AN ENERGY-EFFICIENT APPROACH TO THE INTEGRATION
OF
DAYLIGHT AND ARTIFICIAL LIGHT FOR COMMERCIAL BUILDINGS
IN A WARM-HUMID CLIMATE

by

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STATEMENT BY AUTHOR

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INTRODUCTION

Since the Industrial Revolution, technology has given us a lot of materials including the invention of mechanical systems. These systems made it possible for architecture to ignore actual climate conditions by relying on an environmental control system. The climate-rejecting building, the standard environmental-solution type of the past 40 years, is an example of using form and envelope to diminish a climate-imposed load. The form and envelope serve only as barriers between climate and space for environmental control purposes. Environmental-control strategies are handled from within by equipment, such as electric lighting and some form of heating, ventilation and air-conditioning systems. Of course, these methods lead to higher levels of energy consumption.

Looking at the global economy today, we need to be increasingly aware of energy as a scarce resource. The design of buildings has to be changed in response to the energy crisis - a reduction of the global impacts due to energy use needs to be considered in the design process. “Design with Climate” is one of the solutions that will result in a reduction of overall energy consumption of a building with the use of passive techniques which do not require mechanical devices and benefit from the integration of natural resources, such as wind and light into a building’s design.

The energy use in commercial buildings is of particular interest in this report because electric lighting is a major energy consumer, accounting for 40%, in a typical commercial building. If electric lighting is proposed as a primary target for reducing a building’s energy consumption, the result will not only reduce electric lighting’s energy cost but will reduce heating and cooling loads as well.

The high consumption of electric energy for artificial lighting in commercial buildings has occurred because daylighting has been ignored. Illuminating buildings with daylighting requires more design control to reach the optimum of “quality” and “quantity”. Although a number of designers have avoided dealing with daylight integration, the use of artificial light
in place of daylight also causes many problems. For instance, illumination levels can exceed
the optimum required level, and frequently, artificial lights are used all times, regardless of
the external climate and availability of natural light. Such light discharges heat to the interior
of building, which increases impact the air-conditioning load. Since no electrical energy is
saved unless the lights are dimmed or turned off, daylight should be considered a potential
approach to be introduced into a building design by integrating it in a true approach.

The amount of natural light available to a building depends significantly on latitude and
climatic conditions. Commercial buildings in a warm-humid climate, the subject of this
report, are candidates for utilizing daylight since they are located in a region with abundant
natural light. Moreover, commercial buildings invite substantial savings in electric lighting
because of their potential to use daylight during daytime business hours. However, energy-
savings should not be the entire reason for daylighting design; building occupant satisfaction
is much more important. Therefore, the purpose in designing a daylighted building should
consist of two important goals: first, to provide its occupants with sufficient light to enable
them to perform activities comfortably, securely, and efficiently; second, to create an energy-
efficient building corresponding to its natural environment by using daylight as much as
possible while electric light serves for supplementing daylight. The more natural light used
in a building, the more artificial light savings occur.

How much the building’s interior and exterior design should strive to maximize daylight
penetration depends on many variables, as does the effect of available natural light on energy
consumption within the building. In design with daylight, especially, in a warm-humid
climate, light should be admitted into the building under sufficient control so that only a
qualitative amount of natural light is allowed to illuminate the building. While its thermal
effect and excessive brightness must be avoided by means of a variety of control devices, -
the natural building itself, so forth.

The amount of natural light available to building users depends upon the time of day and
year, latitude, and weather conditions. Available light can also be significantly determined by
the nature of building itself such as the size and location of the windows and skylights, the shape of the building and the corresponding ratio of interior and perimeter areas. Buildings can be designed to take advantage of daylight by adapting them to local climates and sky conditions as well as site constraints, but only if the designer's understanding and knowledge in site conditions and design concepts are conveyed precisely into the design. Therefore, this report pursued the necessary knowledge related to lighting design. This can be categorized in three parts: (1) design with climate, (2) daylighting design, and (3) artificial lighting design.

The information covered in these three parts is contained in chapters 1 through 4 with the purpose of responding to the three primary goals: (1) to understand the factors that affect daylighting design including variations in the intensity and distribution of daylight; (2) to explore the design strategies used for admitting natural light into the building that must be responsive to all of the factors in (1), and controlling daylight to ensure that light will be comfortable and pleasant as well as adequate in quantity; (3) to understand the principles of daylight and artificial light sufficiently to introduce them early in the schematic design phase so that a more functional and efficient as well as energy and cost-saving building can be developed. In chapter 5, the case studies of commercial buildings illustrates how buildings can be fully designed to overcome environmental concerns and summarizes how different kinds of daylighting strategies and artificial lighting systems can be implemented in a variety of buildings. Performance specifications are included to evaluate each project for its efficiency in lighting design strategy.

The study represented in chapters 1 to 5 outlines the early stage of design when daylight is proposed, and massing and orientation of a building play a major part in determining the daylight availability within the building. Each building's mass (form) represents its own particular set of strategies for using and controlling daylight. For example, a building may use its builtform and envelope to access daylight. There is more discussion of this in chapter 6 in the review of daylighting concepts. Further in chapter 7, a set of variables is selected to analyze, utilizing model testing to answer the following questions:
(1) How does daylight affect the design determinants of builtform, envelope, and orientation of a building?

(2) Which daylighting design strategies are appropriate for each building form (such as block, slab, or tower) to enhance daylight penetration and distribution for a building in a warm-humid climate?

In chapter 8, the results of the analyses in chapter 7 establish the alternative approaches and design principles to be used for a daylighted commercial building in a warm-humid climate. Although the design of massing and envelope as well as orientation of commercial buildings are the main concern in this report, they cannot perform their function very well if other elements such as the position, shape, interior partitions, ceilings, floors, and finishing as well as reflective surfaces are ignored in the design of daylit building. These elements can increase the efficiency of natural lighting.

Daylight cannot totally replace artificial light because it is not a reliable light source and it is only available during the daylight hours. To achieve an energy-efficient lighting design, both interior and exterior daylight factors must be well integrated with an artificial lighting system. Therefore, this master’s report proposes daylighting design strategies and covers the information on artificial lighting design which provide both energy efficient and a pleasant environment.

Finally, I hope the information contained in this master’s report provides a useful and practical knowledge to everyone who wants to capture the benefits of daylight in their design and to everyone who wants to pursue further study in this field.
Chapter 1: Design with Climate

1.1 Climate and Architecture

There are many reasons for combining architectural design with climate determinants. The most obvious is the lowering of costs as a result of decreasing energy consumption since the overall life-cycle energy cost of the building occurs during its operational phase. Thus, the savings would justify the incorporation of a climatically responsive design. Another reason derives from the impact on the users of the building. A climatically responsive building can promote a sense of well-being both inside the building physically and psychologically, and the occupants can experience the external climate.

From Yeang's (1994) view, apart from its basic geological structure, climate, as presented in the overall perspective of human history and built settlements, is the single most constant factor in our landscape. While socio-economic and political conditions may change almost unrecognizably over a period of years, as may visual taste and aesthetic sensibility, climate remains more or less unchanged in its cyclical course. History shows us that accumulated human experience and imagination are the architecture of shelter which evolved into diverse solutions to meet the challenges of widely varying climates, indicating that the ancients recognized regional climatic adaptation as an essential principle of architecture. In this regard, the climatically responsive building can be seen as having a closer fit with its geographical context. For this is reason architecture in different climatic regions have differences in their features. For example, buildings in a warm-humid climate are quite different from buildings in a hot-dry climate. In a hot-dry climate, buildings are found with massive walls containing small windows and light colors on the exterior surfaces. These characteristics found together because they respond to the intensive solar radiation predominating in this climate zone. In a warm-humid climate, the typical building responds to the environment by the use of many large windows, large overhangs, light colored walls and high ceilings for the propose of maximizing ventilation, protection from excessive solar
radiation and rain, and minimizing solar heat gain. To design in conformity with the climate, designers need to thoroughly understand the climatic conditions of the site to create good architecture which corresponds to both human needs and the local environment.

1.2 Climatic Elements

Climate is defined as the average condition of the weather at a given place over a period of years as exhibited by several elements, such as temperature, wind, and precipitation. Characteristics of climate in each region are different because of latitude, sky conditions, air movements, geographic characteristics, altitude, vegetation, and extreme climatic phenomena (storms, earthquake). These natural climatic factors can be modified to meet human comfort by changing the natural balance on a local or microclimate level. But the method of modifying needs to be carefully considered for each climatic location. The major climatic elements, when human comfort and building design are considered, are:

- Solar Radiation
- Air Temperature
- Wind
- Humidity
- Precipitation

These five climatic elements emerged primarily as a function of sun angle (latitude), and; divide the world into different climatic zones. The warm-humid climate zone of Miami, Florida is analyzed for this study. Florida is identified as a warm-humid climate region because its high air temperature and humidity emerge from intense solar radiation and precipitation that dominate this area almost throughout the year. The careful analysis of climatic elements (i.e. temperature, humidity) is very important since each element has both advantages and disadvantages for human comfort. The result of analyzing climatic elements is to find the beneficial issues that can be adapted and established as the primary principle of building design in warm-humid climate.
1.3 Analysis of the Warm-Humid Climate in Miami, Florida

1.3.1 Introduction

To design with daylight, it is necessary to understand the sources of daylight. Usually daylight entering a building comes from such sources as direct sunlight, clear sky, clouds, or reflections from the ground and adjacent buildings (fig. 1.1). However, the major source is the sun, which provides energy in the form of light and heat. Both solar light and heat are beneficial if they are within the range of human comfort, which is different in each climatic pattern. The availability of daylight and its thermal effect, especially in a warm-humid climate, needs specific strategies to introduce desirable daylight into the building while controlling the effect of excessive brightness and solar heat. The efficiency of daylight also depends on climatic factors and sky conditions. Therefore, the analysis of climatic factors in Florida provides an understanding of the processes and techniques needed for a climatically responsive design dealing with daylight in this region.

![Figure 1.1 Various Sources of Daylight](source)


1.3.2 Factors Affecting the Climate in Florida

Florida is located in a large lowland peninsula surrounded by a large proportion of the area occupied by the sea (on the east by the Atlantic Ocean, the south by Caribbean Sea, and the west by the Gulf of Mexico) and abundant inland waters. The climate of Florida is influenced by marine types, particularly the trade winds originating over the Atlantic Ocean. These winds come into Florida’s peninsular in an easterly direction. More importantly, they
bring with them large amounts of water vapor. When the high water vapor is combined with the strong solar radiation prevailing in Florida area, these elements affect the climate by causing summer rains. This classifies Florida's climate as a warm-humid climate. Other important factors causing variation in the local climate are:

1.3.2.1 Latitude

Florida is located in southeastern part of the United States between latitude 24°N and 31°N. (fig. 1.2). Due to the angle of the sun's ray Florida receives a high percentages of direct solar radiation all year round.

![Figure 1.2 Florida's Location](Source: Chahin, Oscar, Bioclimatic Architecture for Low-income Housing in Central Florida, 1991)

1.3.2.2 Water and Ground Surface

Florida's climate experiences small seasonal variations because its location near large bodies of water (the oceans and inland lakes). Water can moderate extreme temperature variations on land and can affect high humidity and rainfall within this area. Normally, the ground surface has a higher temperature during the day and a lower temperature at night because the ground surface heats more rapidly than water during the day and cools more rapidly at night. This action also creates air movement between land and water during daytime and nighttime. During the daytime, ground surface heats up; the hot air rises and cool air flows in to
replace it. The land near lakes and oceans benefits from a daytime breeze blowing from the water to the land. At night, the air over ground surface cools faster than air over water; thus, the process is reversed.

1.3.2.3 Prevailing Winds

Wind is air movement generated from high pressure to low pressure due to the uneven heating of the earth’s surface and the rotation on its axis. Wind is classified differently based on velocity and origin. Winds prevailing in Florida’s climate originate from trade winds, tropical storms, and hurricanes. During summer, the easterly trade winds coming from the Atlantic Ocean enter Florida from the southeast. During winter, the northerly winds bringing cool air from the northern latitude affect the local climate from October through March. The special concerns in designing buildings in Florida are tropical storms and hurricanes which always cause a great intensification of both wind and rain. Hurricanes and tropical storms occur in the east and southeast peninsula mainly from September through November.

1.3.2.4 Topography

Florida’s topography is a lowland peninsula with a total area of about 58,600 square miles (land 54,100 square miles, water 4,500 square miles). No point in this state is more than 70 miles from sea water or an inland lake. The highest point is in the northwest, about 345 feet above sea level. The elevation inland ranges between 50 and 100 feet above sea level. One third of the southern part of Florida is swamp land known as the Everglades (Chahin, 1991).

Due to its latitude, topography, prevailing winds, and the characteristics of a lowland peninsula exposed to a large area of sea water. Florida has a long hot summer with
high temperature, high humidity, and abundant rainfall. These conditions cause discomfort during summer months, especially at night, but winters are relatively mild and pleasant.

1.3.3 Climatic Evaluation of Miami, Florida

Miami is located in southern Florida at latitude 24°N. Because of its location surrounded by the oceans and inland lakes, the climate of Florida has a high relative humidity year round ranging from 55% - 65% during daytime to about 90% at night. The average temperature in summer is 79 °F and the highest temperature ever recorded was 96 °F. In winter, the average temperature is 69 °F and has never dropped below freezing. The average annual temperature in Miami is 75 °F.

The direction of prevailing winds is from the South in summer and from the North in winter. In winter (October through March), the winds from the north as well as east are very strong; thus, a design which provides protection from northerly low temperature winds is required. Protection from high velocity winds (hurricanes) from the east and southeast that normally occur from September through November is also needed. The breeze in summer reduces the high humidity and increase the rate of airflow. In addition, the other factors which play the major role in Miami’s climate are:

1.3.3.1 Sunshine

![Sunshine Graph]

Figure 1.3 Sunshine (average % of daylight hours)

The average annual sunshine hour is 72%, reaching a maximum in March and April. Sky conditions are partly cloudy throughout the year. Most clear days occur in late winter and early spring (from November to March), with the maximum occurring in March. The partly cloudy skies of summer cut down the effectiveness of solar heat, while clear skies in spring and winter receive the most intense solar heat, averaging about 1762 BTUs day. This is more than is received in summer despite longer hours of daylight (Bulletin of AIA,1950). Solar radiation in Miami is largely diffused but relatively strong with sky glare.

1.3.3.2 Air Temperature

![Temperature Chart]

Figure 1.4 Air Temperatures

Air temperature is the important climatic factor used to determine human comfort. When temperatures are above human comfort, a design emphasizing protection from the uncomfortable heat is required. For Miami, extreme heat is experienced almost every afternoon from June to September and on exceptionally sunny afternoons in March, April, May, October, and November. A design which reduces solar heat and provides comfort by shading, insulation, or air-conditioning is necessary to increase ventilation and protect buildings from solar radiation.
1.3.3.3 Relative Humidity

Relative humidity (RH) expresses percent of moisture in the air relative to what it can hold at any given temperature. Generally RH is highest in the low temperatures of night and lowest in high temperature of day. The range of RH varies throughout the year from 55% - 65% during the day to 90% at night.

1.3.3.4 Wind Speed

Wind in a warm-humid climate is very important for enhancing natural airflow and producing cooling effects by increasing the rate of evaporation and convection between human bodies and their surroundings via air movement. Wind speed and direction are used to determine builtform and orientation in passive architectural design. Summer winds in Miami from the south and east are a desirable source for promoting a cooling effect during hot temperatures, but winter winds from the north and northeast are not welcome because of their strong movement and low temperatures. Therefore, wind coming from this direction needs to be blocked. The design should also take into consideration hurricanes from the east.
and southeast that occur in Florida from September to November, reaching their maximum strength in September.

1.3.4 Bioclimatic Evaluation of Miami, Florida

The analysis of climatic elements and bioclimatic evaluation of Miami provide significant information about the relationship between microclimate and human comfort condition. Designers need to understand this relationship to adjust the climate in response to human needs. Architectural design can take advantage of the local climate when it is desirable and control the climate when it is adverse.

The bioclimatic chart, developed by V. Olgyay, assembled data from climatic elements, such as temperature and relative humidity into a single chart (fig.1.7). In the chart, the comfort zone, appearing in the center, is surrounded by the climatic element curves, which indicate the nature of corrective measures necessary to restore the feeling of comfort at any point outside the comfort zone. This chart is applicable only to residents of the moderate climate zone in the United States at elevations less than 1,000 feet above sea level, wearing customary indoor clothing and doing light work. The climatic situation throughout the year is represented by the monthly closed curves moving upward until July and downward till January. Each closed curve comes from the climatic data of a typical average day of each month. Later, the information in a yearly bioclimatic chart such as radiation (full lines), shading or overheated period (dotted area), and wind effect (lined indication) is transferred into a timetable of climatic needs to indicate the elements that will restore comfort (fig. 1.8).

The bioclimatic chart shows that Miami has a fairly constant year-round temperature (the range between the hottest and coldest month does not exceed 15°F), and constant high humidity (60% - 90%). The timetable chart indicates the need for shading for at least six hours/day, throughout the year, even in the coldest month, and thus wind can reduce both high temperature and high humidity.
The bioclimatic evaluation chart, composed of the climatic elements and bioclimatic needs, conveys more information than the main climatic elements alone. From the chart, it is possible to estimate the balance of natural forces that can be applied in the design of a building. The interpreted data of bioclimatic and timetable chart can be used to evaluate the proper architectural method to be used in relation to comfort condition and climate. For instance, in overheated periods the methods which can cut out strong radiation, provide shading, increase outgoing-radiation, and reduce air-temperature are required. Similarly, in underheated period the methods that can prevent heat loss and increase air temperature are needed.

Figure 1.7  Bioclimatic Chart of Miami
Source: Olgyay, V., Design with Climate: Bioclimatic Approach to Architectural Regionalism, 1965
1.3.5 Air Temperature and Solar Radiation:

The major impacts in a Warm-Humid Climate

The result of a climatic study in Miami, Florida shows two major climatic elements which strongly affect comfort conditions in a warm-humid region similar to Miami are *air temperature* and *solar radiation*. These two factors shape the characteristics of Miami's climate by causing a long overheated period during the day throughout most of the year, including the small diurnal and seasonal variations of temperature. Both air temperature and solar radiation are dominated by the sun in the form of solar energy.

1.3.5.1 Air Temperature

The variation of temperature depends partly on sky conditions. On a clear-sky day, large amounts of incoming radiation and a free path of outgoing radiation cause wide temperature ranges. The more solar radiation received during the day causes high temperature and the more solar radiation released during the night causes low temperature. On the other
hand, in an overcast-sky, the variation of temperature is less. This is a reason for small
diurnal and seasonal variations in Miami’s weather. The overcast skies most of the year are
due to its high water vapor content.

1.3.5.2 Solar Radiation

Solar radiation is a major natural source generating a thermal effect on the earth’s environment. The intensity of solar radiation on the earth’s surface is based on factors, such as the length of the day, the angle of the sun, the distance and quality of atmosphere where it passes through, and the amount of clouds determined by sky conditions.

When radiation passes through the earth’s atmosphere, some incoming solar radiation is reflected by cloud and some is absorbed by atmospheric elements, such as water vapor, chemical vapor, and dust particles. A certain amount of diffused radiation is scattered by molecules in the atmosphere. Olgyay’s explanation (Olgyay, 1963) indicates that a small part of the radiation received at ground level is reflected by the earth’s surface, but that most of the energy is absorbed; it changes to heat and raises the temperature of the air, the ground and surrounding objects (fig.1.9).

To adapt this knowledge to building design, the impact of incoming and outgoing radiation needs to be understood. Radiant heat transfer affects buildings by: direct short-wave radiation from the sun, diffuse short-wave radiation from the sky vault, short-wave radiation reflected from the surrounding terrain, long-wave radiation from the heated ground and nearby objects, and outgoing long-wave radiation exchanged from the building to the sky.

On a clear day, most solar energy reaching the earth’s surface is direct radiation, while on a cloudy day most of it is diffuse radiation. The overall heat received on a cloudy day is much less than the overall heat received on a clear day (direct plus diffuse). The magnitude of direct and diffuse radiation is a function of solar altitude and the angle of incidence of the sun. To estimate the position of falling sunlight, the application of a sun-path diagram has
been proposed by many authors, but the one stated here is by V. Olgyay. He proposed that the sun-path diagram for Miami, Florida is 24°N latitude. This diagram has been used in tracking sunlight that falls on buildings in Miami at different locales, seasons, and times (fig. 1.10). Moreover, on this diagram, the overheated periods are transferred to the diagram to predict when each area will receive the impact or benefit from sunlight and its radiation. The plotted, overheated period indicated in dark tones shows when shading is needed, and the white area indicates when sunshine is needed. At Miami’s latitude, the need for shading is required throughout the year, except for the months of January and February when the sunshine is welcome. The AIA bulletin suggests that for Miami, sun elevations above 50° on the south side should be excluded from the interior of buildings by shading or overhang, while sun light under 50° should be permitted to enter a building. In summer, the north wall gets more sun than south wall, but the high power radiation of the sun has a greater heat effect on the east and west walls as well as the roof.

Figure 1.9  Heat Exchange

1.4 Architectural Principles for Buildings in a Warm-Humid Climate

In a warm-humid zone, high rainfall and high humidity conditions prevail with a small diurnal range and even temperatures throughout the year. Radiation intensity is high with a large proportion of diffuse radiation causing a strong sky glare. Usually, light winds and long periods of still air dominate these regions during the summer, but in some areas, such as Florida, there is a hurricane season. Rain usually falls in afternoon, especially during summer when air temperature is high. Therefore, the design principles in response to a warm-humid condition based on concepts to reduce heat gain and promote ventilation are:

1) Orientation

The optimum orientation should respond to the requirements that allow maximum radiation in an underheated period while reducing the insolation to a minimum in the
overheated period. For the most desirable design for a building in this climate, its orientation should be perpendicular to the axis of the overheated period, or the building should avoid facing in east and west as much as possible.

2) Form

In a warm-humid region, strong radiation attacks the east and west side of a building. To avoid the extreme effects imposed, a slender elongated structure is the most desirable shape. This shape is beneficial because air flow increases the evaporation rate. If the building is under protective shade, a free plan shape may be used.

3) Shading Device

Shading devices are important to protect buildings from the strong radiation particularly on the east and west sides, but another important factor is that the north wall receives a greater radiation impact in the summer than the south wall.

4) Structure

4.1 Openings and Windows

Since ventilation is required throughout the year, large openings and windows are used wherever air is needed. The elements of the openings admit airflow and, at the same time, their function is needed to protect the building from strong radiation and glare.
4.2 Walls

Building walls have less thermal value than in any other region. Lightweight materials with low thermal capacity are suitable for use.

4.3 Roof

Roofs in this region receive a higher thermal impact than walls. Lightweight, low thermal capacity, ventilated double roof, and reflective roof coverings are preferable for reducing heat gain. In addition, protection from rain (usually falling at a 45° angle) and sky glare need to be considered.

4.4 Surface

The surface of the building envelope should be protected from the impact of humidity, fungal growth, and insects. For thermal impact, materials should be reflective (light colored) or low thermal capacity.

An understanding of the effects of a regional climate helps architects apply traditional methods of design by adapting the building itself to lighting and thermal comfort. For energy efficiency, various strategies need to be examined for optimum ways of designing lighting for commercial buildings in a warm-humid climate. Moreover, it is important to understand how different building forms adapt themselves to daylight and which strategies are suitable to promote light efficiency by means of both passive techniques, relying on daylighting design, and active techniques, relying on mechanical equipment and electric light.
Chapter 2: Common Terms and Properties of Light

Before we can use daylight and artificial light effectively, an understanding of the fundamentals which constitute quality seeing conditions is crucial. Light affects the interrelation between human perception and surroundings.

According to Schiler (1992), light may be thought of in two ways when it involves design. First, certain levels of illumination are necessary for us to use a space and to see well enough to function at our designated tasks. Second, the forms and spaces themselves are perceived in terms of light. How we feel about the sculptural nature of a building is also determined by light. For both of these areas, an understanding of the physics of light and the factors affecting seeing conditions is necessary.

Light has many characteristics that must be named and defined separately. To deal with light in a design, the behavior of interrelated terms, must be defined because this is the only way we to understand how light behaves.

