careful in order to avoid mismatched components. For fluorescent lighting, ballasts and controls must be compatible.
Electronic ballasts are now available for incandescent, fluorescent and HID lighting, although for the latter one continuous dimming from 0-100% is not feasible with today's technology. In general dimming control technologies typically rely on either voltage reduction or waveform management.

4.2 LIGHTING CONTROL

Lighting controls is an integral part of a lighting system. These controls must be responsive to the functional and aesthetic requirements placed upon it, and should perform these duties in an energy efficient manner.
In general, there do not appear to be any general rules or guidelines that congenitally lead one to select specific controls. The factors presented below will have a bearing on the selection of lighting controls:

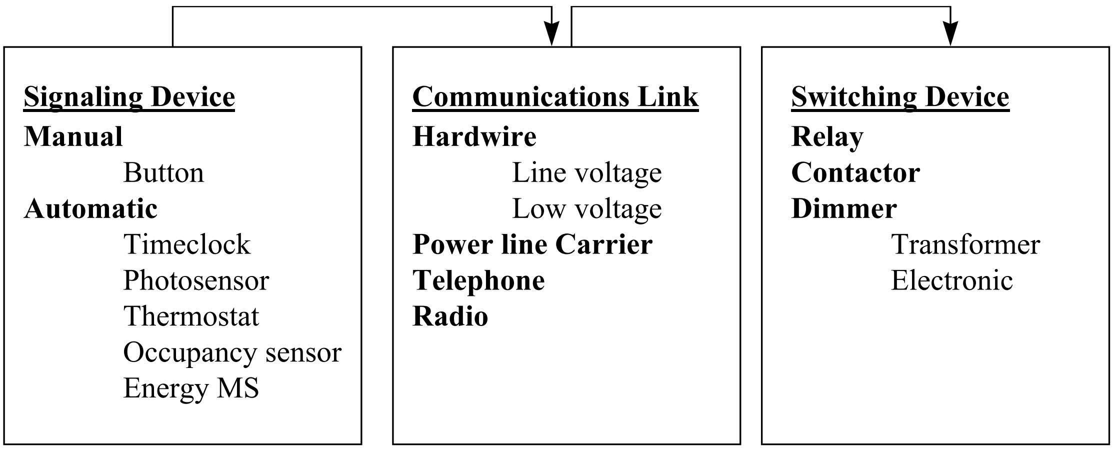
1. Size of the building. A very large building may need a Building Management System while a small one can obtain optimum savings by selecting a time switch control.
2. Type of the lighting system. Ballast selection can be affected. Some controls will operate only specific lamp types.
3. Availability of daylight. Energy savings due to daylight depends on climate conditions, building form and design and the activities within the building. In addition this factors is directly linked with the operating schedule of the building.
4. Type of usage in the building. If the building is an office building, consideration is often given to flexible controls, such as low voltage relays. If its is an educational building, where the lighting requirements are more fixed, other types of controls should be considered.
5. Budgetary constraints.
6. Dimming requirements.

Most of the manufactures of control systems give the system performance and cost in order for the designer to decide how well this system meets the needs of both the occupant and the building management. It is evident that the designer should somehow follow a rating system -based on his experience- in order to choose the most appropriate control system. This rating system can be based in :

- Occupancy sensitivity. Form an occupant's perspective, individual wall switches work fine. Contactors on most building automation systems can be a real disadvantage, since they do not normally allow the occupants to override for after-hour usage.
- Occupant-level selection. This is a function affected by both control system capacity and floor layout. Individual office layouts with manual switching of split wired fixtures or several lighting sources within the space give most occupants the degree of control they need. The dimmable electronic ballast approach provides an even better method for allowing the occupant to adjust the overhead lighting.
- Energy Saving Potential.