2.1 Lighting Terms and The Physics of Light

2.1.1 Units of Measure

**Lumen (lm)**

A quantitative unit for measuring the flow of light energy is referred to as luminous flux. In the English system of units, 1 lumen is equal to the luminous flux emanating from 1 sq. ft. of a hypothetical surface in which all points are 1 foot from a uniform point source of 1 candlepower (candlepower is the intensity of light radiated in a particular direction by a light source). In SI units, 1 lumen is the luminous flux emanating from 1sq. m. of a surface in which all points are 1 m. from 1-candela source. Illumination is the intensity of luminous flux expressed as lumens per unit area.
Footcandle (fc)  One lumen of luminous flux spread uniformly over an area of 1 sq. ft. produces an illumination of 1 footcandle. When an SI lumen is spread over 1 sq. m., the illumination is expressed in lux (lx).

English System: footcandles (fc) = lumens/sq. ft.
SI System : lux (lx) = lumens/sq. m.

(1 footcandle = approximate 10 lux)

Footlambert (FL)  A quantitative unit for measuring brightness or luminance, as an index of the intensity of light being emitted, transmitted, or reflected from a surface. The terms brightness and luminance may be used synonymously. The value of a footlambert is 1 lumen per square foot, which is expressed in the same units as the footcandle. When the illumination is on a surface, the lumens per square foot are measured as footcandles. When the brightness is from a surface, the lumens per square foot are measured as footlamberts.

Efficiency  The efficiency of a luminaire is the ratio of light output (luminous flux) to the light produced by the lamp.

Efficacy  The efficacy of a light source is the ratio of output of luminous flux, expressed in lumens, to the power input in watts, and is expressed in lumens per watt.

2.1.2 Transmission, Reflection, Refraction, and Absorption

All light striking a surface is either transmitted, reflected, or absorbed. Transmitted light passes through the material and the material does not completely change or lose its image, that material is called transparent. Material that is transparent may change the image on the lens or prism. This is called refraction and occurs to some extent with nearly all transparent materials.
Reflection occurs when incident light is left from an incident surface of a material, such as from glass to air. If no image is transmitted, but light passes through, the material, it is called translucent. Translucent materials may actually transmit more light than some transparent materials. If the reflected image is maintained (e.g. mirror), the surface is called specular. If the image is not maintained (e.g. a matte white finish), the surface is called diffused.

2.1.3 Light and Color

Light is defined as that portion of the electromagnetic spectrum to which our eyes are sensitive. The intensity of solar radiation reaches the earth as a function of wavelength. Normally, the solar spectrum at the earth’s surface consists of 47% visible, 48% short-wave infrared, and 5% ultraviolet radiation. Human eyes are limited to the visible spectrum, which is approximately 0.4-0.7 μm wavelength as shown in figure 2.1. In the range of this visible light, human eyes can be sensitive to light in several colors such as red, orange, yellow, green, blue and violet. Ultraviolet radiation causes burn or tan to our skin. Although we cannot see beyond the visible spectrum, we can feel infrared radiation on the skin as heat.

![Figure 2.1](source: Lechner, Nobert, *Heating, Cooling, Lighting: Design Methods for Architects*, 1991)
White Light is a mixture of various wavelengths of visible light. A full spectrum of white light is usually required for an accurate judgment of color. In the real world, it is rare to find a perfect white light. However, daylight on a clear day in summer at noon may be considered the best color balance, because this daylight is made up of an even mixture of the various colors as shown in figure 2.2. North light is also considered an ideal white light, not because it may have the best color balance, but because it is the most consistent source of white light. Light from windows in different orientations varies greatly throughout the day and year. For example, daylight in the late afternoon has much more energy in the red end of the spectrum and less in the blue end. In addition, Lechner (1991) stated that although daylight and many artificial light sources supply white light, there is obviously a great difference in the composition of these sources, which affects the way we see colors. He also stated that the color of a surface is visible because of its reflectance characteristics and the spectral composition of the illumination. When a bright red car is parked at night under a clear mercury lamp, it will appear brown in color since clear mercury lamps emit mostly blue and green light, there is little red light that the car can reflect. Although much of the light of the other colors was absorbed, enough blue and green was reflected to overwhelm the red light. There leads to a better understanding of the color rendering ability of a light source. Care must be considered in the selection of a light source that must be matched to the desired space or area.

![Figure 2.2](image)

Figure 2.2  The spectral energy distribution of average daylight at noon on a clear day in June is almost even distribution of the various colors.

2.2 Performance of Visual Tasks

A number of factors to be considered in the improvement of visibility of a task are:

1. Task Contrast

The contrast between the detail (e.g. the print on a piece of paper) and its immediate background (the paper) should be high. For example, if prints are reproduced in a light color (e.g., gray) and the background is white, they will certainly be more difficult to read than if they were black on a white background. Sorcar (1987) stated that for each 1% loss in contrast between a visual task and its background, there is a need for 15% more light to maintain the same degree of visibility. Therefore, visibility is at its maximum when the luminance contrast of the details in the background is at its maximum.

2. Size/Proximity of the Visible Task

The actual factor of visual performance is not size but the exposure angle, since the object will appear larger if move closer. Whenever possible, the size of the visible task must be large and clear enough to be easily read. According to Lechner (1991), a small increase in size is equivalent to a very large increase in illumination level. For example, a 25% increase in lettering size on a blackboard increases visual performance as much as a change in illumination from 10 to 1000 footcandles.

3. Speed and Accuracy of Reading

The speed of reading of the visual task depends mainly on the eye’s ability to focus on the word, adjust to it, and then pass the message to the brain. Inadequate type size, a low level of illumination, and a lack of contrast and luminance will decrease visual ability, affecting the speed and accuracy of reading.

4. Age of Viewer

Aging of the eye has a serious consequence on vision. All of the foregoing factors are of particular interest if the viewer is an older person. Vision decreases drastically as the eyes
age. The older they get, the higher the amount of quality light required for the same visibility.

Sometimes, to improve the performance of a visual task, the high brightness that accompanies high levels of illumination is required. However, when increasing brightness, the impact of unwanted high brightness (glare) always occurs. This unwanted high brightness can reduce both visual acuity and contrast sensitivity. Glare can be categorized as direct glare or reflected glare based on the path of light.

**Direct Glare**

*Direct Glare* is caused by a source directly visible within the field of view (such as light seen from unshielded luminaries or a window). The severity of glare caused by a light source is in large part due to its brightness. However, it is not only absolute brightness but also apparent brightness that causes glare. A bare lamp against a black ceiling would cause much more glare than the same lamp seen against a white ceiling. For this reason, ceilings are usually white.

Direct glare is also a result of geometry. The closer an offending light source is to the center of vision, the worse the glare. Windows are often a serious source of glare. Direct glare also increases with the size and proximity of the source. There are several possibilities for reducing glare. For example, when there is a direct glare from a ceiling mounted lighting fixture, it can be minimized or avoided by the use of eggcrates, lenses, and diffusers.

**Reflected Glare and Veiling Reflection**

*Reflected Glare* is a glare from a glossy surface that reflects an image from the light source. This reflected glare is often avoided by the use of flat or matte finishes.

*Veiling Reflection* is a reflected glare that occurs when the source of illumination is reflected by a specular task surface. An example of veiling reflection is the image of an electric lighting fixture reflected on the surface of a glossy magazine. Veiling reflections
reduce visibility because the brightness of the reflected image causes an increase in the brightness of both the light and dark features of the task surface. According to Moore (1985), veiling reflections can be controlled by:

- locating all relatively concentrated light sources outside of the reflected field of view
- reducing source luminance by distributing the light source over a larger area

When good visual performance and comfortable illumination of space are required, the avoidance of glare should be a major goal of any lighting design.

Figure 2.3  Direct Glare, Reflected Glare, Veiling Reflection
Chapter 3: Daylighting Design

3.1 The Economics of Daylighting in Commercial Buildings

Commercial buildings are composed of various types, such as offices, institutions, public buildings, retails, restaurants, health, and warehouses. These buildings challenge the designer in an energy-responsive design in terms of daytime occupancy and intensity of energy use. From the information of U.S energy use (AIA Foundation, 1989), the total end use energy breakdown in commercial buildings is shown in figure 3.1. This can be compared to the largest commercial building end user, office buildings, in figure 3.2, which shows the greatest amount of energy use is from lighting systems. Fuel types used for generating energy in commercial buildings on the average are 67 percent electricity and 33 percent fossil fuels. Although figure 3.1 shows that space heating represents a substantial portion of energy end use in many types of commercial buildings, such as warehouses, schools, churches, and small retail stores, space heating is less efficient in buildings, such as offices and large retail stores, where cooling and other internally generated loads are predominant.

![Figure 3.1 End Use Energy in Commercial Building](image1)

![Figure 3.2 Electricity Use in Office Building](image2)

In addition, figure 3.3 shows commercial electricity use in the United States during 1995. Lighting accounts for 37 percent of electrical energy consumption while heating and cooling accounts for 39 percent. Lighting has an indirect impact on total energy use, because the heat generated by electric fixtures can alter the load imposed on the mechanical cooling equipment. As a rule of thumb, Ander (1995) believes that energy savings from reduced lighting loads can directly reduce air conditioning energy usage by an additional 10 to 20 percent.

Because a reduction in lighting energy consumption would provide an additional reduction in the cooling load, there has been a concerted effort to make lighting systems more efficient. In 1970, electric lighting systems in office buildings were designed to provide 100 to 200 footcandles with electricity consumption of about 5 watts per square foot. Currently, recommended light levels have dropped to a range of 25 to 100 footcandles, with typical power consumption around 1.5 to 2 watts per square foot. Over the next few years, the average footcandle levels may drop again, and, with the use of more efficient lighting hardware, electricity consumption of lighting systems may drop to 1 and 1.5 watts per square foot. Savings in electric lighting may be expected in the future with more advanced and possibly more expensive hardware. However, to provide savings now and over the life of the building, daylight can be introduced to displace electric light to achieve energy savings. Johnson (1986) stated that daylight affects costs in three ways:
1. **Annual Electricity Consumption**

Since about 37 percent of the energy used in a commercial building is spent illuminating the interior of the building, anything that reduces the use of electric light will significantly lower energy requirements. Daylight is more efficient at providing light than most electric light sources because less heat is produced for the same amount of light. Therefore, daylighting the interior of a building can reduce not only the building’s use of electric light, but also its use of cooling energy.

2. **Electrical Peak Demand Charges**

Commercial building owners pay for the energy they consume as well as a demand charge, which reflects their peak electrical consumption each month. Since peak electrical demand frequently occurs on summer afternoons when both air conditioning and electric lighting are in use, a daylighted building should reduce peak electrical demand, thus providing an additional economic benefit for the owners.

3. **HVAC Equipment**

Cooling systems are designed to meet peak cooling loads. Two of the major contributors to cooling loads are solar gain and electric lighting. A daylighting design with fenestration designed and managed to mitigate solar gain will reduce both the solar gain and the heat generated by electric lighting. Components of the cooling load will require smaller chillers and air distribution equipment.

However, for the economics of commercial buildings, the most important benefit in the application of daylighting is not energy conservation, but increased occupant satisfaction, since daylight savings are small relative to occupancy costs (wages, etc.). Occupancy costs usually represent the largest single expense item, particularly in an office building. Therefore, improving occupant satisfaction and productivity should receive more attention than energy consumption. The need for occupant satisfaction is a comfortable environment which responds to human needs for air temperature, light, view, and contact with the outside environment via daylight apertures. Accordingly, daylighting designs should be implemented
with two significant goals in mind: to first, improve the quality of the interior environment, and secondly, to save energy.

3.2 Description of Daylighting

Daylighting is defined as the use of daylight which is the generally diffuse light available from the sky vault plus light reflected off adjacent surfaces as an interior illuminant. Daylighting design involves three principle sky conditions which vary the nature and quantity of the light entering a building. These conditions are:

1. **The clear Sky** - is generally less bright than the overcast sky and tends to be brighter at the horizontal than at the zenith. It tends to be fairly stable in illuminance except for the area surrounding the sun, which changes as the sun moves. The clear sky is defined as being a sky in which no more than 30% of the sky dome is obscured by clouds. The total level of illumination produced by a clear sky varies constantly, but slowly, throughout the day. The illumination levels produced can range from 5,000 to 12,000 footcandles.

2. **The Partly Cloudy Sky** - is defined as being a sky in which 30% to 80% of the sky dome is obscured by clouds. This sky condition has the aspects of both clear sky and overcast sky conditions but is quite variable in nature because clouds move and change rapidly. In partly cloudy sky condition, white clouds have a high reflectivity and, when viewed from the interior of a building, can be exceedingly bright, causing excessive contrasts and visual discomfort. Usually, the partly cloudy sky often produces the highest level of illumination.

3. **The Overcast Sky** - produces the most uniform illumination and generally tends to change more slowly than the other types. An overcast sky is defined as one in which at least 80% of the sky dome is obscured by clouds. The overcast sky has a general luminance distribution that is about three times brighter at the zenith than at the horizon. This sky condition is most often used to evaluate a daylighting design condition because it
represents the minimum sky condition to be encountered. The illumination produced by the overcast sky on the earth’s surface may vary from several hundred footcandles to several thousand, depending on the density of the clouds.

For daylighting analysis, only clear and uniformly overcast skies can be simulated by a physical and mathematical model. Partly cloudy skies can only be assessed statistically since conditions may vary enormously from minute to minute. Daylight availability is the term used to refer to the frequency or probability of certain illumination levels at a given location. However, since the amount of daylight available from the sun and the sky tends to change almost constantly, it is impossible to predict with any precision what the interior daylighting conditions in any building will be at any moment. But it is not necessary that precise conditions be predictable. *Energy Design for Architects (1989)* stated that “the building designer should establish a set of goals to be achieved within a reasonable range of expected exterior daylight conditions and then attempt to make the most of that available daylight, while providing a supplemental electric lighting system to contribute the necessary lighting when sky conditions are inadequate.”

In a warm-humid climate such as Miami, Florida, most of the year is dominated by a partly cloudy sky and an overcast sky, 152, and 110 days respectively. During the rest of the year, Florida’s skyvault is clear. Hence, the expected exterior daylight conditions should be based on the characteristics of a partly cloudy sky condition. In such sky conditions, a design has to avoid direct sunlight, because of potential problems of overheating from solar gain and visual discomfort resulting from glare, which generally must be obstructed.

However during the clear sky day, which usually occurs for a few months during the winter, daylight consists of the two components of skylight and direct sunlight. Direct sunlight during this time is welcome because of its solar heat. Moreover, Lechner (1991) suggested that, “although direct beam sunlight has a lower efficacy (lumens/watt) than skylight, its efficacy is compatible to the best electric sources, while its color-rendering
ability is superior (fig. 3.4).” Therefore, it is not always a good policy to exclude direct sunlight. With the proper design, it can supply high quality as well as high quantity daylight.

![Figure 3.4](image1)

The efficient (lumens/watt) of various light source is compared to the efficacy of various daylight conditions.


Not only the light from the skyvault, but reflected light from the ground and adjacent surfaces is often a significant source of daylight. Reflected light is uneven in its distribution because it depends upon the reflectance value of the reflecting surfaces. More explanation about this phenomenon is provided in “Elements that Influence Interior Illumination from Daylight.”

### 3.3 Benefits and Goals of Daylighting

Each building has different requirements, needs, and constraints. The decision to use daylight must be justified in conjunction with other design elements. For most projects, daylight does not have to be the central design determinant. Usually, a designer does not have to choose between using daylight as the key design element or not using it at all. For example, daylight can be used to enhance visual ability along a wall, or at a workstation; it can be used to highlight a piece of art or to add drama and mood to a space. Thus, daylight
should be proposed for use as an important design element or a very minor element. There are a great number of justifications for the use of daylight as a light source in commercial buildings. Among these reasons stated by Robbins (1986) are:

- Quality of the light
  - Daylight, which is a combination of sunlight and sky light, is a light source that most closely matches human visual response. Daylight is a full-spectrum light which provides a good color rendering. Because the quality of daylight is so good, it often takes less daylight to perform a visual task than it would to perform the same task under electric light.

- Importance of daylight as a design
- View (visual communication to the outside is provided via daylight apertures)
- Use of daylighting apertures as fire exits in emergencies
- Use of daylighting apertures as ventilation openings
- Energy conservation resulting from the use of daylight as a primary or secondary illumination
- Energy consumption and peak demand cost savings resulting from the use of daylight
- Opportunity to develop integrated structural and mechanical systems
- Psychological and physiological benefits not obtainable with electric lighting or windowless buildings
- The genuine desire for natural light and sunlight in a room or space

There are a number of works detailing the methodological use of daylight in building design. The famous architects of the twentieth century who used daylight as the central design determinant in their works were Alvar Alto, Le Corbusier, Louis Kahn, and Frank Lloyd Wright. These designers utilized varying quantities of daylight in different spaces of a building to create the general form, spatial arrangement, and massing for the building.

Generally, the functional objectives in daylighting in a building are similar to that for electric lighting in which they must supply a sufficient quality light to a space while
minimizing direct glare and veiling reflections and excessive brightness ratios. However, there are some specific goals that refer only to daylighting such as:

1. Put significant quantities of daylight as deep into the building’s interior as possible
2. Reduce or prevent severe direct glare of unprotected windows and skylights
3. Reduce or prevent veiling reflections (especially from skylights and clerestory windows)
4. Prevent excessive brightness ratios (especially those caused by direct sunlight)
5. Maintain a uniform distribution of daylight with no dark spots from one area to another
6. Diffuse light by means of multiple reflections recoiling off the ceiling and walls.

Beyond these six goals, there is another desired goal when solar heat is not a critical problem and where there are no critical visual tasks. This goal is the use of the full aesthetic potentials of daylighting and sunlight, since direct sunlight can be a major design element to provide moods of drama and excitement.

3.4 Elements that Influence Interior Illumination from Daylight

Building designers can control the intensity and distribution of daylight by manipulating a number of architectural variables. Both local climate and site conditions affect daylight availability. They should be considered in the selection of the building’s orientation as more or less advantageous in terms of access to daylight. The use of daylight will be difficult if the building’s location is too near to tall buildings that obstruct the sky and sun. Sometimes, adjacent buildings can be an advantage if their surfaces are sufficiently light colored to reflect light without causing glare. Other site factors such as concrete, gravel, or water will either detract from or enhance the available daylight resource. It is possible to increase daylight in a building by using the building’s forms and proportions; for example, the use of floorplans.
with projecting wings, enclosed courts, and other design configurations with extended perimeter zones.

The selection of fenestration systems has a major influence on the amount of daylight entering a building’s interior. These systems function to control and admit daylight. For instance, window glazing located near the ceiling in a room produces deeper penetration than glazing low on a window. Strip glazing produces more uniformity across the room than individual windows. Reflective or tinted glazing will reduce the amount of daylight in a space; however, it may be desirable in some cases to control glare. In general, some types of solar control could be used together with fenestration system to provide efficient results.

Moreover, the details of room design, such as furnishings and room geometry, are also important in a daylighting design. Room surfaces should be finished with light colors or high reflective materials. Splayed windows will attenuate the light gradient from the window glass to the wall gradually, rather than abruptly. Task location and orientation of occupants are other variables. The best light for visual tasks is provided when daylight comes from the side of occupant’s position.

The above are examples of the general ideas used to control daylight by means of architectural design methods. However, for best results in energy-efficient aspect, daylighting design needs to be integrated with an electric lighting control system and the use of energy-efficient luminaires. Before beginning daylighting design strategies, key variables and elements that influence interior illumination from daylight are discussed in the following: site elements, massing and orientation, and design elements.

3.4.1 Site Elements

Daylighting design is complicated by the movement of the sun as it changes position with respect to the building throughout the day and the year. Daylight comes from the sun; it may be filtered, diffused, or scattered by clouds, and in some cases, it is reflected by the ground or
other surfaces. The availability of daylight for a particular location depends upon many factors, but two significant factors are:

1. Surrounding Objects
2. The Condition of the Skyvault

1. Surrounding Objects

When a daylighting design is proposed for a building, it is necessary to determine its availability at the site. Surrounding objects such as other buildings, trees, and landforms, all act as daylight obstructions by blocking either direct sunlight or portions of the skydome that are visible from the building's openings. The patterns of obstruction will normally vary for each window. They can have different shapes, different positions relative to the window, and different light-blocking or reflecting characteristics. Sometimes, it is possible to use the surrounding objects to enhance the availability of daylight where the building site is constrained. For instance, reflected light from the ground and adjacent buildings can be used as a major source of daylight (fig. 3.5). The reflectance factor of the reflecting surface is critical in this regard. A building painted white will usually reflect about 80% of the incident light, while an asphalt surface will reflect only about 10%. Table 3.1 shows the reflectance factors in percent for typical surfaces.

Figure 3.5  Sometimes, reflected light is the major source of daylight
<table>
<thead>
<tr>
<th>Material</th>
<th>Reflectance (%)</th>
</tr>
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<tbody>
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<td>70–85</td>
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<tr>
<td>Asphalt</td>
<td>10</td>
</tr>
<tr>
<td>Brick, red</td>
<td>25–45</td>
</tr>
<tr>
<td>Concrete</td>
<td>30–50</td>
</tr>
<tr>
<td>Glass</td>
<td></td>
</tr>
<tr>
<td>Clear or tinted</td>
<td>7</td>
</tr>
<tr>
<td>Reflective</td>
<td>20–40</td>
</tr>
<tr>
<td>Grass</td>
<td></td>
</tr>
<tr>
<td>Dark green</td>
<td>10</td>
</tr>
<tr>
<td>Dry</td>
<td>35</td>
</tr>
<tr>
<td>Mirror (glass)</td>
<td>80–90</td>
</tr>
<tr>
<td>Paint</td>
<td></td>
</tr>
<tr>
<td>White</td>
<td>70–90</td>
</tr>
<tr>
<td>Black</td>
<td>4</td>
</tr>
<tr>
<td>Porcelain enamel (white)</td>
<td>60–90</td>
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<tr>
<td>Snow</td>
<td>60–75</td>
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<td>Stone</td>
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</tr>
<tr>
<td>Vegetation, average</td>
<td>25</td>
</tr>
<tr>
<td>Wood</td>
<td>5–40</td>
</tr>
</tbody>
</table>

Table 3.1 Typical Reflectance Factors


2. The Condition of Skyvault

The condition of skydome for a given site is a function of climate. For a daylighting design, it is necessary to consider sky condition as well as the sun’s position because of its potentially large contribution to illumination.

Although the change is often not discernible by the human eye, the luminance or brightness of the sky changes almost constantly. In a warm-humid climate, the predominant sky condition is a partly cloudy sky which provides both intense and diffuse light, usually with excessively bright clouds in changing patterns. The partly cloudy sky may contribute major quantities of daylight but can be excessively bright and therefore, it should be shielded from view. To shield direct sunlight which is adverse for daylighting in a warm-humid climate, the sun’s angle about 40-50 degrees above the horizontal should be shielded from a field of view because of its high brightness and high thermal effect. Therefore, solar position is important because of its effect on winter sun penetration for passive heating and on the design of summer shading devices.
The position of the sun in the sky can be described by its *altitude angle* (vertical angle from the horizon to the sun ray), and *azimuth angle* (horizontal angle east or west of south) as shown in figure 3.6. The altitude indicates how high the sun is in the sky, and the azimuth indicates how far the sun is east or west from south. Both solar azimuth and altitude angles are a function of site latitude, day of the year, and solar time of day.

![Definition of altitude and azimuth angles.](image)

Solar azimuth and altitude are used advantageously in two graphic methods, sundial and sun path diagrams; which are particularly applicable in daylighting, passive solar design, shading, and reflector design.

**Sundial**
A sundial is a diagram of the locations of the shadow of the tip of a vertical pointer cast on a horizontal plane. Typically, the sundial is used to predict the sun’s position and determine solar obstructions to a site. More details on its application are available in “Concepts and Practice of Architectural Daylighting” by Fuller Moore (1985).

**Sun Path Diagram**
A sun path diagram (Olgyay and Olgyay, 1957) is a two-dimensional plan projection of the sun’s path across the sky. Sun path diagrams can be applied to predict the sun’s position at different times of the day and month of the year.
3.4.2 Massing and Orientation

Massing and orientation of a building can have a significant affect on daylighting performance. Since daylighting is a function of the exposure of interior space to the skyvault, massing and orientation should respond to microclimate and outside sky conditions. Proper design consideration in massing and orientation can promote daylight accessibility within the building, as well as reduce energy demand.

Building Mass

Single-story buildings - A single story building (and the top story of a multistory building) is suitable for skylighting because of the accessibility of interior areas to the skydome. Daylighting coming from an overhead light source is very effective because it tends to occur above the normal field of view of the occupants, thus the potential for direct glare is also reduced.

Multistory buildings - Daylighting in a multistory building will be most effective if the building is long and narrow so that daylight penetrates to the deep interior of both sides. The usefulness of daylighting can be achieved with reasonably sized fenestration openings to a depth of 25-30 feet. A guide based on high windows and a 10-foot floor to ceiling height indicates that a 15-foot perimeter zone can be task-lighted primarily by daylight, the next fifteen feet partially daylighted with supplemental electric lighting, with the remainder requiring electric illumination.

The presentation of how much floor area will have access to daylighting is explained by Lechner (1991). He assumed all three floor plans in figure 3.7 have the same area (10,000 sq. ft.). The results show that:

1. The Rectangular Plan can eliminate the core area that receives no daylight, but it still has a large area that is partially daylit.

2. The Square Plan is usually the worst plan for daylit space because daylight cannot penetrate the overall floor area. Thus, at the core area, it lacks daylight.
3. The Atrium Scheme is an area that is completely daylit. The percentage of core and perimeter zones depends upon the actual area. Larger buildings will have larger cores and less surface areas.

![Diagram of Atrium Scheme](image)

Figure 3.7 The effect of massing on the available of daylight.

To utilize daylighting effectively in multistory buildings, extending the perimeter’s form or an extension such as a wing may improve the building’s performance by increasing the total daylighting area (fig. 3.8). However, if the structure is tall and the space between wing is narrow, each wing becomes a skydome obstruction to the adjacent wings. The most important element here is proper spacing between each wing. This effect can also be minimized by the use of light-colored exterior surfaces. Another design consideration when building forms are extended (increasing building’s envelope exposure to the external climate) is the impact on thermal systems that will lose or gain through these envelopes. Therefore, a massing design of daylighting needs to be evaluated in conjunction with other systems, particularly those of heating and cooling.

![Building footprints for daylighting](image)

Figure 3.8 Building footprints for daylighting
Building Orientation

Usable daylight can be effectively admitted via apertures in walls of any orientation. The amount of daylight available as well as its quality will differ with each orientation. The difference in both quality and quantity of daylighting received by different orientations depends upon the position of the light source (sun) which creates differences in the brightness of the sky in different quadrants by changing its position at a particular moment. The design considerations of daylighting in each orientation are:

1. The north orientation

Apertures facing north will receive more uniform diffuse sky light because of their exposure to less direct sunlight. Although the quantity of north light is rather low, the quality is high. There is also a problem with glare from the direct sun during summer. In very hot climates, the north orientation may be even preferable to the south orientation.

2. The south orientation

The south orientation is usually best for daylighting since this orientation receives the maximum quantity and duration of daylight. Horizontal controls (e.g., overhangs, louvers, and venetian blinds) are effective in this orientation. An advantage with the south orientation is that the sun is high in the sky in the summer, but can easily be shaded by a horizontal device which allows some low-altitude sun penetration during the winter months, when its heating effect is usually desirable.

3. The east and west orientation

Both east and west orientations are the least acceptable for daylighting design because they provide only a half-day exposure to sunlight, making optimum fenestration design more difficult. Both orientations, (especially the west) experience large summer heat gains at unwanted times, while providing little passive solar contribution in the winter. However, the greatest disadvantage is that the east or west sun is low in the sky; therefore, it creates very difficult glare problems. Therefore, the design consideration to solve the problem on the east
and west facade should be the minimizing of facade dimensions, the reduction of the number of apertures, and the utilization of vertical controls (e.g., vertical louvers, vertical fins).

Although we know that the expanding form and puncturing the envelope can reduce a lighting load, we do not know the impact of such changes on heating and cooling loads. To better understand the relative impacts between massing and orientation of a building, two case studies were selected to explain analyzed data. The first is the study in the combined effect of building width and orientation on energy usage of the Tennessee Valley Authority (TVA) Chattanooga Office Complex made by Van der Ryn, Calthorpe, and Partners and the Berkeley Solar Group (Moore, 1985). The second is a study by B.C. Hydro (Nakaska, 1995) on how massing variations (square and rectangular) affect energy usage.

(1) Case Study of TVA Chattanooga Office Complex

- Parameters and Assumptions:
To study the combined effects of building width and orientation on energy usage, the parameter study began by assessing the energy of five building configurations (fig. 3.9 a). Daylighting was assumed for each configuration as was standard windows and shading devices for each orientation. Along with the selection of the basic heating and cooling systems used in the buildings, these assumptions change the relative value of the width and orientations. As shown in figure 3.9 b, the primary energy needs of different configurations were generated by computer. Information was then compared and interpreted by the design team as follows:

- Observations:
1. The annual need for lighting energy was reduced as building massing became thinner north to south. Thin buildings with broad east/west elevations required more energy for lighting since they required more extensive shading devices to block the low morning and afternoon sun. While orientation may not be significant in a building where a cube form and identical elevations are used, the design team found that a substantial difference in energy
usage was possible when shading strategies and facade treatments were varied and climate adaptation was central to the proposed design.

2. The heating requirements increased as a building became thinner. Two variables influenced this fact. First, a narrow building has a larger building skin. Second, a narrow building has a greater daylit proportion than a deeper building and, therefore, a reduced heating contribution from electric lights. However, this liability was small since the need for heating energy was much less than that required for lighting and cooling.

3. Cooling energy needs were consistently high in all configurations. The only significant pattern seemed to be a slight decrease in cooling energy needed in configurations with smaller external surface areas. The impact of this variation was small and counteracted by a reduction in the heat of electric lights due to the larger daylighting potential of the shallow buildings.

From this general analysis, the design team concluded that east-west elevations were a liability and that narrow forms with broad north-south elevations has a distinct advantage.

Figure 3.9  TVA schematic design energy analysis of the effects of width and orientation:
a) Alternative Plan Configurations
b) Source Energy Comparisons for the Configurations
Source: Moore, Fuller, Concepts and Practice of Architectural Daylighting, 1985
(2) Case Study Performed by B.C. Hydro

- Parameters and Assumptions:

To study the effects of changing mass to energy usage, the parameter study began by assessing the energy needs and energy costs of two building floor plans: a rectangle and a square. Runs were performed for a series of rectangular floor plans with a plan 4:1 aspect ratio and for a series of square floor plans with a plan 1:1 aspect ratio. Each series had four, nine, and twenty stories modeled with a total building area fixed constant at 290,000 sq.ft. (fig. 3.10). Other parameters given by the design team are:

- Daylighting was assumed for a 15 ft. wide perimeter zone all on floor plates of both building shapes and lighting loads in this zone were reduced by 30%.
- The perimeter walls had low-E glazing covering 50% of their wall areas. It was assumed that shading devices were utilized primarily on the south side.
- Orientation of the building had its longest axis running parallel to the east-west axis.
- The lighting load used was 1.9 watt/ sq.ft. (reduced at perimeter areas). Plug load was 0.75 watt/ sq.ft.
- All dollar amounts are based on current B.C. Hydro rates.

To illustrate how the sometimes competing objectives of minimizing envelope energy losses versus maximizing daylighting potential influence the massing of a building, a set of computer simulation runs were performed with the parameters stated above. Interpretation of this analysis was given by the design team in the following:

- Observations:

1. The annual total energy cost for the rectangle was about the same as the square for each case with similar height, but the rectangle was marginally lower in cost. It is probable that if low-e glazing and shading control were removed, the square plans would be marginally lower than the rectangular plans. But this model did not take into consideration the original higher cost of these devices.
2. In all cases, as the perimeter area increases, the lighting load decreases with a corresponding increase in both heating and cooling requirements. It should be noted that the 30% lighting load reduction is a relatively crude approximation for potential daylighting savings. Each facade and orientation will have its own peculiar set of circumstance not modeled here.

3. These simulations illustrate in simplistic terms that the optimum massing of a building can be equally influenced by daylighting or thermal considerations. One does not show a stronger influence over the other.

After this analysis, the design team concluded that in most design activities, the massing of a building will need to be designed in conjunction with many other constraints. It is up to the designer to choose the most appropriate method for achieving energy savings. Besides, there is another suggestion from the design team that on the shallower buildings, toplighting and an atrium can be used to further reduce energy consumption associated with lighting and would not become a cooling liability if properly shaded.
### RECTANGLE PLAN 4:1 ASPECT RATIO

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### SQUARE PLAN 1:1 ASPECT RATIO

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Figure 3.10  The Effect of Massing and Energy Cost
3.4.3 Design Elements

Several design considerations (e.g., site elements, climatic data) impacting light affect a building in terms of form and orientation. Probably the most significant design determinant when implementing daylighting strategies is the geometry of a building's walls, ceilings, floors, windows, and how each relates to the other. Effects of the various building elements provide the basis for manipulating form and envelope to achieve adequate lighting levels. These various building elements are the tools for using and controlling daylight. To better understand these design elements, they are categorized in three parts:

1. Exterior Elements
2. In-Wall and Roof Elements
3. Interior Elements

The various kinds of solar radiation predominating in a warm-humid climate need to be understood before they are used to illuminate a building. Solar radiation consists of three components: direct, diffuse, and reflected radiation. In warm-humid regions, diffuse sky radiation can be as significant as direct radiation (fig. 3.11), while in hot-arid regions, such as the Southwest where intense sunlight and high reflectance surfaces usually exist together, encounters are with reflected radiation.

In designing shading devices for buildings in a warm-humid climate, both the diffuse sky component and direct solar component must be considered together. Lechner (1991) stated that of the types of solar radiation relating to shading devices: "The diffuse sky component is a much harder problem, because of the large exposure angle from which the radiation comes. It is, therefore, usually controlled by indoor shading devices or shading within the glazing. The direct solar component is best controlled by exterior shading devices."

The need for shading sometimes conflicts with the demand for daylighting. Fortunately, when solar radiation is brought into a building in a controlled manner, it can supply high quality lighting as well as reduce heat gain. This alternative to shading is discussed in daylighting design strategies.
Figure 3.11 In humid and dusty regions the diffuse sky component is a large part of the total solar load

(1) Exterior Elements

Exterior elements are the most effective barrier against the sun and can have the greatest impact on the aesthetics of a building. These exterior elements, categorized by their feature and functions, are:

1.1 Light Shelves

Light shelves are fixed reflective horizontal devices located at or near a window (usually above eye level). Light shelves collect daylight and reflect it into the building while providing shading from the direct sun. To be effective daylight collectors and reflectors, they must be exposed to direct sunshine. Using highly reflective surfaces for light shelf surfaces will enhance the quality of daylight. The application of light shelves is usually on the south facade of a building where it can be employed as an effective, natural lighting component.

1.2 Daylighting Tracking and Reflecting Systems

These systems are designed to enhance the daylighting potential of skylights by tracking and reflecting sunlight through the aperture and into the open space below. This equipment can be dynamically controlled to follow the path of the sun or completely immobile, using strategically placed mirrors to capture the direct beam daylight.
1.3 Horizontal Louvers and Overhangs

These barriers are an effective method of blocking direct beam light during the summer when the sun angles are high while allowing sunlight to penetrate during milder seasons. Their functions not only block the direct beam from the sun, but they also reduce the amount of sky seen from within a room, reducing the amount of diffuse skylight admitted through the opening. Reflected light from the ground or other surfaces can be caught by an overhang and directed back into the interior of a room. The result will be a slightly higher illuminance level and a more even distribution of light in the space. Both horizontal louvers and overhangs are most effective on south-facing windows.

Horizontal louvers have a number of advantages over solid overhangs. Horizontal louvers in a horizontal plane reduce structural loads by allowing wind and snow to pass through. In the summer, they minimize the collection of hot air next to the windows under the overhang (fig. 3.12).

Figure 3.12  Horizontal louvers both vent hot air and minimizing snow and wind loads.
Designing an overhang for the south facade

(a) Outflanking by the sun

Since the sun comes from the south east before noon and from the south west afternoon, an overhang the same width as a window will be outflanked by the sun. Narrow windows need either a very wide overhang or vertical fins added to the overhang (fig. 3.13). Long strip windows do not seem to have this problem.

![Figure 3.13 An overhang the same width as a window will be outflanked by the sun. Source: Lechner, Nobert, Heating, Cooling, Lighting: Design Methods for Architects, 1991](image)

(b) Design guidelines for fixed overhangs

A fixed horizontal overhang is most appropriate when passive solar heating is not desired. The optimum design of an overhang must consider the length of the overhang that will be needed to shade the south windows during most of the overheated period. Lechner’s design strategy (1991) in figure 3.14, shows the sun angle at the end of an overheated period. Because the sun is higher in the sky during the rest of the overheated period, any overhang that extends to this line will fully shade the window during the entire overheated period. This full shade line is defined by angle “A” and is drawn from the window sill. This angle is given for each climate region. For a warm-humid climate region such as Miami, Florida, the defined angle is 50° for an envelope-dominated building and 40° for an internally dominated building.
If the overhang is moved higher on the wall and is extended to the “full shade line”, it can still block the direct radiation and give a wider view of the sky. However, this would not be desirable in regions with significant diffuse radiation because increasing exposure to the bright sky will cause more overheating and visual glare. Increasing the length of the overhang may not be sufficient in very humid regions where over 50% of the total radiation can come from a diffuse sky. Therefore, it may be desirable to use other devices, such as curtains or plants to block the diffuse radiation from the low sky. Moreover, a design based on this guideline can result in a dark interior. If daylighting is desired, both the ground and underside of the overhang should have high reflectance values or use movable overhangs to allow light during the winter period.

Figure 3.14 The “full shade line” determines the length of overhang required for shade during the overheated period. But, a fixed overhang also shade part of the window during the underheated period.


A recommendation from the Kasian Kennedy Design Partnership (Nakaska, 1995) suggested that although an overhang will limit sunlight penetration, it will also reduce daylight penetration. To determine the optimum design, consider the prevailing sky
conditions, for 50% sunshine and 50% overcast. A trellised shading device, or one that acts as an interior light shelf may be a good choice. Build a model to test is the best options.

1.4 Vertical Louvers or Fins

Fixed or movable vertical louvers or fins are advantageous for east and west orientations to block direct beam when the sun angle is low and to reflect light into an interior. Figure 3.15 illustrates the time every morning and afternoon when the sun shines directly at the east and west facades of a building during the six summer months of the year (March 21 to September 21). Hence, vertical fins that face directly on the east and west permit sun penetration everyday during this period. To minimize this solar penetration, the "exposure" angle need to be minimized by decreasing the spacing of fins, extending the fin depth, or both (fig. 3.16). Better approach is the use of vertical fins slanted toward the north. This system can be designed to completely block the direct sun but it can also severely restrict the view. Therefore, if both effective shading and view to the east and west are desirable, then movable rather than fixed vertical fins should be considered. Movable vertical fins can be slanted toward the north for year round shading or toward the south if the winter sun is desirable.

Figure 3.15 The sun's azimuth angle at different times of the year
In addition, for the building with long overheated periods, it may be necessary to provide shading on the north facing windows because of the sun’s angles affecting this orientation, especially during summer months. A vertical fin design for the north facade is required on both the east and west sides of north windows and small vertical fins are sufficient to give full shade from 7 a.m. to 5 p.m. (solar time) (Lechner, 1991). Figure 3.17 illustrates a vertical fin designed for the north window by using angle “D” at 18° for a building in a 24° latitude.

1.5 Eggcrate Shading Devices

An eggcrate is a combination of horizontal overhangs (louvers) and vertical fins. Controlling the sun’s penetration angle by both altitude and azimuth can create an effective
shading of windows but usually obstructs view. Since shading is a geometric problem, many small devices are equivalent to a few large ones (fig. 3.18). Therefore, eggcrates can be made on the scale of a fine screen that has a shading effect identical to a large scale screen, but the view from the inside and the aesthetic appearance from the outside may vary greatly.

![Diagram](image)

Figure 3.18 Many small elements can create the same shading effect as one large device.

Although the five categories of exterior elements are concerned with shading produced by the building itself, there is often significant shading from the surroundings, such as adjacent buildings, land forms, and plants that all can provide substantial shade.

(2) In-Wall and Roof Elements (Glazing Materials)

Glazing material is a major component of fenestration design in that it always involves many issues, such as a view to the outdoors, daylighting potential, solar heat gain, thermal heat loss and aesthetics. For daylighting design in a warm-humid climate, the goal of glazing material performance is to maximize daylight transmission while minimizing heat gain. To understand the performance properties of glazing, glazing terminology is presented in the following:

- **Visible Transmittance (VT)** is the fraction of visible light energy transmitted through a glazing. Clear, double-strength single glass typically transmits 89% of the light that strikes it and thus has a VT of 0.89. Higher numbers mean more light entering a space and hence clearer views.
- **Shading Coefficient** (SC) is the measure of total solar heat transmitted. Lower numbers mean less energy transmitted and usually, but not always, darker rooms.

- **Glazing Luminous Efficacy** (Kc) = (VT) / (SC)

  Kc describes the relationship between visible transmittance and total solar heat transfer, known as a Coolness Index. The higher the Kc, the more visible light that penetrates without heat gain. A low Kc means a shading coefficient is achieved with poor visibility. Kc should not fall below 1.0, but for an effective use of daylighting, Kc should be 1.2 or higher. Examples of K-values are: single 1/8" clear glazing-0.88, single 1/8" blue-green tinted glazing-1.15, double clear with low-e 1.5, double green tint with low-e-1.45, and double gray reflective-0.5 (fig. 3.19).

![Diagram showing luminous efficacy in different types of glazing](image)

**Figure 3.19** Luminous efficacy in different types of glazing


**Glazing Materials**

Choosing the right glazing material is critical to successful daylighting design. Transparent glazing comes in a variety of types and properties in performance to daylight:

1. **Clear Glazing**

   Clear glazing allows a maximum clear view and daylight penetration, although it is not appropriate to use for daylighting in a hot climate because it can cause excessive brightness...
and solar heat gain. Usually, clear glazing is most appropriate for insulation performance and it is manufactured in various types:

- **a. Single Glazing** - no longer recommended for most climates
- **b. Clear Double Glazing** - a sealed factory unit with an air space known as insulating glass because of its good insulating characteristics
- **c. Clear Double-Glazing-Low-E** - a transparent metallic (low emissivity) coating reflecting heat back into the occupied space

In addition, there are other designs which provide good insulating glaze; for example, the use of multiple glazing layers with an air space between each pane of glass to increase the thermal resistance. The higher the number of layers, the more weight cause a load problem. However the design standard in many climates is double-paned units. For triple-paned units, the demand has been replaced by units using the suspended low-e films, because thickness, weight, and cost of the units are much lower.

2. **Tinted Glazing**

Tinted glazing uses heat-absorbing materials dispersed throughout the glass to reduce the amount of solar radiation passing through the glass. At the same time, it reduces light transmission and distorts the color of the view. The colors of tint and their performance are:

- **a. Gray tint** - reduces light and heat at a fairly consistent rate.
- **b. Bronze tint** - reduces more light than heat energy.
- **c. Blue and Green tints** - reduce heat energy while maintaining a high visible light transmittance. Consequently, blue-green tints perform most effectively in daylighting applications.

3. **Reflective Glazing**

Reflective metallic coating reflects light along with the solar infrared radiation. Therefore, it is not recommended for daylighting applications.
4. **Selective Low-E Glazing**

Low-e (emissivity) coatings reflect more of infrared heat radiation than visible light. Therefore, it is the best choice for daylighting applications. There are two types of low-e coatings: hard and soft coat.

a. **Soft-Coat** - Soft coat is vacuum-deposited and is generally applied to a thin plastic film which is suspended between two panes of glass. Such features will decrease the conductivity of glazing unit.

b. **Hard-Coat** - Pyrolitic or hard coat low-e glazing is fused to the glass while it is still hot to create an integral film that is extremely resistant to abrasion and corrosion.

Another glazing material recommended for daylighting design is a glass block that is “light directing” because of the built in prisms that refract light. This block is used to bounce sunlight up toward the ceiling for an even and deep penetration of daylight into a space.

(3) **Interior Elements**

3.1 **Interior Shading Devices**

Interior shading devices such as venetian blinds, roller shades, and draperies are placed on the inside. They are not as effective as comparable exterior devices, which intercept solar heat before it gets into the building.

a. **Venetian Blinds**

Horizontal or vertical venetian blinds are effective because they can be tilted to respond to changing sun conditions. They can be adjusted manually or automatically to block direct sunshine, or can be partially closed to reflect sunlight either back out the window or deeper into the room while allowing a view to the outdoors. In considering daylighting distribution, the shape of the venetian blind is a major consideration. Flat louvers reflect direct sunlight similar to a single flat
mirror, while either a convex or concave louver shape tends to diffuse the sunlight over a large area, thus reducing glare (fig. 3.20).

Figure 3.20  Light reflected in different shapes and materials of louvers
a) white Venetian blinds, concave down
b) mirror-finish Venetian blinds, concave up
Source: Moore, Fuller, *Concepts and Practice of Architectural Daylighting*, 1985

b. Roller Shades

Roller shades of various degrees of opaqueness can be an effective control device for reducing glare and direct beam penetration. One benefit of interior controls is that they can be easily and completely retracted during those times that sunlight and daylight are desirable. For example, roller shades located on the west facade can be retracted during the morning hours when strong radiation does not hit the window. Conversely, the roller shades on the west facade can be retracted during the afternoon hours.

c. Draperies

Draperies are often used as control devices and for decorating. They can enhance the quality of a space due to their texture, color, and flexibility. Fabrics are available in a wide range of weaves with varying shading coefficients. An appropriate weave pattern can soften the light to desirable levels.
3.2 Room Geometry

a. Window Height

Window size and height are significant factors of interior illumination. Naturally, as the window becomes larger in size, the amount of daylight admitted increases. But the height of the window is the more significant factor. The higher the window, the deeper the daylight penetrates into a room with higher illuminance near the window than further away. As a rule of thumb for unilateral daylighting, the depth of useful daylight penetration is about 2.5 times the distance between the top of a window and a window sill. Moreover, a higher window results in a more even distribution of light (fig. 3.21).

![Diagram of window height and sunlight penetration](image)

Figure 3.21 Higher windows and higher ceilings result in a more even distribution


b. Room Depth

The depth of the room has a direct effect on the intensity of illumination. As the room is made deeper, the level of intensity throughout the room becomes less. This fact is modeled by keeping the floor-to-ceiling height and the area and location of the window constant. The intensity of daylight in the deeper room is reduced because the same quantity of incoming light is distributed over a larger area (fig. 3.22).
c. Ceiling Height

As the ceiling height is increased, light penetrates deeper into a room and is more evenly distributed (fig. 3.21).

3.3 Reflectance of Room Surface

The reflectance values of the room surfaces will greatly impact the performance of a daylit space. The ceiling plane is most effective for promoting daylight distribution within a perimeter room because it contributes the greatest percentage of diffuse reflected light.

The useful information in “Design Smart: Energy Efficient Architectural Design” (1995) stated that “The IES guidelines suggest 70/50/20 (ceiling/wall/floor) reflectivity as a basic minimum for electric lighting only, whereas daylight spaces may be as bright as 75/70/30.” Therefore, increasing room reflectivity will improve the performance of the electric lighting system as well.