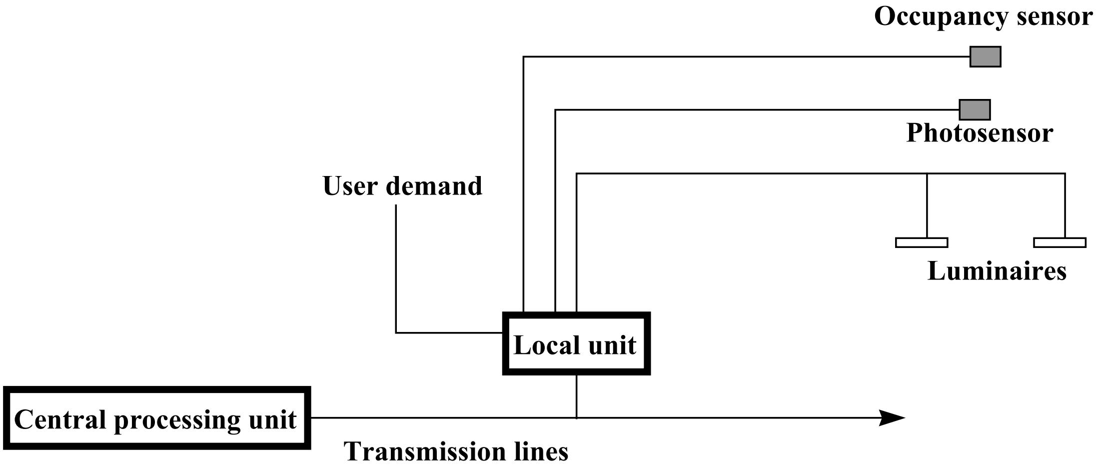
- Management data. This reflects system monitoring analysis and reporting capabilities. These require a communications capability not normally inherent in switches or occupancy sensors.
- Space adaptability. The important point here is that devices physically linked to the occupant's walls or ceiling pose problems when it is time yo rearrange a space.
- Costs. The electronic ballast costs represents a combination of functions not presently available on the market. Occupancy sensors may reduce the installation labor, but the added hardware content still means a relatively high total cost. Both switches and sensors incur added cost for office rearrangements.

The figure below presents the components of a control system.



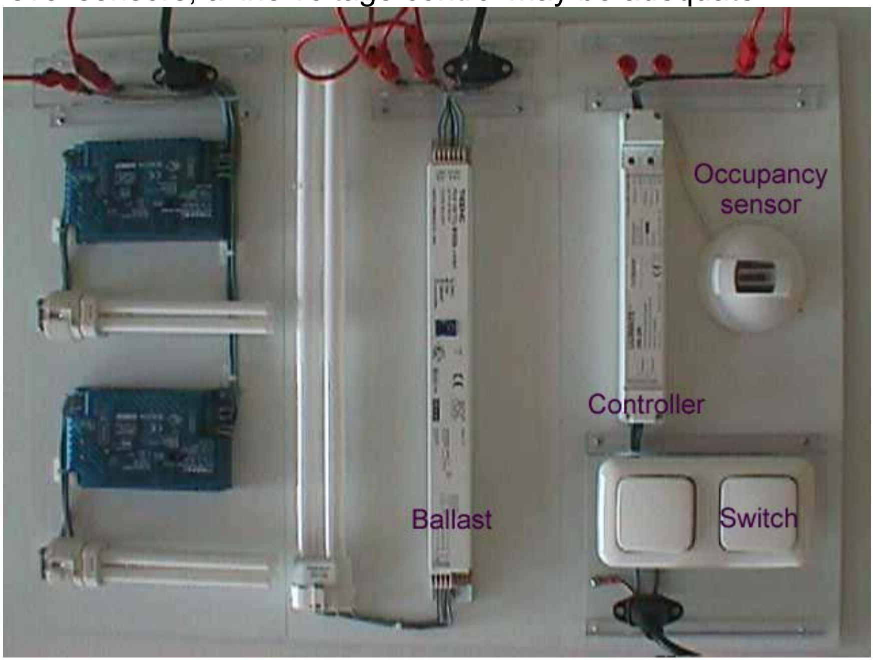
Relationships between the three component groups of a remote switching system

A typical layout of a control system is presented in figure below.



Layout of control system for artificial lighting

It should be emphasized here that the two main types of lighting control systems are line voltage and low voltage. Line voltage controls tend to be less expensive but less flexible, than low voltage controls. If the area does not require low voltage components such as light-level sensors, a line voltage control may be adequate



Typical wiring of a control lighting system (courtesy of 2Kappa). Various types of ballasts connected to a control unit which in turn is connected with a switch.

The aim of the installation of a lighting control system is to adjust, dynamically and in real time , and allow for any divergence from the set comfort parameters with respect to the radiation data used for the design. The current state of the art offers two different control approaches :

- Control systems applied only to the lighting system.
- Building Management Systems capable to regulate the HVAC and the lighting system as well.

The first approach is the most commonly used and most of the lighting manufactures devote their research effort to it.

4.3 CONTROL STRATEGY

There are six common lighting control strategies:

1. Scheduling is the strategy of tuning lights on or off according to need or program. Manual scheduling involves switching by building occupants, while automatic scheduling may include time switches, occupant sensors, photocell switches and other means of switching lights by automatic control devices.