Textures and colors of different materials are variable in reflectance properties. Flat, polished, metallic surfaces reflect specularly. Conversely, ideal matte surfaces reflect diffusely with an even distribution in all directions. In practice, most building materials combine specular and diffuse reflections (fig. 3.23). For the reflective quality of color, light color surfaces are better reflective than dark colors. Therefore, to enhance the daylight distribution within a room, the ceiling should be as light as possible because the ceiling is the most important light-reflecting surface; the floor should be used for patterns or deep colors, which have the least impact on daylit space.
3.5 Sidelighting Concepts

3.5.1 Analyzing Sidelighting Concepts

The characteristics of daylight entering a room are generally illustrated with diagrams depicting penetration, horizontal spread, and vertical spread (fig. 3.24). The penetration of daylight into a room is usually illustrated in a sectional view of the room by a line or series of lines depicting the absolute or relative change in the quantity of light from aperture to interior. Since interior daylight illumination is directly dependent on exterior daylight, the interior illuminances are not presented in absolute quantities. Consequently, “daylight factors” are adapted to estimate the quantity of interior illuminances. Daylight factor is defined as the ratio of interior horizontal workplane illuminance (at a height of thirty inches) to exterior illuminance in the unobstructed horizontal, expressed as a percent.
In figure 3.24, a black dot indicates a location in a room where noticeable changes occur in interior illuminance. Such locations are often used as crossover lighting zones to identify demarcations for task, background, and general lighting areas. The slope of the line is significant, because a simple contrast ratio can occur between any two points along the line. If the slope of the line is a sharp curve, it indicates potential high contrasts of light between adjacent zones and possible glare problems. Therefore, designers need to establish a "lighting zone" as shown in figure 3.25 to determine parts of a room that cannot be illuminated adequately by daylight. The established plan is divided into primary, secondary, or even tertiary lighting zones as they relate to aperture locations and function within the space. Parts of secondary zones and all of tertiary zones rely primarily on electric lighting.
"Sidelighting concepts" use the walls of a building as the location for daylighting apertures. Sidelighting concepts include view apertures and non-view apertures. In a dynamic design, these apertures can be used for ventilation as well. Sidelighting provides a strong directionality of light, which has the potential to be used as primary lighting on horizontal surfaces and workplane. The main disadvantage of sidelighting is the glare it causes because of the high contrast between the aperture and the surrounding wall surfaces. This problem may be mitigated by utilizing exterior or interior shading devices.

3.5.2 Window Strategies

When daylight passes through a vertical window, its illumination is greatest near the window and rapidly drops off to inadequate levels for most visual tasks. An efficient design for window strategies acknowledges that the view of the sky is often a source of direct glare. Additionally, direct sunlight entering the window may create excessive brightness ratios and overheating during the summer. To overcome these problems, appropriate window design strategies are provided in the following:

1. Use of windows - optimum size and height

The amount of daylight received in a space increases as the window area increases. The height of the window above the finished floor dictates the depth of penetration. Higher windows result in a more even distribution. Whenever possible, ceiling height should be increased so that window can be mounted higher. However, because of summer overheating and winter heat loss, it is necessary an optimum window area as a percentage of floor area is 20-40% for a building in a warm-humid climate if windows are also required for ventilation.

2. Reflecting daylight off the ceiling for a deeper and more uniform distribution

There are various methods for projecting light onto the ceiling:

- External surfaces of the building should be light-colored to reflect a significant amount of light to the ceiling (fig. 3.26 a).  
- Using parts of the structure such as wide window sills or light shelves reflect light deep into the interior (fig. 3.26 b, c).
Using effective devices such as an indoor venetian blind or similar outdoor louver system to reflect light onto the ceiling and to control glare. For venetian blinds, there are various designs for selective use; for instance, blinds which are sandwiched between two layers of glasses to prevent dirt accumulation or miniature slats which can reduce the annoying figure/ background effect.

Figure 3.26  
- a) Light-colored external surface can reflect light deep into the interior.
- b) Wide windowsills can be used as light shelves to reflect light deep into the interior.
- c) Light shelves are used to reflect light above eye level deep into the interior and to prevent glare also.


The light hitting the ceiling should be diffused by using matte reflectors that can reflect light in an even distribution, but devices reflecting light onto the ceiling should have a specular finish to maximize the depth of light penetration. Specular reflectors have a drawback in that they often cast excessively bright patches of sunlight on the ceiling. To minimize this problem, both concave and convex specular reflectors can be introduced to distribute daylight over a large area of the ceiling (fig. 3.27). Reflected daylighting examples are shown in figure 3.28.

Figure 3.27  
The performance in reflecting light of both concave and converse specular reflections

3. **Use of outward-sloping glass to maximize daylight penetration**

Outward-sloping glass produces an effect somewhat like cutting an overhang back, allowing significant quantities of daylight to penetrate an interior space. It also increases the opportunity for viewing the exterior sky from inside, usually creating excessive brightness ratios.

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Figure 3.28  Reflected daylight examples

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Figure 3.29  Outward slopped-glass windows
Source: Evans, Benjamin H., *Daylight in Architecture*, 1981
4. **Placement of windows on more than one wall for better light distribution**

Space can be daylit with windows unilaterally, bilaterally, and multilaterally with varying effects. Whenever possible, unilateral lighting coming from windows on one wall should be avoided, and bilateral or multilateral lighting for better light distribution should be used. Moreover, the use of windows on more than one wall reduces glare because the windows in each wall illuminate the adjacent wall, reducing the contrast between each window and its surrounding.

5. **Shaded direct sunlight but not daylight**

Direct sunlight needs to be shaded because of its excessive brightness and high thermal impact, unless it can be diffused by reflecting it to the ceiling. Exterior and interior shading devices can mitigate these problems. However, in some spaces such as lobbies and living rooms, where visual tasks are not critical, direct sunlight can be welcome for its visual and psychological benefits, especially in winter.

6. **Filtered daylight**

Sunlight can be filtered and softened by trees or devices, such as trellises, screens, translucent glazing, or very light drapes.

7. **Splayed walls to reduce contrast between windows and walls**

Glare can be reduced if adjacent walls are not dark in comparison to the windows. Splayed or rounded edges are much better than sharped-edges since they can create a transition of brightness that will be more comfortable to the eye.

8. **Use of movable shades for dynamic control**

Moveable shades provide flexibility in effectively controlling sunlight, especially on east and west apertures, which receive diffused light for half a day and direct sunshine the other half. Movable shades or curtains are a response to these extreme conditions. Exterior shades are more effective than interior shades because exterior shades can intercept solar heat before it gets into the building. However, interior shades are still preferable.
9. **Change of ceiling shapes**

The best uniformity is attained when the back wall is white and most of the ceiling slopes upward from the window. Sloping ceilings downward from the window increases the average illumination level but keeps the light closer to the window and makes illumination less uniform. Additionally, some ceiling shapes are better than flat ceilings in improving uniformity of illumination (fig. 3.30).

![Figure 3.30 - Some ceiling shapes are better than a single slope. Besides, ceiling that slope up from the aperture improve illumination uniformity when the back wall is white. Sloping ceilings downward from the aperture increases the average illumination level but keeps the light closer to the window and makes the illumination less uniform. Source: Lam, William M.C., *Sunlighting as Formgiver for Architecture*, 1986](image_url)

10. **Use of a combination of low windows and high windows**

For illumination under both sunny and overcast conditions, it is best to use a combination of low windows (for sunny conditions) and high windows (for overcast conditions).

11. **Orient windows north or south**

This orientation is effective to use sunlight effectively and simple to control by shading devices. North and south orientations permit the simplest fixed shading/redirecting element to provide complete control. East and west exposures require some use of dynamic shading devices to control glare and overheating.
3.6 Toplighting Concepts

3.6.1 Analyzing Toplighting Concepts

The characteristic of daylight entering a room via a toplight aperture is generally illustrated by longitudinal spread and latitudinal spread (fig. 3.31a). Longitudinal spread refers to the direction parallel to the longer axis of the aperture. Figure 3.31b is the distribution diagram which illustrates relative differences between clear and overcast sky conditions for a roof aperture. Curves are bell-shaped with the point of maximum illumination directly below the aperture and with steep slopes giving rise to higher contrast zones and potential glare problems. Both ends of bell-shaped curve may require other supplemental lights such as electric lighting or window lighting to improve daylight distribution. Usually, overcast sky conditions produce higher levels of illumination than a clear sky without the sun.

![Figure 3.31 a) Illustration of longitudinal and latitudinal spread b) Distribution diagram on clear and overcast sky conditions](image)


A number of analyses on the impact of illuminance in a room with horizontal apertures were illustrated by Robbins (1986); several are proposed here because of their common use in the variation of aperture size and lightwell.
Aperture Size Variation

Aperture size in figure 3.32 is varied to illustrate the changes in light distribution for overcast sky conditions and infinite aperture length. The result of reducing the opening is that it reduces maximum illumination while greatly flattening the curve. Therefore, the design should be considered for numerous small horizontal apertures rather than one large aperture because more even and better light distribution will occur while reducing glare (steeply sloping curves give a high contrast).

Lightwell Depth Variation

Lightwell depth in figure 3.33 is varied to illustrate the changes in light distribution for overcast sky conditions and infinite aperture length. The result of changing the depth of lightwell produces a significant change in distribution. By increasing the depth, the view of sky is reduced, especially for station points directly beneath the aperture. A deeper lightwell will achieve a more even distribution of illuminance across the horizontal plane, but absolute illuminance levels will decrease.
"Toplighting Concepts" allow daylight to penetrate a space from apertures that are located above the ceiling line and usually constitute part of the roof of the building. The light coming from overhead or horizontal openings has three important advantages to a daylit space:

1. This light allows fairly uniform illumination over very large interior areas, while sidelight from windows is limited to about 15-foot depth (fig. 3.34).
2. Normally, horizontal openings receive much more light than vertical openings.
3. The utilization of horizontal openings allows the freedom to place natural light sources wherever illumination is desired, either uniformly distributed or in any part of a room required by the activity of the occupants. This flexibility makes it simple to achieve uniform illumination over vertical openings similar to windows.

Figure 3.34 Toplighting can provide the most uniform light levels, while sidelighting is limited to about 15-foot depth from windows.

Source: Lam, William M.C., Sunlighting as Formgiver for Architecture, 1986
Unfortunately, there are disadvantages with light coming from a horizontal orientation which is discussed as the following:

1. Daylight in this orientation has the intensity of light greater in the summer than the winter, which is the reverse of what human need. Also, it is difficult to shade horizontal glazing. Therefore, it is often appropriate to use vertical glazing on the roof in the form of clerestories, monitors, or sawtooth arrangements (fig. 3.35).

2. Because all overhead sources are a potential source of veiling reflections, it is necessary to either keep light sources out of the offending zones or diffuse the light so that there are no bright source to cause veiling reflections.

However, all top lighting methods (skylights, clerestories, monitors) are not practical strategies for multistory buildings, because they do not satisfy the need for view. They should supplement rather than replace windows.

In toplighting design strategies, the following information will be discussed in two parts: first, clerestory and monitor strategies, and then, skylight strategies. Both strategies have the same goal of solving the problem of direct glare from the bright openings overhead, but since skylights behave differently from monitors and clerestories, they are discussed separately.

![Figure 3.35 The various types of overheaded openings for daylighting](source)

3.6.2 Clerestory and Monitor Strategies

Clerestories, monitors, and sawtooth clerestories refer to the use of vertical or steeply sloped glazing on the roof on one or more sides. They allow the top floor of a building to benefit from a very controlled collection of daylight with less heat gain. When they face south, they collect more sunlight in the winter than in the summer. However, vertical south-facing apertures are easily shaded from unwanted direct sunlight. When they face north, they give a low but constant level of illumination with a minimum or no glare and contribute no solar heat gain. Use of east and west apertures are usually avoided because of the difficulty of shading the low sun. The disadvantage of any vertical opening is that it shows less of the sky than a horizontal opening, and therefore, less light is collected by the vertical opening. Most strategies for monitors, clerestories, and sawtooth clerestories, which have been proposed by Lechner (1991) are:

1. Monitor and sawtooth clerestory spacing

Typical spacing of clerestories is shown in figure 3.36. Usually monitors and clerestories facing either north or south are the most efficient.

![Figure 3.36 Typical spacing of clerestories](source)

Figure 3.36  Typical spacing of clerestories

2. Use of high reflectance materials on the roof

Since the roof is an area that reflects the light off it before it enters the clerestories and illuminates the ceiling inside, the use of reflective roof material helps to maximize the diffused light entering the building, and, at the same time, a high reflective roof can reduce heat gain (fig. 3.37).

Figure 3.37 Maximizing the diffused light entering the building by use a high reflectance roof surface.

3. Avoidance of direct sunlight with south-facing openings

To prevent problems associated with direct sunlight, an opening facing south is a good choice. In this orientation, the opening gets the most constant year-round lighting as well as winter solar heating. In a warm climate, where heat is never needed, clerestories or monitors should be oriented away from sun, and, thus, the north is also preferred.

4. Use of suncatcher baffles to balance interior lighting

A suncatcher baffle is appropriate to use outside a building on the north, east, or west clerestory to increase daylighting on a sunny day, but it also reduces illumination on an overcast day. Usually, clerestories facing north receive less light than those facing south. To increase light collection on the north-facing clerestory, a suncatcher baffle should be applied on the outside (fig. 3.38 a).

Although east and west clerestories are not usually recommended, their performance can be greatly improved by suncatcher baffles. Since east clerestories get too much morning sun and not enough light in the afternoon, a suncatcher baffle can produce a more balanced light level by shading some of the morning sunlight while maximizing the afternoon reflected light (fig. 3.38 b). This action is the same for west clerestories.
5. Reflected light off interior walls

Figure 3.39 shows the reflecting light of an interior wall. Walls can act as large low brightness diffusers for light passing through clerestories. South-facing clerestories work best in this regard. Moreover, there are some advantages in using this strategy: first, a perception of a well lit wall will appear to recede, thus making the room seem larger and more cheerful than it actually is. Second, glare from a direct view of the sky or sun can be completely avoided.

6. Use of an overhang and diffusing baffles for high quality lighting

South facing clerestories need the protection afforded by overhangs and baffles. These two devices are very effective when combined with clerestories to prevent glare, diffuse light,
and increase illumination levels inside a building. The baffle spacing should be designed to prevent direct sunlight and, at the same time, to prevent direct glare in the field of view below 45° (fig. 3.40). For high effect, both ceilings and baffles should have a matte high reflectance finish. The detailed design of baffle spacing is available in "Concepts and Practice of Architectural Daylighting" by Moore (1985).

Figure 3.40 Use baffles to prevent direct sunlight and glare

3.6.3 Skylight Strategies

A skylight is defined as a horizontal or slightly sloped opening in the roof. Skylighting is an excellent toplighting strategy because with relatively small openings, large quantities of light can be admitted to all areas of a single story building or into the top floor of multistory buildings. The layout and spacing of skylights on a roof determine the light distribution characteristics of the area below the skylights. Usually, large, widely spaced skylights are the most economical to install but may result in uneven light distribution, reduced energy savings, and possible glare problems. In contrast, small, closely spaced skylights will provide more uniform lighting conditions and greater energy savings, but may be more costly to install. As a rule of thumb, skylights should be spaced at 1.0 to 1.5 times the ceiling height. Since a skylight sees a large part of unobstructed sky and admits very high illumination levels, this is not desirable for difficult visual tasks. Therefore, a design in which diffuses direct sunlight is required. Some of the following skylighting strategies collected by Lam (1986) and Lechner (1991) will help optimize skylight performance.

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1. **Skylight spacing for uniform lighting**

When there is no light from a window, skylights can be arranged over the roof with spacing as shown in figure 3.4 a. When windows are used, the skylights may be further from the perimeter as shown in figure 3.41 b.

**Figure 3.41**

- a) Recommended spacing for skylights without windows
- b) Recommended spacing for skylights with windows


2. **Placing a skylight over the north wall**

Any wall, and especially the north wall, can be used as a diffuse reflector for a skylight. The daylit north wall will also balance the illumination from the south windows (fig. 3.42).

**Figure 3.42** Place skylights over the north wall for more uniform lighting and less glare

3. **Use of a steeply sloped skylight to improve the summer/ winter balance**

Skylights, steeply sloped toward the north or south will provide light more uniformly throughout the year because they collect more winter light and less summer light (fig. 3.43).

![Figure 3.43 Steeply sloped skylights](source)


4. **Use of splayed openings to increase the apparent size of skylights**

Splaying the ceiling to the skylight will improve light distribution and reduce aperture contrast (fig. 3.44).

![Figure 3.44 Splayed openings distribute light better and cause less glare](source)


5. **Use of outside shades and reflectors to improve the winter/ summer balance**

Shade the skylight from the summer sun and use reflectors to increase the collection of winter sunlight (fig. 3.45).

![Figure 3.45 Use the combination of shades and reflectors](source)

6. **Use of interior reflectors to diffuse sunlight**

A skylight can deliver very uniform and diffused light when a reflector is suspended under the opening to reflect light up to the ceiling (fig. 3.46).

![Figure 3.46](image1.png)

Figure 3.46  Use of interior reflectors (daylight fixtures) to diffuse sunlight and reduce glare

7. **Use of baffling or louver to control glare and redirect light**

Baffling can be located outside the skylight, at the glazing plane, or in the zone of transition between the aperture and end-use surface to control glare and redirect light to large areas of room surfaces. Local interior shading devices, such as trees, banners, or umbrellas, offer selective protection.

8. **Use of dynamic shading for flexibility of control**

Dynamic shading gives the opportunity to redirect unwanted light back to the exterior, rather than allowing it to heat up the interior space (fig. 3.47).

![Figure 3.47](image2.png)

Figure 3.47  An example of a simple dynamic shading device
Source:  Lam, William M.C., *Sunlighting as Formgiver for Architecture*, 1986
9. **Place skylight high in a space**

A skylight placed high above a space will allow the light to diffuse or redirect before it reaches the floor. The problem of glare will be minimal because the high light source will be outside the field of view.

### 3.7 Atrium

An atrium is a centroidially located space which is usually opened up to the sky and isolated from the outdoor by glazing. If it is designed appropriately, it can maximize energy savings and efficiency due to incorporation of many design features such as daylighting, ventilation, and passive cooling and heating techniques. Usually an atrium presents a large exposure to daylight as well as a thermal compact area. The amount of light available at the box of the atrium depends on several factors: translucency of the atrium roof, the reflectance of atrium walls, and the geometry of the space. An atrium can be illuminated by skylights, clerestories, or window walls. An atrium can provide the benefits of daylight by being shaped a daylight collector and distributor, and by the arrangement of the space around it.

The major consideration when designing an atrium is the local climate, especially sky condition. There are different approaches for each climate. In a warm climate, when the solar heat is adverse, it may be preferable to provide a north/south roof-light as it can be shaded from a high angle solar penetration and can deliver considerable quantities of reflected light. Skylights can be shaped and oriented to exclude or admit sunlight. But east and west-facing atrium side walls should be avoided unless specific vista opportunities are important. East and west facing atria admit low angle sunlight in summer and are hard to shade. In a very warm climate, north-oriented walls are valuable as they deliver sky-light without solar penetration. The strategies in admitting and distributing light into the atrium are discussed further below:
1. **Admittance of light by proper orientation and minimized glazing areas**

Since solar gain is a problem in a warm climate, it is better to introduce daylight into a space by reducing the glazed area or by orientation rather than by using mirror glass. Therefore, glazing monitors or clerestories facing north and south are desirable. The use of clerestories are easy to illuminate, especially, in a low, wide atrium (fig. 3.48).

![Figure 3.48](image)

**Figure 3.48**

a) North/ South vertical glazing offers a high degree of seasonal control

b) Selective strategies in admitting light. Light should be directed into work spaces rather than to the floor.

Source: Lam, William M.C., *Sunlighting as Formgiver for Architecture*, 1986

2. **Use of dynamic mirrors to beam sunlight**

Where orientations are constrained or an atrium is narrow, beaming sunlight with mirrors can be invaluable for providing sufficient light (fig. 3.49).

![Figure 3.49](image)

**Figure 3.49** Beam sunlight with dynamic mirrors

Source: Lam, William M.C., *Sunlighting as Formgiver for Architecture*, 1986
3. **Admittance of low angle sun directly and high angle sun by reflection**

To capture diffuse sunlight, passive or active shading devices may be used. A passive approach is to use solar-facing glazing on a sawtooth roof and to fix the external shades at an angle to exclude summer sun rays, but which will reflect the light up onto the underside of the roof and then pass it down into the atrium; winter sun will enter directly, bouncing downwards off the roof (fig. 3.50).

![Admitting low angle sun directly, high angle sun by reflection](image.png)

**Figure 3.50** Admitting low angle sun directly, high angle sun by reflection

*Source: Saxon, Richard, *Atrium Building*, 1983*

4. **Determine the proportion of the atrium court by relating to the sky condition**

The ratio between width, length, and depth of an atrium court will influence the light level in the court. If the brightness of the sky is insufficient, the court must be widened to deliver a useful level of light to the base of atrium.

5. **Reflectivity**

The reflectivity of the side along the atrium is very important since atrium acts as a light funnel that illuminates an surrounding area. Therefore, the atrium should have a maximum wall area for reflection at the top. As the bottom is approached, the wall area is exchanged for an increased aperture size to deliver light to the spaces at the bottom and to ensure that available light is balanced between the top and bottom (fig. 3.51). Other elements affecting reflectivity within the atrium are:

- **Aperture.** Use smaller sized openings at the top and maximum openings at the bottom.
- **Glazing.** Glazing with higher degrees of reflectivity can be used to promote downward penetration of light, although this is less effective than opaque reflecting surfaces.

- **Lightshelves.** Lightshelves can be used effectively on the upper floor on the north side of the atrium where light is the brightest and most direct to compensate for smaller apertures (fig. 3.51). Lightshelves and shaded windows are less necessary lower down an atrium where light enters the room at all angles and without sky brightness.

- **Planting.** Planting within the atrium can conflict with daylighting performance. The use of plants on upper levels need to be carefully controlled. The low reflectivity of plant material reduces the effectiveness of a reflecting surface. The atrium floor is the best location for plants although it limits reflectance to adjacent spaces.

Figure 3.51  Atrium

3.8 Translucent Wall and Roof

A translucent wall and roof is a design option for a building envelope providing diffuse daylight to an interior space. Most translucent walls and roofs are made of either fabric membranes or composite panels. Membrane tension structures are the most appropriate for large buildings with long spans; for example, stadium and tennis courts. The translucent membranes, usually made of a Teflon- or silicone-coated fiberglass fabric, provide a very diffused low-glare light source. Although the light transmittance of these fabric membranes is often less than 10%, an abundant high quality light is available inside because the translucent materials are used to cover a very large area. The major drawback of most translucent membrane materials is the low quality insulating value. A translucent membrane would be appropriate for buildings that are not air conditioned and for buildings in a very mild climate. However, double membranes with air space between them make it possible to increase the insulating value. Such membrane makes it feasible to use heating and air conditioning but lowers light transmittance.

A composite panel system is a good material providing diffuse light the same as a fabric membrane. The use of composite panels is desirable on a small scale translucent wall or roof. A composite panel's thermal resistance can be raised by sandwiching a translucent fiberglass insulation between two plastic panels. Raising insulating value will lower the light transmittance.

3.9 Principles for Energy-Efficient Daylighting Design

With an understanding of a number of factors affecting daylight availability as well as design strategies used in controlling daylight, full benefit will be gained from daylighting if designers apply this knowledge in the early design stage. The daylighting design principles which are useful for promoting energy-efficient buildings are:
1. Consider the characteristics of site climate

Site climate is the major influence for building form and orientation, and sky condition can help determine which kind of strategies will be appropriate for bringing daylight into the building.

2. Increase perimeter daylight zones

Extending the perimeter form of a building may improve the building's performance by increasing the total daylighting area. This method must be concerned with the trade-off between an increased perimeter exposure and a compact building form.

3. Allow daylight penetration high in a space

With the location of an aperture high in a wall (use of high windows or increased ceiling height), daylight can penetrate deeper, and excessive brightness in the field of view may be reduced by reflecting and scattering light before it gets to the task level.

4. Reflect daylight within a space to increase room brightness

An increase in visibility and comfort can be achieved by increasing the room's brightness by spreading or redirecting light to change the brightness patterns. A reduction in intensity occurs from a reflected or partially absorbed light throughout a space. For example, a light shelf, if properly designed, has the potential to increase room brightness and decrease window brightness. Many types of shading devices can be used in this manner also. However, the reflectance values of interior surfaces (ceilings, walls, floors, furniture), play a major part in reflecting light within a room. Therefore, interior components should be selected properly.