2. Tuning is reducing power to electric lights in accordannce with the exact lighting needs of the user and work task. For instance, older workers and workers performing highly detailed tasks need more light to perform their respective visual tasks. Younger workers, workers performing fairly easy to see tasks, and workers using video dispaly terminals can often work with less light than is

being generated by their respective lighting systems. Tuning is accomplished with dimming devices.

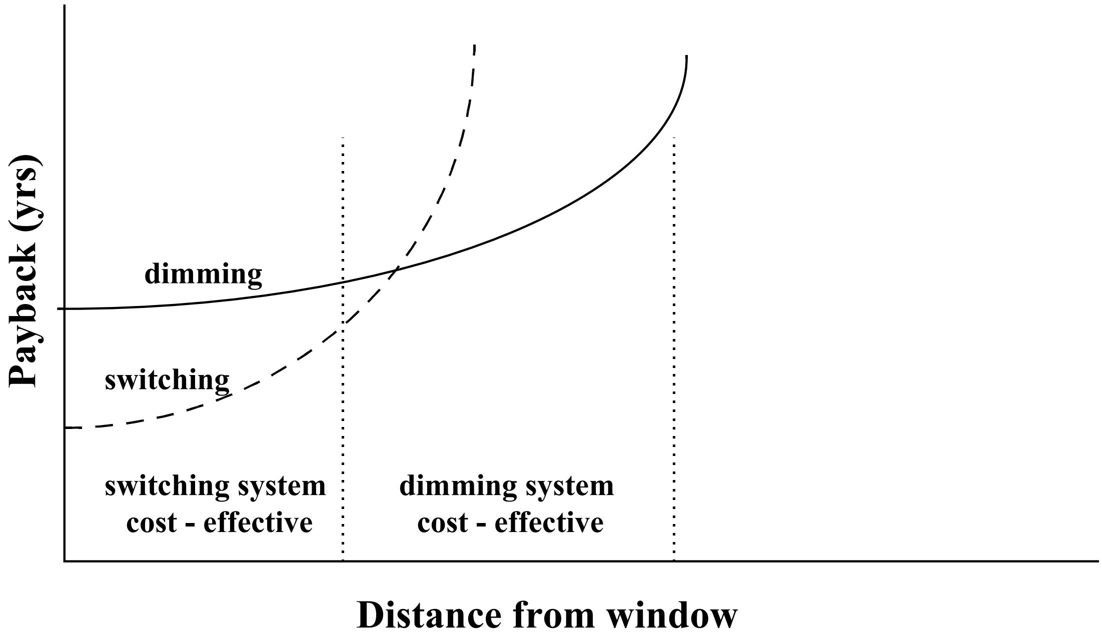
3. Daylighting is the act of tuning lights off or reducing power to electric lights in the presence of natural light from windows and skylights. Daylighting controls employ a photosensor-controller device, linked to a switching or dimming unit that varies electric light power in response to natural light.

4. Lumen maintenance. Most lighting systems are designed to produce maintened “lux”, a worst case design strategy, which produces excess illuminance until the end of the lamp-luminaire maintenance cycle is reached. As a result, at the beginning of the maintenance cycle, when lamps are new and luminaires are clean, most properly designed lighting systems produce 25 to 30% more light than is needed. Over the anticipated maintenance cycle (~2 years), light levels fall steadily until the design illuminance level is reached. A lumen maintence control strategy reduces lighting power at first, gradually increasing to reach full power at the end of the maintenace cycle. Illuminance remaons contant throughout the cycle. Savings are typically 12% to 20% of the energy that would have been consumed had the lights been operated at full power throughout the maintenance cycle. Control is achived through the same type of hardware used for daylighting controls.

5. Demand limiting. Costly power demand peaks can be reduced by saving non-essential loads, or by cycling semi-essential loads. Electric lighting levels can be reduced by 10% or more with a minimal impact on visual performance or productivity. Since lighting can consume 40-50 % of many office buildings’ total electric load, even a slight reduction in lighting can result in a significant decrease in demand. Most any type of control device can be employed to limit demand. However, automatic dimming controls allow this to occur without occupant awareness.

6. Adaptation compensation. In extended hour interior applications, such as 24 hour markets, and in exterior applications like tunnels, electric lighting must be brighter during daylight hours to enable people with daylight adapted eyes to see in darker or covered areas. However, lighting power can be reduced substantially at night, as human eyes are night adapted and do not require as much light in those same areas. Electric power, in these cases, could be reduced as much as 80% for approximatelly 10 hours each day. Adaptation compensation control strategies employ dimming devices or switching relays combined with automatic timers to vary illuminance accordingly.