5. Slope ceilings to direct more light into a space

Sloping the ceiling can improve the illumination level and light distribution within a space as explained in window daylighting strategies.
6. **Avoid direct beam daylight on critical visual tasks**

Direct beam daylight, which is usually composed of excessive brightness and high thermal effect, will cause poor visibility and discomfort to humans performing visual tasks. Fenestration control should be considered if direct beam illumination is undesirable. On the other hand, where noncritical tasks occur, direct sun can be used cautiously to create patterns of light and shadows for architectural effect or add an exciting and dynamic feature to a space.

7. **Filter daylight**

To soften and distribute light more uniformly, filtering can be accomplished by, for example: vegetation, curtains, or louvers.

8. **Maintenance**

To get the full benefit from daylighting, all reflecting and transmitting surfaces, such as light shelves and atrium windows, should be kept clean.

9. **Size window according to use and orientation**

Because window glass has little or no resistance to heat flow, it is a primary source of energy waste and discomfort. For daylighting design, it is not necessary to increase the number of windows. Fenestration is very important for introducing useful daylight and controlling direct solar gain during overheated hours. Therefore, window should be kept to a reasonable minimum, justified by clearly defined needs for view, ventilation, or/and daylighting.

10. **Locate work stations near the window**

Most working areas can use daylighting effectively by locating work stations requiring the most illumination nearest the windows. Hence, daylighting can be used to replace some of the electric lighting near the windows during substantial periods of the day. However, it will be most appropriate if workstation lights are dimmed or switched off.
11. Consider other environmental control systems

Since fenestration systems have many functions that can allow light, heat, air, and sound into a space, every system (ventilation, view, acoustics, electric lighting, and HVAC) needs to be considered collectively during the design process (fig. 3.52).

![Glazing-related decision point diagram]

Figure 3.52 Glazing-related decision point diagram

Source: Ander, Gregg D., *Daylighting Performance and Design*, 1995
Chapter 4: Artificial Lighting Design

4.1 Integrating Daylight and Artificial Light

Generally, it is difficult and often impossible to illuminate a building exclusively by daylighting. Outdoor conditions continually fluctuate, and the shape and size of a building is limited in its ability to benefit fully from daylight. The optimum solution may be to integrate daylight with electric lighting. To achieve energy-efficiency and promote cost-savings, daylight should be used as the dominant source, supplemented by electric lighting. Furthermore, the major objective of supplemented light is to reduce the contrast between the daylighted areas near windows and the relatively dim areas deeper in the interior. By controlling the luminance ratio for the whole area, glare can be avoided, thus, optimizing the quality of the visual environment. Electric lighting can extend the range of ordinary activities in that all activities can be performed beyond the limited daylight hours.

To gain the full benefit in designing illumination space, daylighting, artificial lighting, and internal finishes of occupied space need to be considered together. The daylighting concept outlined delivers diffuse light, laterally, and upwards onto the ceiling for reflection onto the working plane. Ideally, artificial light should perform similarly. For the best performance of both types of lighting, the ceiling is an important factor for both natural and artificial light.

Up-lighting, the concept of bouncing light off the ceiling rather than delivering it direct from a luminaire, can be as efficient as downlighting, given the appropriate design. The reflective quality of the ceiling needs to be selected carefully since it can reduce the losses caused by diffused or lowered light. Normally, a white flat, matte ceiling will reflect light better than a textured one. The up-lighting concept is often combined with the use of an exposed structural ceiling, with services in a raised floor. Unless a flat-slap structure is used, beams should be arranged to run perpendicular to the windows to provide adequate reflecting surfaces to channel the light deeper into the room.
To obtain full economy potential, daylight and artificial light must be interlinked by electric lighting control systems. The amount of savings increases as more ambient light is provided by natural means and a similar quantity of electric light is displaced. This can occur in a building planned for daylighting in which some part of the working area are arranged to access ambient light naturally and the rest of the building needs only partial electric light during working hours (fig. 4.1). When the amount of outdoor natural light changes and affects the light level within a room, an artificial light source from the center of the plan outward should progressively supplement the situation. Automatic controls are preferable for ambient light, just as personal controls are preferable for task light.

Automatic controls use a photocell to determine how much light is available on the workplane. The controls can be either the on/off or dimming types. To take advantage of these automatic controls, the lighting fixtures must be arranged to complement the available daylight and zoned to work with an individual control system. Fig 4.2 illustrates that lighting zones should consist of fixtures in rows parallel to the windows on each orientation. Thus, any number of rows can be turned on or off as needed. Certainly, the perimeter lighting will be switched off first, and the center lighting last.

In most cases, automatic controls are a necessary part of a daylighting system and are better than manual controls, which depend on occupant response. Usually, people are not motivated enough to turn lights off when they are not needed or when they leave a room. Therefore, electric lighting may remain on even when not needed. Automatic photosensitive controls are most effective in this case. They can be programmed to sense either daylight levels or occupants. For occupant sensor controls, the systems will turn off or turn on light fixtures based on motion detection, ultrasonic sound waves, or infrared radiation. For daylighting controls, the systems will vary or dim the output of the light fixtures by providing only the necessary light that daylight does not provide. Obviously, to obtain full benefits from electric savings and good visual environment, daylighting needs to be integrated with electric lighting.
1. Most daylight admitted at clerestorey and bounced off light shelf.
2. 85% (min) reflective ceiling, preferably structural as a heat sink.
3. View windows shaded to reduce reflection on VDUs.
4. Uplighter on automatic dimmer, varying output with daylight levels.
5. Uplighter for constant ambient light. Light shelf and shaded window are less necessary lower down an atrium where light enters room at all angles and without sky brightness.

Figure 4.1 Integration of daylight and artificial ambient lighting

Figure 4.2 The comparison of lighting zones
4.2 Artificial Lighting Sources

An electric lighting system can be separated by its function into two parts: light-producing systems and light-distribution systems. The light-producing systems consist of light sources (lamps), fixtures (luminaires), and controls. Each of these components of light-producing systems are detailed in the following parts.

Artificial light sources used in illuminating a space can affect the efficiency of the entire lighting systems. The decision to use artificial light sources must be based on factors such as efficacy, color-rendition, shape, light distribution, life, and application. Various light sources have different efficacies. Efficacy is the ratio of lumens per watt which refers to the efficiency of a light source given by the number of lumens emitted for each watt of electricity used.

Figure 4.3 compares the efficacy (lumens/watt) of various light sources and the efficacy of various daylight conditions. The efficacy of each lamp types is shown as a range because efficacy is a function of several factors including wattage. High wattage lamps have a greater efficacy than low wattage lamps. Besides wattage, the spectral distribution also influences the efficacy of lamps. Generally a yellow-green monochrome light is considered to have the highest efficacy because the human eye is most sensitive to a yellow-green light. Thus, a lamp that contains these color will have the highest efficacy. Unfortunately, the lamps with the best quality or best color rendition of white light do not have the highest efficacy, because the human eye is not very sensitive to colors such as red and blue. Any light containing these colors, such as white, is considered a low efficacy component. However, the lower efficacy of white light is still widely accepted because of its good color rendition.

The theoretical maximum efficacy occurs when 100% of the electrical energy is converted into light without heat. As shown in figure 4.3, the clear sky is the highest efficacy because it has the least heat content for a given amount of light, while direct sunlight has the highest heat and the lowest efficacy. This concept can be applied when examining the
efficacy of modern lamps. The incandescent lamp is a very inefficient source of light because it converts only about 7% of electricity into light while 93% is turned into heat. Although the fluorescent lamp is far more efficient because it converts about 22% of the electricity into light, it still produces much more heat than light. Most of heat produced by these lamps contributes greatly to the air conditioning load of a building. Using high efficacy lamps can reduce the impact on a cooling load. Various kinds of electric light sources, including incandescent, fluorescent, and high-intensity discharge (HID) lamps, are discussed by ascending order of efficacy:

<table>
<thead>
<tr>
<th>Light Source</th>
<th>Light Delivered (Lumens/Watt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CANDLE INCANDESCENT</td>
<td>0</td>
</tr>
<tr>
<td>FLUORESCENT</td>
<td>1</td>
</tr>
<tr>
<td>HIGH PRESSURE SILICON</td>
<td>2</td>
</tr>
<tr>
<td>METAL HALIDE</td>
<td>3</td>
</tr>
<tr>
<td>HIGH INTENSITY DISCHARGE</td>
<td>4</td>
</tr>
<tr>
<td>THEORETICAL MAXIMUM FOR WHITE LIGHT</td>
<td>600</td>
</tr>
</tbody>
</table>

![Figure 4.3](image)

The comparison in the efficacy of various light sources

4.2.1 Incandescent Lamps

The light of incandescent lamp is emitted by electrically heating a tungsten filament. Incandescent lamps produce light in all parts of spectrum but they are dominated by red and orange which makes incandescent light flattering to skin tones. Generally, the color-rendering quality of incandescent lamps is considered to be very good. But they are the least efficient of all lamps, having a typical efficacy of less than 20 lumens per watt.

The advantage in using incandescent lamps is their low initial and replacement costs, inexpensive fixtures, compact size, simple installation, accurate color rendition, instant start, no ballast required, simple and inexpensive dimming, various types, sizes, and wattages, and easy beam-light control.

The disadvantages are low efficacy, large heat gain, and short lamp life. Incandescent lamps are poor in energy efficiency; therefore, these lamps should be restricted to applications where (1) use is infrequent or of short duration; (2) low-cost dimming is required; (3) focusing fixtures are needed; or (4) minimum initial cost is required.

Normally, the average life of an incandescent lamp is 1000 hours. To overcome the disadvantage of short lamp life, long-life lamps have been designed for a 2500-hour life with slightly higher voltages. However, the longer life bulb severely reduces light output and efficacy. Long life lamps are rarely economical. If a longer life is required, then another type of light source should be used (see table 4.1).

4.2.2 Fluorescent Lamps

The light from a fluorescent lamp is emitted from a low pressure ionized mercury vapor. Fluorescent lamps are more efficient than incandescent lamps with 20 times longer life than some incandescent light. They are widely used in place of incandescents except for specialty lighting and residential use. The color-rendering capabilities of fluorescent lamps are warm white, cool white, and white (different colors are a product of the phosphorous coating on the inside surface of glass tube) and are appropriate for industrial, institutional, and office
applications, where economical light production is the primary concern. Special deluxe fluorescent lamps are available that give excellent color rendition but low efficacy.

Because of its large physical size (fig. 4.4), the fluorescent lamp is suitable as a light source for a large area. It is an excellent source of diffused lighting, but a very inappropriate source when beam control is required. Because of the large physical size and the concern with energy, compact fluorescent lamps with integral ballasts have been developed to replace the much less efficient incandescent lamp (fig. 4.5).

In addition, high-efficient fluorescent lamps which are the same size as typical standard lamps are also available. High-efficient lamps provide the same light output and useful life as standard lamps even though they consume only 34 watts while the standard lamp consumes 40 watts.
4.2.3 High-Intensity Discharge Lamps (HID): (Mercury, Metal Halide, High-Pressure Sodium)

High intensity discharge lamps have significantly greater efficacies than fluorescent or incandescent lamps even though their size and shape are similar to incandescent lamps (fig.4.6). HID lamps are especially useful for indirect lighting systems, where light output is modified by reflectance from ceiling and wall surfaces. One important characteristic of all HID lamps is they require a few minutes to reach maximum light output, and they will not restrike immediately when there is a temporary voltage interruption. The lamps have 5 to 10 minutes delay for start or restart. Therefore, public areas should be provided with a supplementary emergency light source of incandescent or fluorescent lamps as a part of design.

![Common shapes of high-intensity discharge lamps](source: Lechner, Nobert, Heating, Cooling, Lighting: Design Methods for Architects, 1991)

4.2.3.1 Mercury HID Lamps

Metal halide lamps are long-lived but have efficacies lower than other discharge lamps (fluorescent, metal-halide, and high pressure sodium). They produce light in the blue-green spectrum that tends to render color poorly. When good color rendition is desired then metal-halide lamps are preferable, and when high efficacy is most important, then the high-pressure sodium lamps should be used. However, mercury lamp is still available in the market because of its very long life (16,000-24,000 hours) and low initial cost.
4.2.3.2 Metal Halide HID Lamps

Metal halide lamps are one of the best sources of light today because they have many good characteristics contained in one lamp, such as high efficacy (80-125 lumens/watt), long life (10,000-20,000 hours), good color rendition, and small size for optical control. Metal halide lamps come in three sizes, which are the equivalent of 100 watt and 200 watt incandescent and a two-way 50/150 watt lamp. They are designed to use about a third of the electricity that comparable incandescent use. These lamps are appropriate for stores, offices, schools, industrial plants, and the outdoors where color rendition is important.

4.2.3.3 High-Pressure Sodium (HPS) Lamps

HPS lamps provide the high efficacy of up to 140 lumens per watt and have a very long-life. However the spectral output of HPS lamps peak predominantly in the yellow range, causing objects to appear yellowish in color. A high-pressure sodium lamp is most appropriate for outdoor applications, such as lighting for streets, parking areas, sport areas, and building floodlighting.

All electric light sources have their own characteristics; therefore, the choice of a lighting system should be based on many factors, such as lighting effect desired, color rendition, energy consumption, illumination level, and maintenance cost as well as initial costs. Table 4.1 prepared by Lechner (1991) shows the comparison of the major lamp groups by advantage, disadvantage, and major application for each group. Moreover, the lamp efficacy (lumens/watt), the significant factor when energy consumption and illumination are taken into account, is also available in this table.
<table>
<thead>
<tr>
<th>Lamp Group</th>
<th>Advantages</th>
<th>Disadvantages</th>
<th>Applications</th>
<th>Efficacy (lumens/watt)</th>
<th>Life (hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Incandescent</td>
<td>Excellent optical control (e.g., very narrow beams of light are possible)</td>
<td>Very low efficacy (high energy costs)</td>
<td>For spot, accent, highlighting and sparkle (residential, restaurants, lounges, museums)</td>
<td>10–25</td>
<td>750–2500</td>
</tr>
<tr>
<td></td>
<td>Very good color rendition (especially the warm colors and skin tones)</td>
<td>Very low lamp life (high maintenance costs)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Very low initial cost (especially useful when many low-wattage lamps are used)</td>
<td>Adds high heat load to buildings</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Flexible (easily dimmed or replaced with another lamp of a different wattage)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fluorescent</td>
<td>Very good for diffused, wide area, low brightness lighting</td>
<td>Little optical control possible (no beams)</td>
<td>For diffused even lighting of a large area (offices, schools, residential, industrial)</td>
<td>40–90</td>
<td>8000–20,000</td>
</tr>
<tr>
<td></td>
<td>Good color renditions (varies greatly with lamp type)</td>
<td>Large and bulky (except new compact types)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Very good efficacy</td>
<td>Sensitive to temperature and therefore not used much outdoors</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Long lamp life</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Metal halide</td>
<td>Good optical control</td>
<td>5 to 10 minute delay in start or restart</td>
<td>For diffused lighting or wide beams (offices, stores, schools, industrial, outdoor)</td>
<td>80–120</td>
<td>9000–20,000</td>
</tr>
<tr>
<td></td>
<td>Excellent color rendition (especially of blue, green, and yellow)</td>
<td>Fairly expensive</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>High efficacy</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Long lamp life</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>High-pressure sodium</td>
<td>Good optical control</td>
<td>Color rendition is only fair (mostly orange and yellow)</td>
<td>For diffused lighting or wide beams where color is not important (outdoor, industrial, interior and exterior floodlighting)</td>
<td>80–140</td>
<td>20,000–24,000</td>
</tr>
<tr>
<td></td>
<td>Very high efficacy</td>
<td>About 5 minute delay in start or restart</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Very long lamp life</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 4.1 Comparison of the Major Lamp Groups

Ballasts

All gaseous discharge and HID lamps require either a ballast or control equipment to provide adequate starting voltage and to limit current after the lamp has started. At present, the traditional standard ballasts (Standard Magnetic Ballast) have been improved by solid-state electronic ballasts (High-Efficiency Electronic Ballast). Solid-state electronic ballasts allow dimming of fluorescent lamps, have higher efficiency and consume less energy than the conventionally standard magnetic ballasts. The combination of reduced ballast energy consumption and lower wattage use decrease heat buildup. Solid-state ballasts operate the source at a high frequency, increasing source efficacy and eliminating the fluorescent flicker. However, attention needs to be paid to the frequency because it is in the radio-frequency range, and may affect other electronic equipment.

Ballasts affect the cost of discharge lighting systems and can be a source of noise in a poorly made fixture. However, the long life of discharge lamps and their efficacy are usually more than enough to offset the extra cost of the ballasts and the higher cost of each lamp when compared to incandescent lamps.

4.3 Artificial Lighting Fixtures (Luminaires) and Light Distribution Systems

Lighting fixtures, also called luminaries, have three major functions:

1. Support the lamp with some kinds of socket
2. Supply power to the lamp
3. Modify the light emitted by the lamp. In this function, a luminaire will block the glare of the lamp from direct view, and then introduce the light into the space with the proper diffusion, modification, or redirection necessary to establish the desired lighting result.
A luminaire consists of a housing unit (a reflector, lens, louver, one or more lamps, possibly a ballast, and/or lamp bracket), and wiring for the system. The efficiency of luminaries depends on materials and finishes used, and the design of the reflector and housing. High-efficiency luminaries will allow as much of the light source output to reach the workplane as possible, while maintaining comfortable vision conditions with minimum glare and contrast as well as less heat distribution to a space.

Light may be concentrated so as to reach from a high mounting height to the working surface, while still providing uniformity of lighting. Or, a low-mounted fixture may have a spread pattern so that its light covers a large area. Lighting systems are conventionally divided into six categories according to how they control or distribute light:

<table>
<thead>
<tr>
<th>Illustration</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1.png" alt="Direct Illustration" /></td>
<td>0–10%</td>
</tr>
<tr>
<td><img src="image2.png" alt="Direct Illustration" /></td>
<td>90–100%</td>
</tr>
</tbody>
</table>

1. **Direct**
   These system are efficient since direct lighting fixtures send most of the light down to the workplane. However, direct glare and veiling reflection are often a problem. Also, shadow reduction should be controlled as much as possible because direct lighting provides very little vertical surface. The problem of shadow are reduced when the spacing between fixtures are not too large.

2. **Semi-Direct**
   A semi-direct system is similar to a direct system except that the minor upward component serves to illuminate the ceiling. This system creates some diffused light as well as a brighter ceiling. Although problem of shadow can be reduced, veiling reflection still exists.
3. General Diffuse
This type of fixture emits light equally in all directions. The horizontal component can cause severe direct glare unless a large diffusing element or a low-wattage lamp is used.

4. Direct-Indirect
Fixtures of this system distribute approximately an equal amount of light upward and downward. Since the ceiling is a major, although secondary, source of room illumination, it is a useful diffuser which provides satisfactory vertical-plane illumination and minimizes shadow and veiling reflection. Direct glare is not a severe problem for this system since there is a little light, emitted in the horizontal direction.

5. Semi-Indirect
In this system, a fixture will reflect much of the light off the ceiling and thus yields high quality lighting, allowing a higher level of diffused illumination without glare. However the efficiency is reduced, especially if the ceiling and walls are not of a high reflectance.

6. Indirect
Nearly all of the light in this system arrives at the horizontal workplane indirectly. It is first reflected from the ceiling and upper walls. Therefore, the walls and ceiling must have a high-reflectance finish. The very diffused lighting eliminates almost all direct glare, veiling reflection, and
shadow. The resultant condition of this system, is called *ambient lighting*.

Various distribution systems of lighting fixtures have both advantages and disadvantages depending on designers who apply these systems according to their design objectives. Normally, the luminaires with a large direct component are most appropriate when high illumination levels are required over a large area, or when the ceiling and walls have a low reflectance factor. However, the quality of light distributed from these luminaires is not as high as their energy efficiency.

Luminaires with a large indirect component, however, can be used to reduce or eliminate unwanted shadow, direct glare, and veiling reflection. Therefore, to create a satisfactory lighting environment, the combination of both direct and indirect lighting distribution should be implemented efficiently. Task/ambient lighting can provide benefits by using ambient light coming from indirect fixtures for non-critical visual task areas or background light, and by utilizing task light coming from small, low-wattage, direct fixtures for critical visual task areas near the working plane.

Since most of the light distributed from a luminaire creates problems, such as glare, veiling reflection, and quality of light reaching the working plane, there are a number of improvements focused on the design of the luminaire; for example, design shielding materials, arrangement of the light source positions, and consideration of reflector shapes. Some of significant techniques which tend to improve the quality of lighting from direct fixture are:

1. **Selection of fixtures with batwing light distribution patterns**

   The light leaving the luminaire from 0° to 30° zone tends to cause veiling reflection, and the light in 60° to 90° zone tends to cause direct glare. Fixtures with “batwing” light distribution patterns give a significant quality of light, because they minimize the light output in these glare zones (fig. 4.7). The principle of direct lighting fixtures with batwing light
patterns is the same as the principle of up-directed light which reflects light off the ceiling to reduce both direct glare and veiling reflection.

![Diagram of light distribution patterns](image)

Figure 4.7  Fixture with “batwing” light distribution patterns

2. **Use of baffles, louvers, and eggcrates to shield against direct glare**

These devices limit direct glare by restricting the angle at which light leaves the fixture (fig. 4.8). It is important to provide optimum depth and spacing between each louver so that components will not block the useful distributed light. At the same time, direct view of light sources should be shielded up to 45°. For example, if one-way waffles such as louvers are used to shield the direct glare, they will be effective only if viewed perpendicular to their direction. Baffles, louvers, and eggcrates can be either small and part of the luminaire, or they can be large and part of architecture (e.g. beam, waffle slab, or joists).

These devices are often used with larger sources such as fluorescent lamps to shield luminaires. An effective design to reduce direct glare is the “parabolic louvers”. This type of louver is made of parabolic wedges with a specular finish. It prevents direct glare because the light distribution is almost straight down (fig. 4.9). It is also very good in avoiding veiling reflection in computer monitors and video display terminals.
3. **Shield small light sources with reflectors or lenses**

Small sources such as incandescent, compact fluorescent, and high-intensity discharge lamps are usually produced with a single reflector or lens inside the covering designed to control the brightness of the source. When the light strikes the lens, it is refracted so that most of the distribution is down and direct glare is reduced.

A reflector cone for downlight (incandescent or compact fluorescent) is designed by setting the cutoff and shielding angles, which are based on the size of the lamp, the width of the aperture, and the distance from the bottom of the fixture to the bottom of the lamp (fig. 4.10). The successful fixture design depends on the proper form and finished reflector surface. Therefore, fixtures are generally designed with a semi-specular finish so that most of the light reflected by the surface is redirected within the cutoff angle.
4.4 Artificial Lighting Application (Task/Ambient Lighting Systems)

The proper application of task and ambient lighting systems can provide great benefit to any illuminated environment for both human satisfaction and energy efficiency. Task and ambient lighting should be well integrated and supplemented to daylighting. The degree of success in the application of task/ambient lighting depends on two significant factors: designed luminaires and planned locations. If these systems are poorly designed, they can cause a number of disadvantages, such as direct glare, inadequate amounts of quality light, veiling reflection, and reduced contrast.

4.4.1 Task Lighting

Task lighting may be defined as the amount of light needed to make a task visible. There are many factors affecting the visibility of the horizontal task as explained in chapter 2. However, the most important factor for the task to be visible is that the light concentrated on the task should be sufficient in quantity and adequate in quality.
Quantity of task lighting

The quantity of light usually implies the amount of light falling on the task plane, measured by a footcandle meter. To determine the quantity of light level needed, the Illuminating Engineering Society (IES) has recommended the levels of illumination for indoor activities as shown in table 4.2. Because the exact illumination level for any activity will depend upon a number of variables, IES has divided the levels into “lighting categories”, which give a range of footcandle for certain types of activities. The information for light level in this table represents the quantity only. It does not relate to the quality concerns of lighting, such as the glare produced by luminaires which may impact visibility. According to Sorcar (1987), “For most situations, in general ambient lighting, meeting the quantity is sufficient. For task lighting, however, it is essential that it meet quality as well.”

<table>
<thead>
<tr>
<th>Type of Activity</th>
<th>Illuminance Category</th>
<th>Ranges of Illuminances</th>
<th>Reference Work-Plane</th>
</tr>
</thead>
<tbody>
<tr>
<td>Public spaces with dark surroundings</td>
<td>A</td>
<td>20-30-50</td>
<td>2-3-5</td>
</tr>
<tr>
<td>Simple orientation for short temporary visits</td>
<td>B</td>
<td>50-75-100</td>
<td>5-7.5-10</td>
</tr>
<tr>
<td>Working spaces where visual tasks are only occasionally performed</td>
<td>C</td>
<td>100-150-200</td>
<td>10-15-20</td>
</tr>
<tr>
<td>Performance of visual tasks of high contrast or large size</td>
<td>D</td>
<td>200-300-500</td>
<td>20-30-50</td>
</tr>
<tr>
<td>Performance of visual tasks of medium contrast of small size</td>
<td>E</td>
<td>500-750-1000</td>
<td>50-75-100</td>
</tr>
<tr>
<td>Performance of visual tasks of low contrast or very small size</td>
<td>F</td>
<td>1000-1500-2000</td>
<td>100-150-200</td>
</tr>
<tr>
<td>Performance of visual tasks of low contrast and very small size over a prolonged period</td>
<td>G</td>
<td>2000-3000-5000</td>
<td>200-300-500</td>
</tr>
<tr>
<td>Performance of very prolonged and exacting visual tasks</td>
<td>H</td>
<td>5000-7500-10000</td>
<td>500-750-1000</td>
</tr>
<tr>
<td>Performance of very special visual tasks of extremely low contrast and small size</td>
<td>I</td>
<td>10000-15000-20000</td>
<td>1000-1500-2000</td>
</tr>
</tbody>
</table>

Table 4.2 IES Recommended Illumination Level

Quality of task lighting

Quality in task lighting relates directly to the shadow and glare present in a lighting system. Sharply defined shadows reduce visual efficiency that usually are not desirable on a task; however, they are sometimes preferable for adding depth or creating an aesthetic effect. Shadows may be minimized by using proper light diffusion and high-reflectance matte-finished surfaces.

There are two types of glare: direct and indirect. For task lighting, it is necessary to consider indirect or reflected glare, because it directly affects visual ability on a task. To improve the quality of lighting, the effect of indirect glare that results mainly from light emitted in the 0 to 45° zone (fig. 4.11) reflected by a shiny or specular surface on the task and pointed toward the eyes needs to be minimized. Besides the effect of reflected glare which presents a patch of light visible on the surface known as “veiling reflection”, it can cause a loss of visibility. Thus, to improve the quality of task lighting, the reflected glare from the luminaire must be controlled.

Figure 4.11 Glare zone of the luminaire which is measured from the nadir 0 to 45° is the reflected glare zone; 45 to 90° is the direct glare zone.


Improvement of visibility is often no more difficult than repositioning a desk, seating arrangement, or luminaire by 90° to avoid veiling reflection. With the proper combination of angles, reflected glare can be almost eliminated by the use of various media to control the distribution of light as it leaves the light source.
Vertical task lighting

Contemporary offices and other commercial areas are becoming increasingly dependent on the application of high-tech equipment: desk-top computers, word processors, and other video display terminals (VDTs). With this equipment, the task has been raised from desk level to the glossy surface of the screen. This presents unique problems that cannot be solved by traditional task lighting alone. The problems of a glossy surface of a screen may present as in figure 4.12.

![Diagram](image)

Figure 4.12 The position of luminaires affects visual tasks.

In figure 4.12 a, luminaires in front of the operator cause discomfoting glare and those above contribute to a reflected image of the surroundings. The convex-shape screen projects an image of the rear field of view and reduces screen contrast.

In figure 4.12 b, light rays arriving from behind create an excellent contrast to the horizontal task, but on the vertical screen the effect is the opposite. Reflected images of the rear luminaires appear on the screen, causing a veiling reflection and reducing screen contrast.

The performance in figure 4.12 presents the fact that the brightness of the luminaires (or the image of other surface such as window, or specular material) visible on the screen makes
it almost impossible at times to read the characters because the brightness of the luminaire or other images distort the field of view on the monitor screen and reduces the contrast. It is a difficult problem to provide the differences in lighting levels required for the two types of tasks. Characters on the screen can be read with ease in a dim environment of about 20 fc. Principles derived by Sorcar (1987) to solve the problem where both horizontal and vertical task lighting are required in two different situations are:

"In an existing room with a ceiling full of bright fluorescent luminaires
Place the VDTs screen where the ambient lighting is fairly low. Position the VDTs screen facing a vertical surface that does not reflect light and no luminaires are in the operator's immediate field of view. If this is not possible, use a bookcase, file cabinet, or room divider to obstruct the glare (fig. 4.13). In addition, the use of a parabolic louver covering the light source is also effective in reducing glare while maintaining desirable light output.

Figure 4.13 The use of bookcase, file cabinet, and partition to obstruct the glare.
In new applications
Use the uniform illumination on the entire ceiling by the method of indirect lighting. The luminaires may be pendant hanging from the ceiling, self-standing on the floor, or furniture integrated, but care must be taken to eliminate “hot spot” and “batwing patterns.” All surfaces around the work station should have a non-glossy or matte finish. If direct luminaires must be used, the luminaire ratio of the bright and dark surfaces of the ceiling should not exceed 5:1 from the field of view. When a large number of VDT screens are positioned in multidirections, the solution is to use low-glare-producing but efficient luminaires, such as parabolic-louvered luminaires as well as an application of ceiling methods, such as deep cells, specular finishes, or coffer ceilings.

4.4.2 Ambient Lighting
Ambient lighting is indirect lighting reflected off the ceiling and walls. It is a diffused low-illumination level lighting that is sufficient for easy visual task and circulation. It is usually used in conjunction with task lighting and is know as “task/ambient” lighting.

Ambient lighting is largely dependent on surface reflectance. The higher surface reflectance will provide higher amounts of light. Colors should be selected to provide the maximum reflectance that will optimize lighting efficiency (for office interior, the IES recommended surface reflectance are: ceiling 80-90%, wall 40-60%, and floor 20-40%). However, color selection should never be based on reflectance alone; it must be considered in conjunction with other factors, such as visual and psychological effects.

With the application of ambient lighting, most direct glare and veiling reflection can be almost avoided completely. The luminaires creating the ambient lighting can be suspended from the ceiling, mounted on walls, supported by pedestals, or integrated into the furniture. To provide optimum effects in ambient lighting, Lechner (1991) recommended that indirect fixtures should be at lease 12-inch below the ceiling to prevent hotspots, and they should be above eye level to prevent direct glare. Generally, the ambient illumination level should be about a third of the task light level.
Task/Ambient Lighting

The application of task/ambient lighting is very appropriate, especially in large offices where task locations are unknown because flexibility of space is required periodically, but quality light in terms of good task contrast and visual comfort are important. In this system a large space is divided into many small movable booths with low partitions. Each booth is provided with a task light for normal office work including the installation of a lighting control for each occupant to decide the individual desired lighting level. Moreover, each work-station is defined the use of a partition which is low enough to take advantage of the general lighting system. Because of the small area configuration that obstructs glare, this arrangement is also ideal for VDT screen operation. The greatest advantage that a task/ambient lighting system can provide is the right amount of light wherever needed, so that no electric energy is wasted. The appropriate amount of quality light is available for the task in any location, whereas a low level glare-free ambient light creates a perfect environment for VDT screen and circulation lighting.

4.5 Lighting Control Concepts

A complete daylighting system not only involves the various architectural design methods in using and controlling natural light, but also incorporates automatic control systems in adjusting the level of the electric lighting when sufficient daylight is available. The automatic controls are essential to an energy saving daylighting system, especially in nonresidential buildings that are not convenient for manual switching.

Automatic controls are usually consist of two components: is a sensing device to measure daylight, and is a controller that either switches or dims the electric lighting. The principal types of lighting controls can be categorized by their performance in three types: switching controls, stepped controls, and dimming controls.
4.5.1 Switching Controls (On/ Off Controls)

Switching controls will turn off electric lights when there is sufficient daylight, conversely, they turn the light on when available daylight drops below the required illumination levels. Switches can be controlled by photosensors responding to the level of daylight available by timers and by occupancy sensors that switch electric lights on or off based on the proximity of persons. Switching controls are typically the most economical in first cost but they provide only little energy savings since the luminaires remain on any time that available daylight is below the specified design level. Besides, switching also produces the most noticeable changes in illumination, which can be disconcerting to the occupants.

4.5.2 Stepped Controls

Stepped controls are selective switchings that provide a simple method to achieve transitional levels of illumination. They control the individual lamps within a luminaire to allow different combinations of lamps to operate at appropriate times. They can be categorized as two-step, three-step, four-step, or five-step, as in the following:

- The performance of a two-step system is a simple on or off of all lamps on the circuit.
- The three-step system is used with luminaires with two lamps, or multiples of two.
  The three steps are: a) all lamps on, b) half of the lamps on, and c) all lamps off.
- The four-step system is applied to luminaires with three lamps, or multiples of three.
  The four steps are: a) all lamps on, b) one-third of the lamps on, c) two-third of the lamps on, and d) all lamps off.
- The five-step system is applied to luminaires with four lamps or multiples of four.
  The five steps are: a) all lamps on, b) one-fourth of the lamps on, c) one-half of the lamps on, d) three-quarters on, and e) all lamps off.

Although stepped controls are not as effective as continuous dimming, they are less expensive. Because of the incremental levels of the turning on and off of light, the three or four-step design are less perceptible to occupants and there is no perception of the light levels
constantly changing. In addition, stepped control can provide more comfortably lit space by avoiding a darkened ceiling because at least one lamp may remain lit at all times.

### 4.5.3 Dimming Controls

Dimming controls provide the additional footcandle needed to supplement daylight and maintain the required illuminance level. Dimming controls adjust electric lighting continuously by modulating the power input to the lamps to complement the level of illumination provided by daylight.

This type of controller can achieve the most graceful blending of artificial and natural light and can be virtually unnoticeable in use. Savings are generally greater because the dimming controls provide only the amount of light required to meet a specified level of illumination. However dimming controls have drawbacks; for example, dimmers consume some energy even when the lights are effectively dimmed off, and not all lamps and ballasts are guaranteed from manufacturers that they will function properly with dimming controllers.

### 4.5.4 Selection of Electric Lighting Controls

Proper selection of electric lighting controls is an important step in the design of a daylighted building. Some considerations are:

1. **Quality of Space**
   Lighting controls can affect the quality of interior space. For example, they can cause unpleasant changes in the light level, poor color rendition, and items that may reduce the quality of space. These changes are serious problems, especially in critical task areas, such as office building, where light switching may reduce productivity resulting in economic losses that far exceed energy savings.

2. **Types of Lamps and Ballasts**
   The type of lamps or ballast used in a building will affect the selection of electric lighting controls. Dimming controls are made specially for certain types of lamps,
but some controls, such as switching devices, can be used on any lamp type. Therefore, the compatibility of control and lamp type is a very important issue for the designer.

(3) Fixture Layout and Room Size
Fixture layout and room size affect the selection of controls. As described by Moore (Moore, 1985), multifixture dimming and switching systems rely on the layout in which many fixtures are receiving similar quantities of daylight. In large buildings where this occurs, the multifixture systems are typically cheaper and easier to maintain than numerous single-fixture controls. However, in small buildings or individual rooms, single-fixture controls, which normally control one or two ballasts only, are more appropriate.

(4) Quantity of Light
The quantity of daylight in a space will affect the control device selection. Since most dimming devices have a minimum power consumption, they may not be appropriate in areas in which a large amounts of daylight are available, or low illuminance levels are required. Briefly, when daylight level is low, the optimum device should be dimming. On the other hand, when daylight level is high, switching is more appropriate.

The optimal control system will adjust electric lighting without impacting the illumination quality of the space. Time delays are recommended to reduce rapid responses to varying light intensity changes, particularly on partly cloudy days.

4.5.5 Integrating the EMS and Lighting Control
Many lighting control systems can also be interlinked with existing energy management systems (EMSs) to provide additional control possibilities. For example, EMS can schedule the time of operating light to accommodate building occupancy. In addition, the extra intelligence available in an EMS may allow the building operator to prevent the control
system from reacting in an undesirable manner. Most of the following discussion of the EMS is derived from Ander (1995).

EMSs are known as intelligent, microprocessor-based building monitoring and control systems that are an integral part of most large commercial buildings. EMSs are generally composed of numerous controllers residing on a distributed local area network (LAN). This distribution of EMS allows a wide range of control options for both standing-alone function and building-wide supervisory applications. In either option, the LAN provides additional benefits of centralized information access from any operator work station (fig. 4.14).

At present, there are widespread applications in Energy Management Systems (EMS) for scheduling both interior and exterior lighting systems. EMS is typically implemented at the circuit breaker level. Most of the times, the EMS will be used as a master schedule for the building’s overall lighting, whereas zone level control remains dependent on manual occupant actions.

With the more extensive occupancy and daylighting based controls which have been incorporated into building designs, energy savings from these controls are increased by respectively tailoring lighting schedules to a building’s zone level occupancy and by raising ambient light. These new types of lighting controls can be implemented in either a stand-alone (EMS-independent) or supervised manner. An example of both types of lighting controls is presented in figure 4.15.

EMS-based daylighting controls are more complicated than zone level. In large daylit portions of a building such as an open-area, the EMS may include light sensors that convert measured footcandles into a proportional voltage monitored by the EMS. Then, EMS will act on the input signals to control the area’s electric lighting sources. This may include stepped controls or continuous dimming controls. The use of direct EMS daylighting control is typically not economical for the small zone level (e.g. a perimeter office). In this case, the zone level daylighting control will possibly be applied to the zone’s occupancy sensor. Such
devices are available for either stepped or continuous dimming control that are suitable for the specific lighting system installed in the zone.

Figure 4.14 Energy Management System Control Diagram
Source: Ander, Gregg D., *Daylighting Performance and Design*, 1995

Figure 4.15 Lighting Control System
Source: Ander, Gregg D., *Daylighting Performance and Design*, 1995
4.6 Principles for Energy-Efficient Artificial Lighting Design

Based on the previous presentation of this report, design principles can be categorized as follows:

1. Install High-Efficiency Ballasts in all Fluorescent Fixtures

High-efficiency ballasts (electronic ballasts) are better than standard ballasts because they take less input to operate than two standard lamps. A direct reduction in energy use of 10 to 15 percent can occur with the use of high efficiency ballasts because less internal heat is generated, resulting in a reduced cooling load.

2. Replace Standard Fluorescent Lamps with High-Efficiency Lamps

High-efficiency lamps provide the same light output and useful life as standard lamps, although they consume 34 watts instead of the usual 40 watts. With only a 3 percent reduction in lumen output, high-efficiency lamps can reduce wattage used up to 15 percent.

3. Install Automatic Daylight Dimmers

This principle reduces electric consumption and costs over the entire year because the dimmers dim unneeded lights on bright summer days. This can cut both peak electric demand and consumption at a time of the year when electric rates are highest in many utilities. According to BHKRA (Burt Hill Kosar Rittlemann Associates, 1986), dimmers offer benefits in buildings with either clear or tinted glass (but not reflective glass) as long as the glass area is at least 20 percent of the exterior wall area. Optimum results are achieved in buildings with 30 to 40 percent glass area. Dimmers may control one or more fixtures up to a depth of 15 feet from the window wall and may be used with most standard or high-efficiency ballasts, but usually not with electronic ballasts.

4. Replace Standard Fixtures with New High-Efficiency Designs

Replacing standard four-lamp fixtures with three-lamp parabolic designs can reduce lighting energy about 25 percent while maintaining lighting levels. The use of high-efficiency ballasts and lamps can bring the total savings in lighting to 40 percent. Nearly the
same effect can be achieved in the combined usage of standard fixtures and high-efficiency prismatic lenses.

5. **Use a Nonuniform Lighting**

A nonuniform lighting system should be designed to match occupancy needs by varying intensity. Nonuniform lighting makes some areas brighter than others, usually determined by task requirements or desired effects. It can provide 50 footcandles at the desk and spread 10 footcandles elsewhere. This practice can be energy-efficient, interesting, and adaptable.

6. **Increase Manual Switching**

When sufficient light switches are provided, especially for task light at workstations, occupants can manually control light and reduce unnecessary energy use. Switches should be separated by functions and periods of use.

7. **Install Energy Management Systems**

EMSs can reduce building energy consumption, including electrical demand. They can be used to control a wide variety of building conditions and subsystems, including temperature, HVAC, and lighting. Since the cost of EMS systems are often too expensive for smaller buildings, this strategy is recommended for buildings with 25,000 square feet or more.

8. **Provide Lower Light Levels in Areas of Heavy VDT Screen Use**

Since glare on the glossy screen is the greatest lighting problem in most offices, light levels in general need to be lower in areas of heavy VDT use. Moreover, the VDT should be positioned away from windows or blinds or shades should be used. The wall behind the VDT screen should be midtoned or medium colored, if possible.
9. **Group the Same Activity of Tasks Together**

Tasks having the same illuminance requirements or widely separated work station should be grouped together to be convenient in providing essential light and in closing off unused space.

10. **Consider the Use of Interior Surfaces**

Interior surfaces affect the performance of electric lighting. Consider the use of light color for walls, floors, ceilings and furniture to increase utilization of light, and avoid glossy finishes on room and work surfaces.

11. **Consider Color-Rendering Capabilities**

Good color-rendering capabilities of light sources are important to provide a comfortable visual environment corresponding to activity needs. For effective lighting design, designers should select lamps with higher efficacy (lumens per watt) compatible with the desired light source color.

12. **Use Heat Removal Luminaires**

Wherever possible consider using heat removal luminaires to improve lamp performance and reduce heat gain to space.

13. **Lighting Maintenance**

Maintenance is required to maintain the efficiency of a lighting system. It is important to select luminaires that do not collect dirt rapidly and that can be easily cleaned. After installation, lighting systems (luminaires and lamps) should be programmed for maintenance and revised as necessary to provide the most efficient use of the lighting system. In addition, all components need to be checked to determine if they are in good working condition. The transmitting or diffusing media should be examined, and badly discolored or deteriorated media should be replaced to improve efficiency without producing excessive brightness and unwanted visual discomfort.
14. **Institute an Education Program for the Building’s Occupants**

The building’s manager should institute an education program to stimulate occupants to turn off lights when they are not needed. According to the IES energy guideline (1981), it is significant to inform and encourage personnel to turn off light sources such as:

(a) incandescent - promptly when space is not in use
(b) fluorescent - if space will not be used for five minutes or longer
(c) high-intensity discharge lamps (mercury, metal halide, high-pressure sodium) - if space will not be used for 30 minutes or longer
Chapter 5: Methodological Analyses of the Case Study Buildings

The analysis of case study buildings will be used to enhance the overall idea about daylighting. The following six case studies represent a variety of daylighting strategies. All selected case study buildings are a part of this report because of their successful completion of their goal to combine exemplary energy-efficiency with an environment superior to conventional practice. In addition, they result from architectural programs and forms responding to the influence of climate. Daylighting can provide a substantial advantage to commercial buildings to produce electric power savings and enhance the visual environment of those buildings.

Although the strategy and design elements of daylighting in different buildings seems to be a result of various methods. They are affected by several factors, such as site conditions, owner’s requirements, or budget constraints derived from the same objective: to create and enhance the quality of daylit space.
5.1 The Gregory Bateson Building, California

Case Study 1

**Gregory Bateson Building (1981)**

<table>
<thead>
<tr>
<th>Building Type</th>
<th>State Office Building</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location</td>
<td>Sacramento, California</td>
</tr>
<tr>
<td>Building Area</td>
<td>267,000 sq.ft. (4-story)</td>
</tr>
<tr>
<td>Architects</td>
<td>Sim Van der Ryn, Calthorpe &amp; Partners</td>
</tr>
</tbody>
</table>

This government office building was designed to serve two primary concepts: to establish a humanistic approach to design for institutional buildings and to conserve nonrenewable resources. Daylighting was selected to solve these goals.

To achieve the design concept of view and natural light, a narrow building form was required. But, due to the constraints of site and requirement of gross area, the Bateson Building was designed by splitting the building from within and adding a large 144x150x75 ft. high atrium to the center of squarelike building form. With atrium, no point in the building is more than 40 feet from the natural light source. The atrium is topped by smaller north-facing skylights and by large south-facing skylights with exterior motorized louvers that are operated automatically in response to the sun movement and the intensity of daylight, by either admitting sunlight or shutting it out. The atrium receives diffused skylighting from the south-facing glazing. In the summer, the south-facing clerestories in the sawtooth roof are shaded by moveable vertical louvers while the north-facing skylights allow the penetration of diffused light from the northern sky year-round.

To avoid glare and excessive brightness ratio from the direct sunlight entering the atrium during winter, banner type screens are hung from the ceiling to bounce sunlight into the space. The atrium of the Bateson building allows office space to have a second “perimeter”
for view and access to daylight without attendant thermal loads. The atrium acts as a thermal buffer space, passively heated by the sun, and cooled by night ventilation.

Since the east and west facades are not easily shaded by fixed elements, motor-operated fabric exterior roller shades are placed on the east and west windows to avoid sun by blocking the sun on the east in the morning and on the west in the afternoon. In addition, reflective venetian blinds are used to shade the windows along these sides to cut glare and cast useful daylight on the ceiling. At the south side, a fixed system of concrete trellis (precast louvers run in east-west axis) is located to shade the south clear glazing windows during summer, but allows insolation during winter. In the case of access to view and daylight, terraces, step-backs, and reentrant corners were designed into the exterior facade to protect the glass from unwanted solar gains and to provide greater opportunities for exterior views.

Although offices are of an open-plan design, no special devices have been used to direct daylight deeper into the interior. Therefore usable daylight probably is limited to 15 ft. or so from the exterior wall.

Since the budget would not allow automated lighting controls, daylight was treated conservatively. The conservative use of daylighting in this building is exemplified in the use of space at the atrium/building boundary. This zone is used primarily for circulation. Office space in this area would have the greater energy conserving potential since it has a higher lighting load than corridors. Hence, most of the times artificial light can be turned off in this area.

In addition, an efficient glare-free visual environment is provided by task/ambient lighting from indirect fluorescent fixtures, and each workstation has locally controlled task light. Fenestration controls, daylighting features, and other energy saving devices allow the Gregory Bateson Building to use 70% less energy than a conventional building.
Summary of Method Relating to Daylighting:

1. Massing  
   Block with central atrium in which no point in the building is more than 40 ft. from a natural light source

2. Atrium  
   Sawtooth Skylight Atrium:
   2.1 North-Facing Skylight
   2.2 South-Facing Skylight with Exterior Motorized Louvers
   2.3 Banner Type Screen

3. Fenestration  
   40% clear glazing with different shading devices in each orientation
   3.1 East/West window
      - Motor-Operated Fabric Exterior Roller Shade
      - Interior Reflective Venetian Blind
   3.2 South Window
      - Exterior Concrete Trellis

4. Electric Lighting  
   On/Off
   Task/Ambient Lighting

Figure 5.1  Isometric of The Gregory Bateson Building

Figure 5.2  Section and section isometric show the detail in admitting and controlling daylight

Source:  Solar Energy Research Institute, The Design of Energy-Responsive Commercial Building. 1985
5.2 The Hongkong Bank, Hong Kong

Case Study 2

The Hongkong Bank (1985)

<table>
<thead>
<tr>
<th>Building Type</th>
<th>Financial Institution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location</td>
<td>Hong Kong</td>
</tr>
<tr>
<td>Building Area</td>
<td>1,067,000 sq.ft. (47-story)</td>
</tr>
<tr>
<td>Architects</td>
<td>Foster Associates</td>
</tr>
</tbody>
</table>

General Description:

The 47-story Headquarters of the Hongkong Bank presents the strategy in using daylight from an architectural basic design to an innovative technique. For instance, the computer-operated solar-tracking system with a sunscoop device is used to provide daylight into the building, and artificial lighting system is controlled by computer to provide an adequate amount of supplementary light. The artificial light can be dimmed or switched off automatically when the quantity of daylight is ample to illuminate office space.