Dimming hardware should be chosen if daylighting, lumen maintenance or tuning are the selected control strategies. With the cost of dimming ballasts still high but falling, dimming control is at least twice as expensive as switching control but it is the best for implementing these strategies. It is also generally the most acceptable to occupants, because changes in the electric light levels are least distrurbing. Daylight and lumen maintenance strategies integrate well, since they use the same hardware. Dimming is generally not cost effective in non-daylit areas unless coupled with scheduling controls. For spaces with adequate daylight all day long, switching may be acceptable, since the lights may adjust only once or twice during stable daylight hours [5].



Indicative payback periods for switching/dimming systems

Scheduling can be implemented effectively with switching controls. Switching technology is inexpensive and do not require special expertise to install. Manual switching is generally not well used by the typical office occupant. Use automatic controls to ensure that projected savings are actually achieved over time. It is advisable to use programmable time controls. This control strategy typically yields at least 15 % savings in lighting energy.

Type of Control	Small Office	Open Office - Daylit	Open Office – Interior
Occupancy Sensors	++	++	++
Time Scheduling	+	++	++
Daylight Dimming	++	++	-
Bi-Level Switching	++	+	+
Demand Lighting	+	++	++

Suitability of various typical lighting control applications in different type of buildings (++=good savings, +=some savings, -=no savings).

Dimming is in general a more expensive daylighting control technology (when including the cost of dimming ballasts) in comparison to switching and is ideal in applications where occupants are engaged in small motion activities
(sitting, reading, typing). In an old installation (where there are no dimming ballasts) switch is more appropriate even though the light changes caused are more abrupt.

4.4 DAYLIGHTING CONTROL SYSTEMS

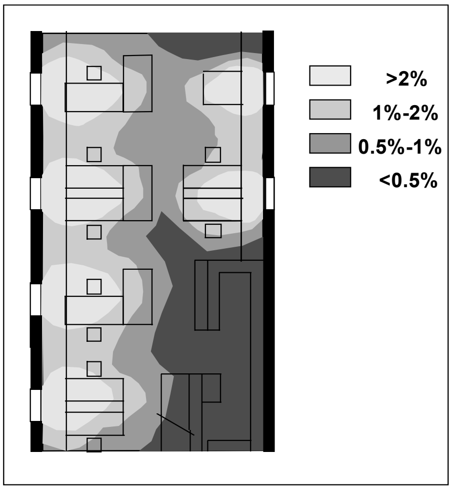
Providing daylight in a building does not by itself lead to energy efficiency. Even a well daylit building may have a high level of lighting energy use if the lighting controls are inappropriate. Case studies [6] have shown that in a conventionally daylit commercial building the choice of control can make 30-40% difference to the resulting lighting use. A typical electric lighting system control concept appropriate for a daylighted building usually consists of at least two components that are often not part of non-daylighted buildings:

- Integrated lighting control zones
- Automatic control strategy for each zone

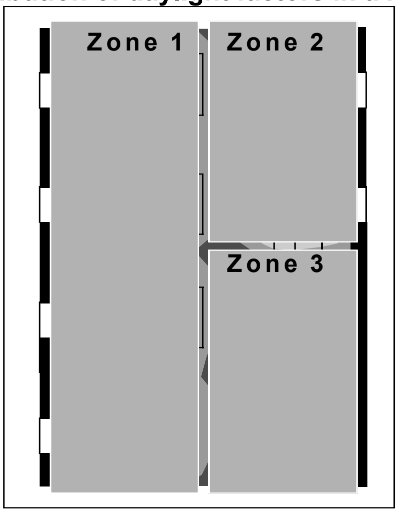
The integrated lighting control zones are areas in the building that use daylight and electric lighting jointly to provide task, background or general illuminance. The size of a zone depends upon aperture configuration, sky condition and solar location. In order to establish the lighting zones illuminance measurements are needed or results from simulation procedures for a minimum of four different months representing winter, spring, summer, fall). In order to establish the usual minimum/maximum range of performance, only winter and summer need to be analyzed.
The data sets should be for at least two time periods. Usually, noon is used for one while the other period is at least three hours before or after noon. Many daylighting systems function in such a way that some time other than noon provides the maximum performance characteristics; if the daylighting concept performs considerably differently in the morning than in the afternoon at the same station point, both cases should be reviewed. Finally data sets should be established for the two sky conditions: clear and overcast.
Lighting zones link areas which have similar daylighting distribution characteristics. Within a zone the light at the station point of maximum illuminance should not be more than about three times brighter than that at the station point of minimum illuminance. This guarantees a reasonable contrast ratio within the zone. A ratio of maximum to minimum illuminance greater than 9:1 is somehow the limit and the area should be divided into more zones.
In general , the greater the number of zones in a space, the greater the opportunity for energy savings. First costs may increase as the number of zones increases. When a small number of zones are present in a room, the reduction of first costs is often offset by the reduced performance characteristics of the integrated lighting system. Consequently a combination of performance, first costs and operating and maintenance costs should be appraised to determine the optimum control strategies. Daylighting works best with indirect lighting systems because with indirect lighting, occupants are less likely to notice changes in electric light output. Conversely, daylighting control does not work well with spot lighting.
Same basic rules for the choose of the appropriate number of zones are:

- In open plan areas with a uniform window facade, group fixtures in runs parallel to the window with separate control for each row from the window (for strip windows) or in groups associated with each window.
- Limit the number of zones where possible.

- Any circulation space running along a window-wall should be a separate control zone



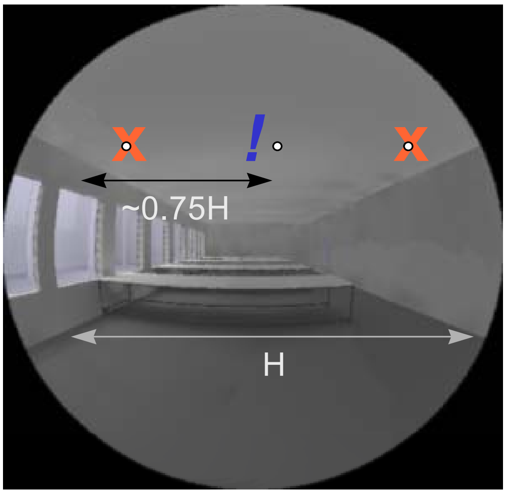
Distribution of daylight factors in a room.



Division of the room into three zones.

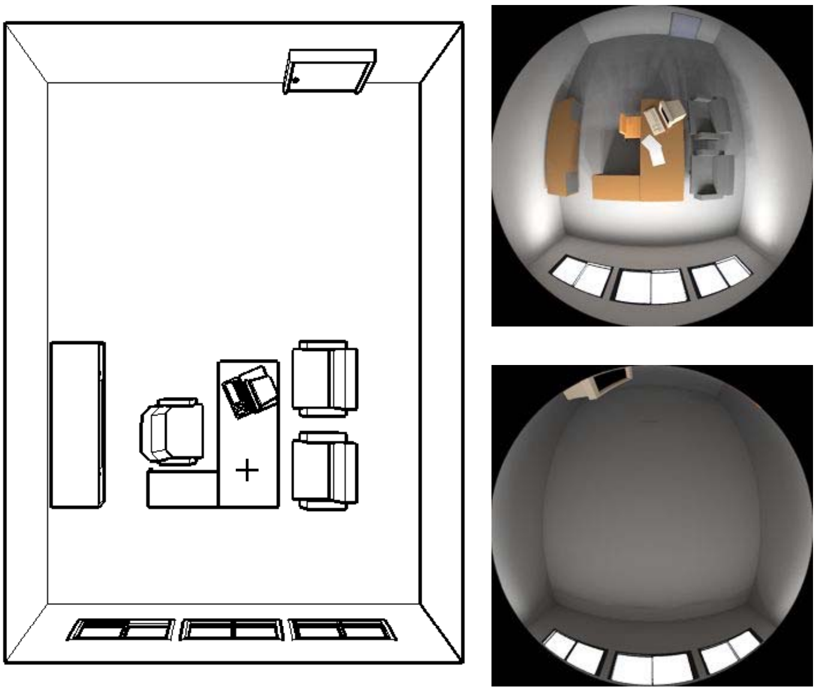
Once the lighting zones have been chosen, the one station point in the zone that will be used to establish the lighting control strategy for the zone must be selected. Usually neither the highest nor the lowest illuminance point in the zone should be chosen to represent the zone. If the station point with the highest illuminance value is used, the rest of the space will be underlighted when the illuminance on that point is equal to or larger than the design illuminance.

In a room with only one task area the ceiling - mounted sensor should be placed above the task. In a room with more than one task area, the sensor should be placed above the task that best represents the daylight available.