The Bank was designed with open office areas and floor-to-ceiling windows to access the view and natural light. Unlike most other all-glass office towers, the Hongkong Bank has exterior shading device over all windows by using horizontal louvered overhangs to block both the direct sun and glare from the bright sky on the north and south of the building. Actually, the main reason for using exterior sunscreens on the north windows is not for protection from the sunlight because this side of the building receives direct sunlight only few months of the year. Aesthetics and maintenance access is more important. These horizontal louvered overhangs composed of extruded blades are angled so as to keep out the strong tropical sun without obstructing the downward view from inside the building. Moreover, miniature venetian blinds are fixed on all window-walls to protect the interior from solar radiation, and they are also used to bounce direct light onto the ceiling.
To introduce as much daylight as possible into the office areas, the ceiling height is increased around the perimeter of the building, and the central space from ground floor to the twelfth floor is punctured to be a high central atrium which is illuminated by daylighting by means of a systems of reflectors called “sunscoop”.

A sunscoop is a simple optical device, a kind of huge periscope that projects sunlight into the atrium and through the clear glazing underbelly to the plaza pavement below. It is composed of a bank of moveable flat mirrors attached to the south side of the building at level 12, and a curved canopy of convex mirror suspended inside the building at the same level, over the atrium. To minimize the cooling load, most glazing is located on the north and south facades and is also protected by external and internal sunscreens while the east and west sides are protected by service cores. For the electric lighting system, the cooling load from this system is minimized by several techniques: daylighting and task/ambient lighting are used, much of heat from the fluorescent lamp is vented outside by exhausting air through the lighting fixtures, and a light-sensor system is installed to control the optimum light level, which can cut the problem of heat gain due to excessive brightness from electric lighting.

Summary of Method Relating to Daylighting:

1. Massing Rectangular Tower with Central Atrium

2. Atrium The central atrium receives natural light by the method of a solar tracking system with reflectors called “sunscoop” which is installed on the exterior south facade. This device directs sunlight onto the mirrored ceiling located on the twelfth floor within the building. Then, the mirrored ceiling passes the reflected light received from the sunscoop down into the atrium.

3. Fenestration To maximize light penetration and avoid the effect of heat and glare, the Bank is designed with floor-to-ceiling window walls with exterior shading devices, and increased ceiling height around the perimeter of the building.
3.1 North/South Facade
- Curtain Wall with Exterior Horizontal Louvered Overhang
- Interior Miniature Venetian Blind

3.2 East/West Facade
- Minimum use of glazing curtain wall combined with exterior horizontal louvered overhang
- Most of the area along these sides are placed by service core to reduce solar heat gain.

4. Electric Lighting  Dimming, On/Off
Task/Ambient Lighting
Recessed fluorescent lamps with a system of exhausting heat through the lighting fixture

5. Interior Arrangement
Open Office Plan
Translucent and transparent partitions are used to divide space and allow some amount of daylight to penetrate over the office area.

Figure 5.3  Left - Perspective of The Hongkong Bank
Right - Typical Office Floor Plan
Figure 5.4 The extruded blades of the horizontal louvered overhang are angled so as to keep out the sun rays without obstructing the downward view from inside the building.


Figure 5.5 Perspective view of solar tracking and reflector system illustrates how sunlight is beamed for atrium and ground floor below the atrium.

5.3 Menara Mesiniaga, Malaysia

Case Study 3

Menara Mesiniaga (IBM Tower) (1992)

<table>
<thead>
<tr>
<th>Building Type</th>
<th>Office Building</th>
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<tbody>
<tr>
<td>Location</td>
<td>Selangor, Malaysia</td>
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<tr>
<td>Building Area</td>
<td>112,000 sq.ft. (15-story)</td>
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<tr>
<td>Architects</td>
<td>Ken Yeang &amp; T.R. Hamzah</td>
</tr>
<tr>
<td>General Description</td>
<td></td>
</tr>
</tbody>
</table>

The 15-story Menara Mesiniaga is a headquarters building for an electronics and business machine company (IBM's Malaysia agency) that employs a bioclimatic approach to produce an operationally low-energy use building by adapting its tropical climate. Instead of relying solely on mechanical systems to condition, circulate, and ventilate air, the building supplements those systems with operable windows, natural ventilation, shaded outdoor space, and proper orientation to the sun.

To capture the benefit of daylight while avoiding solar-heat gain, many principles are applied to this building. Passive low-energy features are also incorporated. Considering the envelope, the building's skin is a combination of curtain-wall glazing on the north and south facade and sun-protected windows on the west. Because the building's orientation changes along a 360-degree curve (circular form), the architects designed two kinds of solar protection: the first is a screen made of closely placed aluminum strips that block most of the sun, the second is a sun breaker of aluminum strips set farther apart that allow more light to penetrate. Lift lobbies, stairways, and toilets placed on the hot east side have natural ventilation and sunlight. These areas do not need artificial light during daytime, and the lift lobbies do not need pressurization for fire protection.
To protect lower floor from the sun, the architects bermed earth around half of the building’s base and landscaped the 35-degree slope. A curving skylight and window punched through the berm bring natural light into demonstration rooms on the ground floor. In typical floor area, the designers put workstations on the perimeter so views and daylight are shared by everyone while the private offices which occupy the center of the floor, use glass partitions to enclose areas so as to allow daylighting to penetrate. At the roof terrace, a shading device made of trussed steel and aluminum is fixed to shade and filter natural light onto the swimming pool. Moreover, this shading device is designed to provide space for the possible future installation of solar cells.

By responding to local climate conditions, a great deal of energy used in operating mechanical systems can be saved. By making this building more energy-efficient, the BAS (Building Automation System) and other intelligent building features are used to reduce energy consumption in equipment and in the air-conditioning system.

Summary of Method Relating to Daylighting:

1. Massing Circular tower which is comprised of various features of designed sun-controls varying along its envelope and orientation.

2. Skylight A small skylight is placed over the demonstrating room on the east side to allow daylight to penetrate deep into the ground floor.

3. Fenestration 3.1 North/South Orientation Curtain-Wall Glazing

3.2 East Orientation Recessed and shaded windows are used to provide natural light and air to the service tower located on this side.

3.3 West Orientation - Recessed balcony and planting

Since this orientation is the hottest side, the combination of a recessed balcony and plantings can provide shade to the interior
space and to the exterior wall as well as minimize heat reflection and glare into the building.
- Aluminum strip sunscreen is also used to protect the window on the west side

4. Roof Shading Device

An aluminium shading device is fixed to shade and filter natural light over the swimming pool on the roof floor.

5. Interior Arrangement

To access view and daylight, workstations are placed on the perimeter while private offices occupy the center of the floor. Further, glass partitions are used to enclose space for private offices.

Figure 5.6 Exterior View of Menera Mesiniaga and Isometric of the Relation Between solar Orientation and Shading Device
Source: Yeang, Ken, *Bioclimatic Skyscrapers*, 1994
Figure 5.7 Left: West Side: There are applications of recessed balcony with planting and aluminum sunscreen to minimize the effect of strong solar radiation.

Middle: East Side: Recessed and shaded windows of service tower provide natural light and air to lavatories.

Right: North Side: The north curtain-wall glazing can be used on this side since it receives a small amount of direct sunlight.


Figure 5.8 Sun shading and details

Source: Yeang, Ken, *Bioclimatic Skyscrapers*, 1994
Figure 5.9  
Left  East-West Section  
Right  Lay-out Plan on Sunpath Diagram

Source:  Yeang, Ken, *Bioclimatic Skyscrapers*, 1994
5.4 NMB Bank, The Netherlands

Case Study 4
The NMB Bank (1987)

<table>
<thead>
<tr>
<th>Building Type</th>
<th>Financial Institution and Small Retail</th>
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</thead>
<tbody>
<tr>
<td>Location</td>
<td>Amsterdam, The Netherlands</td>
</tr>
<tr>
<td>Architects</td>
<td>Albert en van Huut (partner in charge, Ton Albert)</td>
</tr>
</tbody>
</table>

The new corporate headquarters for NMB (the Naderlandsche Middenstandbank), one of the three largest banks in the Netherlands, represents one of the most imaginative attempts at bringing together human and environmental concerns with those of flexibility, efficiency and low operating cost. A working environment has been created which is attractive and successful for its users.

The building is a series of ten towers, strung together in an “S” shape. Each is a different color, providing distinct identities for different departments. From the exterior, the separate towers emphasize the organizational structure of the Bank, but an interior street plays an important connecting role, and creates a common area: all the building’s general service are along this street, as are restaurants and small shops. The street passes through a series of sunlit atria, open at all levels of the building (Mackenzie, 1991).

The office accommodation is in the towers, each containing a roughly T-shaped floor providing space for about 60 people. Where the arm of the T’s touch, there are elevators, toilets and service space. In the center of each T is an atrium void containing the stair that links it to the internal street at ground level. The result is first that all office space is within 7m. of a window and, second, that the stairs, rather than the elevators, are the predominant means of circulation, giving more opportunity for people to meet, saving energy and provide exercise. The circulation at the center of each tower also serves, via its glass roof, to bring
light to the floor of the street. In addition the light from the windows provides views of the gardens as the street meanders across the site. As well as ensuring that the Bank'employees feel good about their building, the design team has tried to make the whole place healthy. They have attempted to avoid the problems of "sick building syndrome" by maximizing natural light and ventilation and by giving a high degree of individual control to the users. The windows are designed to provide adequate light, about 500 Lux during an average day, while excluding traffic noise and preventing excessive heat loss and unwanted gains.

About 20% of the wall area is glazed, with windows double-glazed in color-thermally-broken aluminium frames. At the top of each is a glazed panel backed by reflective louvers which bounce light onto the white ceiling to increase the illumination at the back of the space. The rest of the window has motorized external blinds which operate when the temperature outside rises above 16°C (to reduce solar gain), combined with internal blinds that the users can adjust as required.

All the windows can be opened for ventilation. Electric lights adjacent to the windows are turned on automatically when daylight levels drop, and task lighting is provided at the desks to reduce the need for high overall light levels. This saves energy and gives visual contrast to the spaces. Users can switch lights on or off as required. The overall aim is to give as much control as possible at each workplace. Artificial lights are all compact fluorescent lamps in a variety of fittings, some designed specifically by the service engineers. For instance, low energy downlighters fitted with Philips lamps provide background lighting to the internal street. The use of compact fluorescent lamps reduces internal heat gain within the building and provides the same illumination for less electricity, while avoiding the institutional appearance of conventional fluorescent tubes (Vale, 1991).

Summary of Method Relating to Daylighting:

1. Massing
   "S" shaped slab contains a series of ten towers. At the center of each tower is a daylit atrium.

2. Atrium
   Atrium receives natural light in two ways:

135
3. Fenestration

Since this building is located in the area that has high temperature fluctuation, windows are treated carefully to perform their functions well in both daylighting and thermal design. The application of double-glazing windows with both interior reflective louvers and motorized external blinds are generally used in this building.

4. Electric Lighting

- Dimming, On/Off
- Task/Ambient Lighting

Figure 5.10 Exterior View of NMB Bank

Figure 5.11 Internal street is illuminated by both daylight and artificial light
Figure 5.12  Ground and First Floor Plans
5.5 Bullock's Oakridge Store, California

Case Study 5

Bullock's Department Store (1978)

Building Type : Department Store
Location : San Jose, California
Building Area : 150,000 sq.ft. (2-story)
Architects : Environmental Planning & Research, Inc.
General Description :

Bullock's Oakridge Department Store, San Jose, California, served as the first prototype and small scale experiment to reinvention of the design of energy-responsive commercial buildings. Traditional design of a department store is usually composed of building huge, fully enclosed black boxes, then serving them full of artificial lighting, which requires vast amounts of energy for cooling. The Bullock's created a new concept in developing a parklike atmosphere with small trees and hanging plants to enhance the appearance of the merchandise and uses the translucent fabric membrane roof at the center of the building to allow soft daylight to illuminate the store's area. The filtered daylight has correct color balance and, therefore, permits true color rendition of the merchandise. The column-free space creates an open-market effect without the discomfort of rain, noise, and humidity. Streetlike pole lighting combined with indirect lighting bounced from the ceiling reinforces this effect at night.

The prototype of fabric membrane roof is a design with a 90x160 ft.-wide opening that covers about one-third of the roof area of the 2-story structure. The punctured area is covered with a double layer of Teflon-coated fiberglass material separated by an airspace of 2-4 in. and supported by a pair of diagonally intersecting cross arches. This roof configuration has a light transmittance of about 7% and on a clear day can flood the merchandise area with 550 foot-candles of natural light. On the energy side, the reflectivity of the fabric also helps reject
solar heat from the outside, but its translucency allows high lighting levels and a vibrant interior appearance as well as a reduction in the use of electric lighting: Bullock's expects to save $18,000 a year by using daylighting.

Because of the enthusiastic response of the public to the stimulating environment of Bullock's Oakridge and because of the reasonable payback through energy savings, the firm's management decided on using a similar fabric roof for a new store at Meriner's Island in Bay Area, California.

Summary of Method Relating to Daylighting:

1. Massing
   Block shape with a central opened-space covered with translucent roof

2. Toplighting
   In the day time, toplight is from natural light that penetrates through a translucent fabric membrane roof.
   At night time or when the amount of daylight is not ample to illuminate the internal space, electric lighting is used as a supplement by the method of indirect lighting over the area of the translucent roof to provide the same effect as daylight does.

Figure 5.13 Section and Second Floor Plan

Source: Freiwald, Joshua, "Fabric Membrane Roof in Northern California Lights a Store Naturally and Save Energy". *Architectural Record*. Mid-August 1979: 90-93
Figure 5.14 The interior of Bullock's under translucent roof

5.6 Government Service Insurance System Headquarters, Philippines

Case Study 6


<table>
<thead>
<tr>
<th>Building Type</th>
<th>Government Office Building</th>
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<tbody>
<tr>
<td>Location</td>
<td>Manila, Philippines</td>
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<tr>
<td>Building Area</td>
<td>1.35 million sq. ft. (8-story)</td>
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<td>Architects</td>
<td>Jorge Y. Ramos &amp; Associates</td>
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<td>General Description</td>
<td></td>
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</table>

The Government Service Insurance System Headquarters represents an excellent combination of orientation, sunshades, trellises, daylighting and breezes to make the most of natural energy from the environment. The GSIS building is designed in a "V" shaped slab that faces west for a spectacular view of Manila Bay.

The office wing is strung along the southern edge of the trapezoidal site so that its narrowest side faces east and west, reducing the size of walls that must control heat gain from the low-angled sun. The concept of the architects in capturing daylight while heat and glare must be avoided was a breaking up mass of the office space, disposing the area in three pods and an executive tower. "Notches" between the pods provide an assortment of environmental advantages. Most important, they increase peripheral areas to access daylight, reducing the amount of required electric light of workstations located around those areas. Further, they act as wind scoops to catch and direct the afternoon sea breeze.

In the notch's area, a system of overlapping trellises is used instead of an overhang. The laths of the trellises, oriented north and south, are designed to exclude all rays lower than 45°. The trellises are painted white to direct diffuse light to light shelves for the office space on either side and cast pleasant shade on the garden below (fig. 5.16).
The GSIS building is designed with particular care because of heat and glare. The architects recommended a variety of sunshades affecting three different facades:

1. The north facade - The north wall, which receives indirect light, except for a brief period in the summer, maximizes the penetration of daylight with stepped-back upper floors.

2. The south facade - The south wall receives more direct sunlight than the north, and has twice as many vertical shades both above and below the light shelf (fig. 5.17).

3. The east and west facade - Toward the east and west, where the low-angled morning and afternoon sun provides unacceptable heat gain as well as glare, three horizontal sunshades were added to the protection offered by the exterior light shelf. The architects determined that the sunlight could not penetrate the office space after it reached the window at an angle greater than 25°.

For the effective use of daylighting in the work space, high ceilings and high windows are necessary. At GSIS, daylight enters through clerestories just below 11-ft. ceilings. A pair of light shelves, their top surfaces painted glossy white, further boosts daylight penetration (fig. 5.18). The outside shelf doubles as a sunshade, and the inner shelf bounces light 45 ft. into the room.

On the clear summer day, workers at the perimeter are expected to get about 40 fc. of natural light, while those inside should get 20-40 fc. Clerical workers sit at light-colored desks around the periphery, while private offices occupy the center. Moreover, conference rooms and private offices have glass above the partitions to admit natural light.

For supplementary electric light, the grid layouts of indirect fluorescent lighting that grew out of the building’s structural system were made for a complex switching arrangement. Fixtures encircling the perimeter of each bay are controlled by a low-voltage relay system that is assignable at any time to various types of control zones, depending on the use of that zone, the degree of partitioning, and the location relative to fenestration of various kinds. Each bay is assigned to a time-of-use zone and to the daylight control zone. In addition, the local switches were added in the building to allow overriding of the computer-controlled energy
management system in case the system is not “smart” enough to anticipate illumination needs. After several methods of energy-efficient design were performed, the results showed that the energy budget for GSIS was calculated at 30,000 Btu/sq.ft./yr., against an average 65,000 Btu./sq.ft./yr. for a similar building in Manila.

Summary of Method Relating to Daylighting:

1. Massing
   “V” shaped slab with stepped-back upper floors on the north side

2. Fenestration
   High windows with clerestories are typical apertures used in this building. To maximize daylight and minimize glare, a pair of light shelves (exterior and interior light shelves) are fixed between window and clerestory glazing. Further, precast horizontal and vertical sunshades are added on the openings outside the building. The detail of sunshades varies according to orientation (fig. 5.17).

3. Trellis System
   The laths of trellises are designed to run on the north-south orientation and to exclude all rays lower than 45°. They are painted white to reflect more diffuse light to light shelf.

4. Interior Arrangement
   ■ Placement of workstations around the periphery and private offices at the center
   ■ Increased amount of natural light within enclosure spaces such as conference rooms and private offices accomplished by using partitions topped with glass

5. Electric Lighting
   On/Off
   Task/Ambient Lighting
Figure 5.15  Layout Plan of GSIS
Source: Lam, William M.C., *Sunlighting as Formgiver for Architecture*, 1986

Figure 5.16  Trellised Lightcourt Section
Source: Lam, William M.C., *Sunlighting as Formgiver for Architecture*, 1986
Figure 5.17 Each facade has a different shading condition which is affected by the orientation.

Source: Lam, William M.C., *Sunlighting as Formgiver for Architecture*, 1986
Figure 5.18 Section shows how light shelf can maximize daylight penetration, and how indirect artificial lighting can be integrated with daylight.

Sources: Lam, William M.C., *Sunlighting as Formgiver for Architecture*, 1986
### Summary of Daylighting Methods of the Case Study Buildings

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<thead>
<tr>
<th>Daylighting Principles</th>
<th>Case Study 1 Bateson Building</th>
<th>Case Study 2 Hongkong Bank</th>
<th>Case Study 3 Menara Mesiniaga</th>
<th>Case Study 4 NMB Bank</th>
<th>Case Study 5 Bullock's Store</th>
<th>Case Study 6 GSIS Building</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Consider characteristics of site climate as they influence on the determination of builtform and orientation</td>
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<td><img src="image2" alt="Diagram" /></td>
<td><img src="image3" alt="Diagram" /></td>
<td><img src="image4" alt="Diagram" /></td>
<td><img src="image5" alt="Diagram" /></td>
<td><img src="image6" alt="Diagram" /></td>
</tr>
<tr>
<td>2. Increase perimeter daylight zones</td>
<td>Placement an atrium with sawtooth-skylights at the center of a cubical builtform</td>
<td>Use of a system of solar tracking called “sunscoop” to reflect daylight into a central atrium</td>
<td>Use of a circular builtform to capture the wide angle of sunlight</td>
<td>Use of extending form and central atria topped with gable roof skylights</td>
<td>Placement an atrium covered with translucent fabric membrane roof at the center of a large block form</td>
<td>Increase daylight by having extending form, central courtyard, stepped-back on the upper floor</td>
</tr>
<tr>
<td>3. Allow daylight penetration high in a space (high window or high ceiling)</td>
<td>High window with exterior concrete trellis</td>
<td>Floor-to-ceiling window walls with exterior horizontal overhangs on the north/south facades</td>
<td>Floor-to-ceiling window walls on the north/south facades</td>
<td>High recessed windows</td>
<td>Admit daylight into the building by toplighting only</td>
<td>Windows and clerestories with intermediate light shelves</td>
</tr>
<tr>
<td>Daylighting Principles</td>
<td>Case Study 1 Bateson Building</td>
<td>Case Study 2 Hongkong Bank</td>
<td>Case Study 3 Menara Mesiniaga</td>
<td>Case Study 4 NMB Bank</td>
<td>Case Study 5 Bullock's Store</td>
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</tr>
<tr>
<td>4. Place service cores or common rooms on the east/west orientation so that they do not block the useful daylight</td>
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<td><img src="image2" alt="Diagram" /></td>
<td><img src="image3" alt="Diagram" /></td>
<td><img src="image4" alt="Diagram" /></td>
<td><img src="image5" alt="Diagram" /></td>
<td><img src="image6" alt="Diagram" /></td>
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<tr>
<td>5. Size window according to use and orientation</td>
<td>Use of optimum size and quantity as well as various types of shading devices on every window orientations</td>
<td><img src="image7" alt="Diagram" /></td>
<td><img src="image8" alt="Diagram" /></td>
<td><img src="image9" alt="Diagram" /></td>
<td><img src="image10" alt="Diagram" /></td>
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<td>6. Slope ceiling to direct more light into a room</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
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<tr>
<td>7. Reflect daylight within a space to increase room brightness (control a reflectance value of interior surface)</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
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<tr>
<td>8. Place public workstation near window, and locate private office inside a room</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
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<td>Case Study 3</td>
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<td>Bateson Building</td>
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<td>Menara Mesiniaga</td>
<td>NMB Bank</td>
<td>Bullock's Store</td>
<td>GSIS Building</td>
</tr>
<tr>
<td>9. Maintenance all reflectance and transmittance surfaces</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>10. Control and filter daylight</td>
<td>No shading device on the north windows</td>
<td>Glazing window walls with exterior horizontal louvered overhangs</td>
<td>Recessed glazing window walls</td>
<td>Recessed double glazing windows</td>
<td>Interior reflective horizontal louvers</td>
<td>Motorized external blinds</td>
</tr>
<tr>
<td>10.1 Sidelighting</td>
<td>North Orientation</td>
<td>High windows with fixed exterior concrete trellises</td>
<td>-Same as the north-</td>
<td>-Same as the north-</td>
<td>-Same as above-</td>
<td>-</td>
</tr>
<tr>
<td>South Orientation</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

- Using stepped-back upper floors to increase daylight penetration at lower floors
- Windows and clerestories with intermediate light shelves
- Windows with eggcrate shading devices
- Recessed high windows with intermediate light shelves
- Eggcrate shading devices outside the windows
<table>
<thead>
<tr>
<th>Daylighting Principles</th>
<th>Case Study 1 Bateson Building</th>
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<th>Case Study 5 Bullock's Store</th>
<th>Case Study 6 GSIS Building</th>
</tr>
</thead>
</table>
| ■ East Orientation     | ■ High windows with motor operated fabric exterior roller shades  
                          ■ Interior reflective venetian blinds  
                          ■ Minimum use of glazing window wall combined with exterior horizontal louvered overhangs  
                          ■ Most of floor areas on this orientation is placed with service cores |
| ■ West Orientation     | ■ Same as the east-  
                          ■ Atrium with north and south-facing sawtooth skylights  
                          ■ No shading device on the north-facing skylights  
                          ■ Use of exterior motorized louvers on the south-facing skylights  
                          ■ Use of banner screens hung inside the atrium to bounce direct sunlight during winter |
| 10.2 Toplighting       | ■ Atrium  
                          ■ Light Court  
                          ■ Skylight  
                          ■ Sawtooth Clerestory  
                          ■ Translucent Roof  
                          ■ etc. |
|                        | Increase daylight in the atrium by using a system of solar tracking with suncoop  
                          ■ Recessed balconies with planting  
                          ■ Recessed windows with aluminium sunscreens  
                          ■ Use of small operable skylight on the east side of the building over the demonstration room  
                          ■ Use of fixed aluminium sunscreen on the roof floor to shade and filter natural light  
                          ■ Use of a gable roof skylight on the top of the atrium |
|                        | ■ Same as above-  
                          ■ Use of a translucent fabric membrane roof at the top of the atrium to provide diffused light into a space  
                          ■ High windows with intermediate light shelves  
                          ■ Use of exterior vertical and horizontal sunshades as well as supplementary horizontal sunshades which function for blocking sunlight higher than 25°  
                          ■ Introduce and control light into a light court by using trellises that their laths are run on the north-south orientations to exclude all rays lower than 45° and painted white to reflect light (see fig. 5.16) |

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Chapter 6: Review of Daylighting Concepts

6.1 Introduction

The study of research in the characteristics of a warm-humid climate, the design principles of daylight including artificial light, and the analyses of case study buildings leads to an understanding of the overall concepts of good integrated (daylighting/electric lighting) lighting design. A good daylighted architecture usually responds to three significant goals: (1) promote an energy-efficient approach, (2) enhance the quality of illumination space, and (3) respond to the need for occupant satisfaction for air temperature, light, view, and contact with the environment. Site planning, in conjunction with light design, should include the following:

1. Architectural Design
   Daylight will affect architectural design in the determination of built form and orientation, geometry of space, and fenestration design.