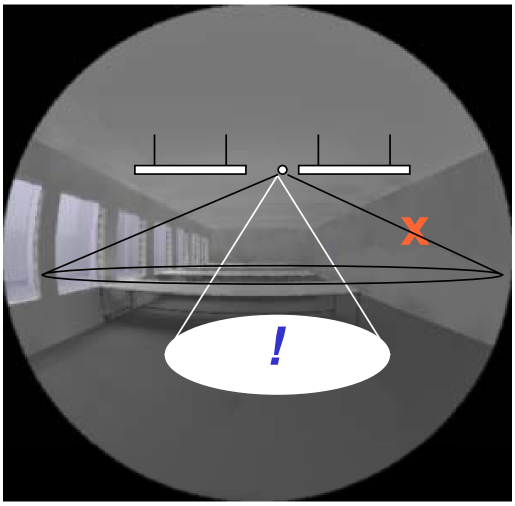
Position of a photosensor

Some controllers support inputs from more than one photosensor. This allows daylight to be sampled at more than one location.
With indirect and indirect/direct lighting systems, the photosensor should be located in the plane of the fixtures aimed downwards. Make sure that the sensors cannot directly view the electric lights they control. For direct lighting systems the photosensor should be placed in a recessed position in the ceiling.



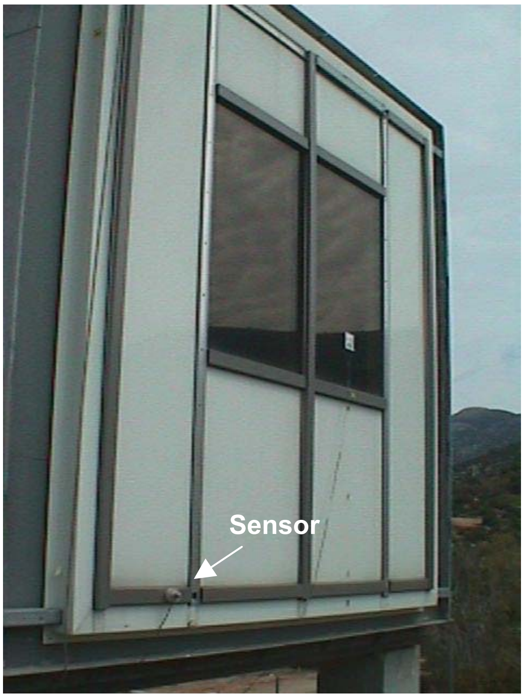
Fish eye view from a sensor located on the working surface and on the ceiling

Another important factor is the photosensors field of view which should not be too narrow or the sensor will be to sensitive to small incidental changes. A ceiling mounted closed loop sensor should have a large field of view and be shielded from direct light from the window.



Field of view of a photosensor.

Some sensors come with sun shields for cases where the cell cannot be placed far enough from the window. For switching systems the sensor is located so that it views the external daylight source with minimal view of the electric lights.



Open loop control, the sensor is located outside of the controlled zone.

Photosensor location is less critical with open - loop systems and can be compensated for during commissioning.
Manufactures have specific recommendations as to where to locate the photosensor.
In practical terms , daylighting control systems do not use models to calculate the effect of daylight inside the spaces as a function of the external variables. In fact they merely measure ambient conditions in real time.The various control systems adapt to varying needs in different ways depending on the type of the plant and set comfort levels. American standards call for high lighting levels, whereas the general European level and the present trends tend to concentrate on other parameter (contrast, uniformity, colour, etc). The purpose is to obtain good comfort levels with lower lighting levels. In defining the minimum parameters for the control units, the following factors should be kept in mind:

- Uniformity in relation to the daylight factor.
- Current and future use of the spaces.
- Possible need to build-in local human adjustment to the parameters.
- Different visual needs and consequent different lighting levels.

Once the minimum control levels have been defined on the basis of these parameters and needs, the sensors will be positioned in the light of these needs.
As already mentioned daylight control can be realized either by using a control system for the whole building, space etc or stand-alone products , like ballasts equipped with photosensors

Ballast equipped with photosensor

The latter are more difficult to calibrate during set-up.They are used generally in closed loop systems and are ideal in small rooms or spaces where daylight contributions are relatively even or balanced (i.e., enclosed offices, hallways).

4.5 HOW DAYLIGHTING CONTROL WORKS?

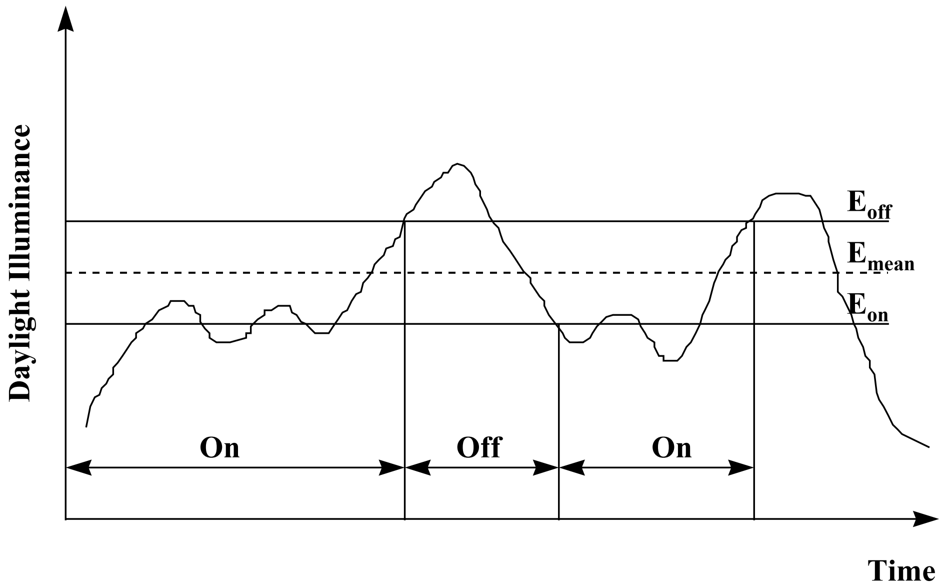
1. ***Simple on/off switching***

When daylight illuminance in the station point is reached, switches the electric lights off and switches them on again when the daylight illuminance drops below the control value.

A problem with the automatic on/off photoelectric switch has been the user reaction to its operation. Especially, people do not like automatic controls which switch lights on when they could have been off under manual control. A special problem with the photoelectric switch is the rapid switching of lights on and off on occasions when daylight levels are fluctuating around the switching illuminance. This can annoy occupants and reduce lamp life. Various techniques have been developed to reduce the number of switch offs such as:

❖ **Differential switching control**

Unlike the standard photoelectric switch, the differential control has two switching illuminance; one (E_{off}) at which the lights are switched off, and another , lower illuminance (E_{on}) at which the lights are switched on. As a consequence, before the lights switched on then off in succesion, the daylight illuminance at the station point has to traverse the whole of the illuminance differential between E_{on} and E_{off}. Thus, rapid switching is reduced. Furthermore switching off is making less obtrusive, as it is performed when daylight pepresents a higher proportion of the illuminance to which the eye is adapted.



Differential On-Off controller

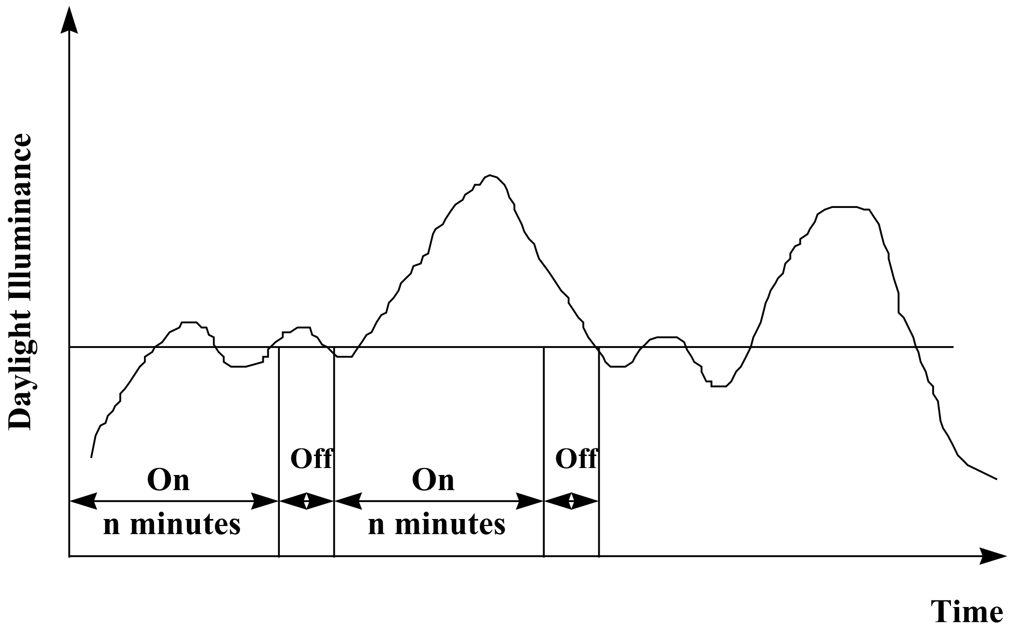
❖ **Photoelectric switching with time delay.**

By indrotucing a time delay in the process the frequency of switching operations is reduced. Two types of time delay are the following:

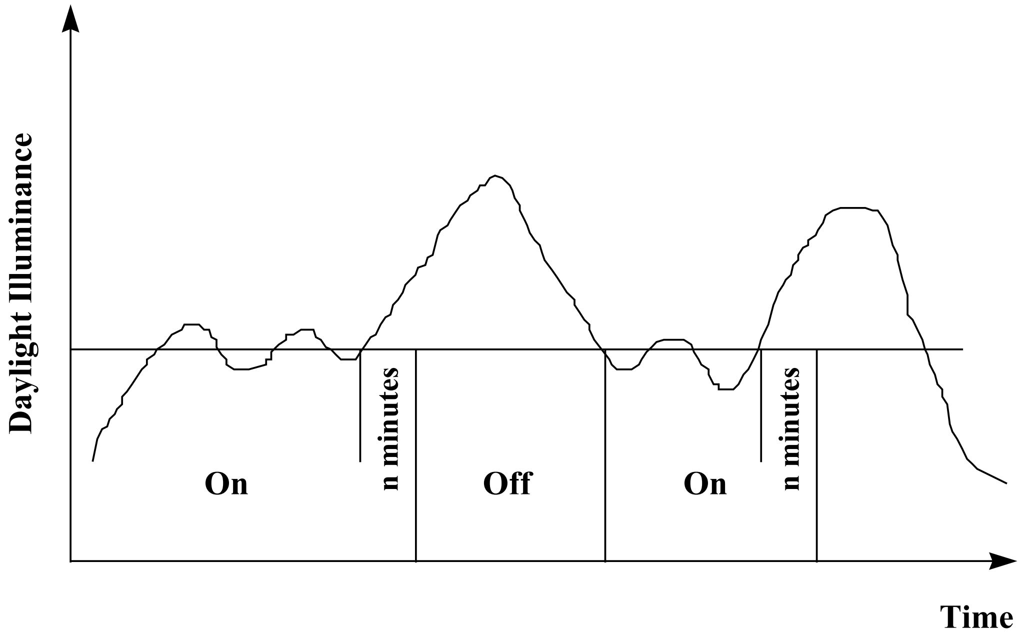
- Switching linked time delay, where switching off cannot occur until at least n minutes after the last switch on, where n is a preset delay.

- Daylight linked time delay, where switching off cannot occur until the daylight illuminance has exceeded the target value E_s for n minutes.

No delay in switching on is considered because that could lead to illuminance falling below desired levels.



Linked time delay photoelectric control



Daylight linked time

Of the two above mentioned time delay strategies, the second one gives significantly less switching. For the same time delay, the switching linked control will give lower energy use than the daylight linked version.

4.6 REFERENCES

1. Jack Lindsen , "Applied Illumination Engineering", Fairmont Press, USA.
2. Kao Chen, "Energy Effective Industrial Illuminating Systems", Fairmont Press, USA.
3. Notes from Vic Roberts (kirther@ix.netcom.com).
4. Notes from Graig Larson (larson@freenet.msp.mn.us).
5. Tips on daylighting , Lawrence Berkeley National Laboratory, LBNL-39945.
6. Slater A. "Lighting controls: an essential element of energy efficiency", BRE Information Paper IP5/87, Garston, UK.
7. Littlefair P.,"Predicting Lighting Energy Use under Daylight Linked Lighting Controls", BRE PD 246/96, September 1996.
8. Hunt DRG, "The use of artificial lighting in relation to daylight levels and occupancy", Building & Environment 14(1), pp.21-33, 1979.
9. Hunt DRG and Cockram A., "Field studies of the use of the artificial lighting in offices", BRE, CP 47/78, 1978.
10. Hunt DRG, "Predicting lighting use - a method based upon observed patters of behavior", Lighting Research and Technology, 12(1), pp.7-14, 1980.
11. Littlefair P., "A comparison of sky luminance models with measured data from Garston, UK", Solar Energy 53(4), pp 315-322, 1994.

12. Perez R., Seals R. & Michalsky J. "All weather model for sly luminance distribution-Preliminary Configuration and validation", Solar Energy, 50, pp 235-245, 1993.
13. Tregenza P., "Daylight coefficients", Lighting Research and Technology, 15(2), pp. 65-71, 1983.
14. Herkel S., Jankowski S., Pasquay T., Sick F., "New procedure for dynamic lighting simulation in buildings. Achivements and results, Annual report", Fraunhofer Institute, Solare Energiesysteme, 1995.