2. Interior Space Planning
   To maximize daylight penetration within a space, interior open-space planning should consist of minimum interior partitions, or greater use of glass partitions when partitions are required.

3. Lighting Design
   Electric lighting should be integrated with daylight to provide the optimum level of illumination. For example, the utilization of automatic lighting control systems and indirect lighting systems can be used to minimize occupant perception of lighting control systems and to increase lighting quality as well as to conserve electricity energy.

Among these aspects of design consideration, architectural design seems to be the most important since it affects the availability of daylight within a space directly. An architectural design relating to the daylighting aspect is categorized in three parts according to stage of
implementation: (1) influence of daylight and site climate on the design determinant of built form and orientation, (2) daylighting concepts: the concepts used for manipulating the building's form and envelope, and (3) sun control and shading concepts.

6.2 Influence of Daylight and Site Climate on the Determinant of Built Form and Orientation

When daylight is introduced into a building design as an energy-efficient approach, it needs to be considered in conjunction with other constraints (i.e. the site, building program, client needs, user requirements, and budget) in generating the optimum design. The case studies in chapter 5 show that no matter what the size of the buildings, daylight can used to provide a number of advantageous results only if the conditions of the site and climate are significantly concerned as part of the design. The conditions of the site considered in terms of orientation, latitude, landscape, obstruction, and the conditions of climate considered in terms of temperature, season, cloud cover, day and time, directly influence daylight availability on a given site. Therefore, any building in which daylight is the primary goal of design must be adjusted to built form and oriented to access the daylight available on its site.

Since a building's efficiency in collecting daylight depends on its shape (assuming it has been constructed within the limits of a solar envelope), any shape that has a maximum of perimeter has a greater area to access daylight. For example, a slab or extending form maximized perimeter in the horizontal direction, and a tower form maximized perimeter in the vertical direction can provide more natural light than a compact or block form. A major factor determining the daylight access characters of the space would be "the proportions" (the width of the space and the height of the buildings). To obtain the desirable proportions for daylighting purposes, the methods of court, atrium, reentrant, and narrow floor plan are used to manipulate the form of the building's perimeter. Besides, the methods of manipulating forms, the methods of manipulating the envelope, such as toplighting, sidelighting, and shading devices, are necessary to introduce more daylight into the building while controlling
or reducing the impact of glare and heat. The details of these design methods are discussed further in the following parts.

According to the case study of TVA Chattanooga Office Complex in chapter 3, the results of the analysis concluded on the daylighting potential of the shallow building shows the east-west elevation was a liability and the narrow form with broad north-south elevations had a distinct advantage. Therefore, for daylighting purpose, the building should be oriented so that large areas of roofs and walls receive solar energy from the south as well as north. The best building orientation is on an east-west axis.

In a warm-humid climate, where cooling needs predominate, a building should be designed to capture natural ventilation and minimize heat gain to maintain a comfort temperature. Although the elongated east-west built form is an ideal, it may not be achievable for all types of buildings (due to the restriction of site and other requirements). If the facades of these buildings do not face south, daylight access must be limited to the horizontal surface (using toplight).

6.3 Daylighting Concepts: The Concepts used for Manipulating Building’s Form and Envelope

The overall configuration of the building and the predominant sky condition have a major impact on which daylighting concepts can best be used to illuminate the building. For further discussion, the daylighting concepts will be grouped in three as:

1. Sidelighting Concepts (Window Strategies)
2. Toplighting Concepts (Clerestory, Skylight, Sawtooth, and Monitor Strategies)
3. Atria, Light Courts, Reentrants

Both sidelighting and toplighting concepts are used to illuminate parts of the building that are close to daylight apertures, whereas atria, light courts, and reentrants are used to
manipulate the form of the building (reduced core area). However, all these concepts require the use of a building's envelope as a filter through which daylight reaches the interior of the building.

Daylighting concepts need to be considered in conjunction with predominant sky condition. Different sky conditions will affect the characteristics of light in different ways, and different daylighting concepts will be adopted to provide the desirable effect according to the light of each sky condition.

Under an overcast sky, the primary source of light is often the sky, while light reflected off the ground or exterior surfaces usually represents a minor contribution to interior illuminance. This type of sky provides deeper penetration of sky light into a room. At the same time, however, the light provides a softer set of shadow patterns and sometimes more glare than the clear sky.

On the other hand, under a clear sky, the contribution of daylight reflected from the ground can be significant. In addition, daylighting performance under this sky varies considerably depending upon the orientation of apertures with respect to the sun, and this type of sky provides a source of light that establishes sharp shadow patterns. Glare under this sky condition is usually caused by an excessive contrast between the aperture and the surrounding surfaces.

According to Robbins (1986), “the level of interior illuminance under an overcast sky is significantly greater than that under clear sky (without sun) during either winter or summer. Under normal conditions, the quantity of interior illuminance is always greater in summer than winter.”

In a warm-humid climate, as in the case study of Miami, Florida, the sky condition is predominated by a partly cloudy sky for an annual average of 152 days. The rest of the sky conditions are 110 overcast days, and 103 clear days. Therefore, the effect of both overcast
and clear sky conditions must be considered where the partly cloudy sky is predominant on a building's site. However, in a warm-humid climate, the overcast sky condition is more important to the proposed design than the clear sky condition since the sky is not really clear as in a hot-dry climate because of the large amount of water vapor in the air.

After considering the characteristics of light in a specific sky condition that will reach into a room, the next step for the designer to understand are the daylighting concepts involved with the design of building's envelope. Robbins (1986) further stated "... how the envelope-and hence the form and massing of the building - is manipulated depends on the functional requirements and the arrangement of rooms and areas in the building, and on the lighting needs of each room or space that can use daylight as an interior illuminant ... the actual design of the building's daylighted areas is based upon the geometric relationship between the room or space being daylighted and the sizes, shapes, and locations of the various daylight apertures that provide the room's natural illumination." Therefore, the understanding in the proportional relationships between the space and the appropriate apertures allows the designer to manipulate them so as to change the penetration, distribution, quantity, and quality of daylight in a space.

In the daylighting design process, the geometric relationship between the space and each aperture usually must be established before the impact of glazing, solar controls, interior finishing and other modifying attributes can be considered. For example, there is a rule of thumb affecting the relationship between spatial proportions and aperture proportions in that "... daylight penetrates about 2.5 times the head height of the aperture into the room from a window." This rule of thumb can be used to establish the floor plan and the window's height.

A daylighted building may have more surface area and volume than a nondaylighted building. An increase in the surface area and volume of a building usually indicate a corresponding increase in first costs and probably heating and cooling costs. However, according to the case study by B. C. Hydro about the effect of massing and energy cost
appearing in chapter 3, the design team concluded that in most design activities, the massing of a building (surface area and volume ratio) can be equally influenced by daylighting or thermal considerations. One does not show a stronger influence over the other. It is up to designers to choose the most appropriate method for achieving energy savings. For example, Hydro stated that increasing daylighting surface would not become a cooling liability if the building is properly shaded. Hydro's conclusion is further supported by Robbins (Robbins, 1984) in that "if the design team can integrate a reasonable structural system with the daylighting concepts and can find an appropriate (possibly downsized) cooling deck for the HVAC system, ... , the majority of the first costs of the daylighting system may be offset in other areas of design."

Discussion of Daylighting Concepts:

6.3.1 Sidelighting Concepts (Window Concepts)

![Daylighting Sidelighting Concepts Diagram]

**Fig 6.1:** Daylighting penetration in the base case room with window ($H = 1.5:1$, $V = 1:1$, $M = \infty :1$)

a. aperture facing the sun, clear sky
b. overcast sky, any orientation
c. aperture opposite the sun, clear sky

**Source:** Robbins, Claude L., *Daylighting: Design and Analysis*, 1986
A window can be designed to provide a wide range of lighting performance characteristics. According to the Robbins' (1986) analysis, "the slope of penetration (fig. 6.1) can be altered by changing either the H or the V ratio (fig. 6.2). Change in the M ratio affect both spread and penetration. The point of maximum illuminance can be adjusted by changing the sill height with respect to the workplane height." In addition, the slope of penetration can be changed by using bilateral or multilateral lighting concepts. This adjustment sometimes provides an important way to control interior contrast and to significantly increase the primary lighting zone.

Robbins also suggested that "variations in lighting performance under clear and overcast skies can be significant but manageable with solar controls, proper glazing, and an understanding of which sources of daylight are most critical for a given locale, design, and aperture." Robbins' (1986) results are used to confirm the window strategies presented in chapter 3:

- Windows should have optimum size and height for light penetration
- Placing windows on more than one wall for much better light distribution
- Control and filter daylight
6.3.2 Toplighting Concepts

6.3.2.1 Clerestory Concepts

Figure 6.3 Illuminance curves of bilateral clerestory daylighting
(a) with another clerestory, and (b) with a window

Source: Robbins, Claude L., Daylighting: Design and Analysis, 1986

Clerestories are an excellent daylighting concept for providing task illuminance on either horizontal or vertical surfaces. They can allow deeper daylight penetration into a building than can a window since they open onto the bright part of the sky dome close to the zenith. Further, glare from ground reflection is also minimized. Usually a clerestory provides less variation between its maximum and minimum illuminance than does a window. So, they are an excellent lighting concept when relatively even illuminance is required throughout a room. The major drawback of clerestories is they require tall floor/ceiling height, usually 8+ feet if they are to work to the best advantage.

The difference between an overcast and clear sky will affect the point of maximum illumination on the illuminance curve of clerestories. In all cases, there is more light at the top of the surface from an overcast sky than from a clear sky, caused by the bright horizontal on an overcast day. Figure 6.3 shows that clerestory apertures, in bilateral lighting schemes, can be used to create relatively even illuminance throughout a space. Clerestory aperture can be used in combination with window concepts to provide the best result in daylight penetration and distribution, especially under overcast sky condition. Moreover, a clerestory
aperture on one surface and a window on the opposite surface make it possible to establish a large primary lighting zone extending from the window wall to an area beyond the point of maximum illuminance of the clerestory.

6.3.2.2 Skylight Concepts

Skylights provide a relatively uniform level of illuminance throughout a space and allow for the use of both sky light and sunlight as an interior illuminant. Usually in a warm-humid climate, sunlight is adverse, and, in most cases, it must be treated by the various methods as explained in chapter 3 to control or minimize its strong brightness and thermal impact. The use or control of sunlight entering through horizontal apertures depend upon the height of the lightwell and the aperture size variation (fig. 3.32, 3.33). Changes in light distribution also result from changes in the placement of shading devices that might be part of the design concept. Generally, skylights are most commonly used to illuminate the horizontal workplane. Furthermore, they are very efficient when used to provide general illuminance or to illuminate a three-dimensional display.

6.3.2.3 Sawtooth Lights

Regular sawtooth lights provide uniform illuminance throughout a space with small variations in brightness patterns depending upon the sky conditions and the orientation that they face. The configuration, height, depth, and spacing of the sawtooth range all affect the distribution pattern and quantity of daylight in a space.
6.3.2.4 Monitor Lights

Monitor lights are similar in many respects to sawtooth lights. They have traditionally been used in industrial applications where the central high bay area lies between two low bay areas. The monitor serves to illuminate the high bay areas and part of the adjacent low bay areas. Since a monitor has two glazed surfaces, it provides bilateral lighting. Its multiple glazings may sometimes raise contrast and sun control to the level of critical design issues.

In summary, toplighting concepts (clerestories, skylights, sawtooth lights, and monitor lights) are the most desirable and easiest daylighting strategies to integrate with electric lighting since both electric lighting and toplighting provide light into a space from the ceiling. Although the toplighting concepts are limited to single-story or low-rise buildings, they are popular because of the evenness of light distributed throughout much of the space and the breadth of the area lightable to the same illuminance level.

In toplighting, penetration is often less important than in sidelighting, which is a key distribution concern. In most cases, the penetration of toplighting is not a primary concern because the distance between the floor and ceiling is usually well within the optimum
penetration range of 8 to 20 feet. When toplighting concepts are used to illuminate more than one level, they must be considered by expanding in scale and combining with a light court, a light well, and an atrium. In addition, toplighting apertures usually have a view of a larger portion of the sky dome, and, consequently, the available exterior illuminance is often much greater than in sidelighting concepts. Of course, a brighter sky view increases the possibility of glare, and this must be considered in the design process.

6.3.3 Atria, Light Courts, Reentrants

The concepts of atria, light courts, and reentrants are used to manipulate the form of a building's perimeter by increasing the daylighting perimeter of the building and, consequently, reducing the core area and the amount of the building that cannot be daylighted. These three concepts can work well for a core area, whereas most of sidelighting concepts work well for illuminating parts of the building that are close to the daylight aperture.

6.3.3.1 Atria and Light Courts

Atria and light courts are discussed together since they have the same purpose of reducing the nondaylightable core of a single or multistory building by increasing its daylighting perimeter. While light courts increase the thermal and daylight perimeters of building, atria increase the daylighting perimeter without an impact on the thermal perimeter.

Atria can be used to solve the problem of lighting the core by reducing it. Since an atrium is an enclosed part inside a building, the roof over it can be used for toplighting or clerestory concepts to filter light into the building. Light entering the atrium must provide task lighting on the floor of the atrium space and secondary light to adjacent spaces. The difficulty in designing an atrium is to avoid excessive glare at the lower levels while maintaining enough natural light to illuminate adjacent spaces.

Usually, daylight distribution in the atrium is similar to light in a light court. The primary difference is that an additional set of apertures is present on the atrium roof. These additional
apertures reduce the level of interior illuminance in the atrium space and in adjacent rooms. Generally, as Robbins’ (1986) stated “daylight distribution under an atrium at level one (the top floor) is approximately equal to that at level three or four of a light court.”

6.3.3.2 Reentrants

A reentrant is an undulation of a building’s perimeter designed to optimize daylight penetration. The reentrant extends the perimeter of a building in such a way that the core is significantly reduced or eliminated. Since the reentrant is a method of manipulating form and not an aperture concept, it must be used in conjunction with sidelighting concepts. For optimum results, apertures in a reentrant or facing a light court with a view of the building are usually larger than apertures with an unobstructed view of the sky.

The concepts of reentrants can be applied in a three-dimensional context, for example; a stepped reentrant designed by changing it from floor to floor. Moreover, the reentrant can also be used as the interior surfaces of an atrium and even as the facades of a light court. However, the reentrant in the interior do not significantly increase the quantity of daylight in the building as they do in the exterior, but the interior reentrant may change the distribution pattern of the daylight within the space and probably add to the aesthetics of the design.

Figure 6.5 Examples of Reentrant Forms
Source: Robbins, Claude L., Daylighting: Design and Analysis, 1986

Figure 6.6 Vertical/Stepped Reentrant Forms
Source: Robbins, Claude L., Daylighting: Design and Analysis, 1986
6.4 Sun Control and Shading Concepts

In addition to discussing ways to maximize the daylighting perimeter of a building, this section presents perimeter and interior methods of sun control and aperture shading. Sun control and shading device are reviewed here because they often involve an exterior perimeter treatment, much like the daylighting concepts presented in this chapter, and they are applicable to almost all daylighting concepts.

A good daylighting design must prevent overheating of the building while permitting daylighting. Shading devices can be used to control sunlight to maximize light gain in the winter and minimize it in the summer. The most common sun control and shading concepts are:

1. Overhangs
2. Light Shelves
3. Horizontal Louvers and Blinds
4. Vertical Louvers, Fins, and Blinds

1. Overhangs

Overhangs are used in conjunction with sidelighting concepts to control direct sunlight, and reduce or control the daylight entering the space. Overhangs are often an extension of the roof plane past the plane of the aperture. In multistory buildings, an overhang may be a horizontal plane extending from the wall above the aperture or in the form of a balcony. The depth of the overhang, must be considered in conjunction with the height of the aperture to determine how much of light can penetrate into a space to strike the workplane. Usually, the overhang of a building in a warm-humid climate should prevent the entrance of direct sunlight higher than 45°. Overhangs (and most other horizontal shading devices) are only effective on apertures facing south. Horizontal overhangs are not effective on east or west facing apertures, and in most cases no overhangs are needed on the north facade of a building.
2. **Light Shelves**

Light shelves are devices with the ability to project daylight deep into the building core, beyond the normal daylighting perimeter of the building and beyond the normal penetration from shelfless apertures. Moreover, light shelves can reduce cooling loads caused by solar gains and can improve visual comfort in a space.

Since a light shelf divides the aperture into a view light below the shelf and a clerestory light above the shelf, the distribution pattern of the view light is similar to that of a view light with an overhang, and the clerestory light above the shelf has a distribution pattern similar to that of a clerestory aperture.

Based on Robbins' (1986) analysis of the various light shelves (exterior light shelf, interior light shelf and combined exterior and interior light shelf):

- The interior light shelf provides less penetration than an exterior one under all sky conditions excluding the effect of the direct sun.
- The exterior light shelf improves the penetration of daylight into the space under all sky conditions. In addition, the exterior shelf acts as a shading device for the view glazing and reduces the solar gains of that light.

He continued “If the sun is not present, penetration at the aperture with light shelf is no better than the base case aperture with no shelf.”

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**Fig. 6.7** Impact on daylight penetration in a sunless room with various light shelves

**Source:** Robbins, Claude L., *Daylighting: Design and Analysis*, 1986
For the combined exterior and interior light shelves (intermediate light shelves), this configuration does not increase illuminance deep in the room. The principal advantage of intermediate light shelves is the reduction of glare from the skydome at locations near the window. To improve the performance of a light shelf, a designer may consider two aspects of design: the reflectivity of the shelf's upper and lower surface, and the glazing type used.

Normally, specular reflectors can be used on the upper surface of a light shelf to reflect light deep into an interior; however, a specular surface can be a source of glare, as can the bright band of light it reflects into the space. For the glazing used in combination with light shelves, a design should permitted the use of high transmittance glass above the light shelf and low transmittance glazing below without the difference in transmittance being visually obvious.

3. Louvers and Blinds

Louvers and blinds can be applied in a horizontal or vertical position to reflect daylight and sunlight into a room, to act as shading device, and to reduce a view of the sky that might cause glare. The term of louver refers to the slat boards used as window treatments to allow light through a window but keep rain out. Blind is defined as a thin blade designed to keep out light and to obstruct vision.

Blinds are usually designed as an interior shading devices, while louvers can be placed on either the interior or exterior of the building. Since they reduce the shading coefficient, exterior louvers function better than either interior blinds or interior louvers in lowering cooling loads caused by solar gains through the glazing. Generally, horizontal louvers and blinds function best on the south facing aperture while vertical louvers and blinds can be used on any facade of a building. However, vertical louvers, blinds, and fins are often used on east or west facing apertures to control sunlight penetration in the morning or afternoon hours.

Both blinds and louvers can reduce the view of the sky. For example, a vertical member placed in front or on either side of an aperture reduces the horizontal width of the view out
the aperture, but not the vertical view of the sky dome. The reduction in performance is less consequential than with a horizontal aperture. Since blinds and louvers reduce the view of the sky, therefore glare and thermal transmittance through glazing will be reduced or controlled. If the direct sun does not strike the blades, or if the sky is overcast, the penetration of daylight into the room will vary with the slope of the blades. In such situations, operable or automatic blinds and louvers are desirable because they can be designed to track the sun or to track shade. If they track the sun, they continuously change their slopes with respect to solar altitude to allow much of the desirable light into the room. Louvers and blinds can function with sidelighting, and can be used with toplighting and angled aperture schemes to reduce glare and control the distribution patterns of light from the aperture.
Chapter 7: Investigation of Daylighting Performance under Different Sidelighting Strategies by Method of Physical Model Testing

7.1 Introduction

In the warm-humid climate, most of the year is dominated by a partly cloudy sky with the percentage of the overcast day higher than that of clear days. In such sky conditions the amount of daylight available from the sun and sky tends to change almost constantly depending upon the amount of cloud covering. In a partly cloudy sky condition, white clouds have high reflectivity and when viewed from an interior of a building can be exceedingly bright, causing excessive contrasts and visual discomfort. Moreover, this climate region also has a long overheated period. Therefore, any design for a building in this climate has to avoid direct sunlight, because of potential problems of overheating from solar gain and visual discomfort.

Generally, building designers can control the intensity and distribution of sunlight in a space by manipulating a number of architectural variables and using the controlled sunlight as a major source of daylight. For example, using the building’s forms and proportions increases daylight available in the building and orienting the narrowest sides of the building to face the sun, reduces the impact of solar heat. However, the best way to admit daylight into the building while keeping the impact of heat and glare to a minimum is the selection of fenestration systems.

Fenestration systems have a major influence on the amount of daylight entering a room. They function to control and admit daylight by several methods. For instance, window glazing located near the ceiling in a room produces deeper light penetration than glazing low in a wall, and the technique of placing windows on more than one wall can provide much better light distribution. Yet, these methods have rarely been applied solely for fenestration
design in a warm-humid climate. Windows have always been integrated with other types of solar control devices since controlling the effect of sun is a primary concern. The utilization of sun control and shading devices may conflict with daylighting design because it can reduce the amount of light penetrating a building. Usually, sun control and shading devices have to be designed to provide full protection from direct sunlight during overheated periods or when the sky is clear. In a clear sky condition, there is adequate daylight to illuminate the building’s interior, although some type of shading controls are used on the openings. But we do not know the effect the use of sun control and shading devices have on interior illuminance levels, or how they affect the pattern of daylight distribution and penetration on an overcast day which always predominates in a warm-humid climate since the sky condition is rarely clear because of the high amount of water vapor in the air.

These, are then, of particular interest and are investigated in this research by the use of physical model tests under a simulated overcast sky condition. A set of tested variables with some types of sun control devices that have been applied in the case study buildings in chapter 5 is selected from various methods of fenestration systems. The 11 selected variables analyzed under the artificial overcast sky condition are grouped into three sections for the propose of this study. These variables are:

**Part 1: Position of unprotected window**
1. Window wall
2. Window positioned in the middle of a wall
3. Window positioned close to a floor
4. Window positioned close to a ceiling

**Part 2: South-window**
5. Unprotected window with clerestory
6. High-window with opaque overhang
7. High-window with horizontal louvered overhang
8. High-window with light shelf
Part 3: East/ West window

9. Window with vertical slanted fins
10. Window with horizontal louvers
11. Eggcrate system (combination of horizontal louvers and vertical slanted fins)

It is obvious that all of the tested variables above are window strategies (sidelighting concepts). The reasons for investigating only window strategies derived from a number of overviews is to determining the benefits of window daylighting and are classified as follows:

(1) Window strategies are more frequently used than atrium, skylight, or clerestory because they can:
   - provide view
   - provide natural ventilation
   - easy to construct
   - easy to design applicable control device

(2) There is no limit of application to sidelighting strategies, while toplighting, such as skylights and monitors, are limited to the use of multistory building.

(3) The limitation of daylight on its penetration, distribution, and interior illuminance level are due to the method of sidelighting which influences the design of the builtform and proportion. For example, since the distance of useful daylight from window openings at any point within a room is limited, the depth of a daylighted building floor plan or the configuration of the floor plan is limited by the ability of daylight penetration (if other lighting methods, such as toplighting and electric lighting are not used).

Eleven variables of sidelighting strategies were tested in overcast sky conditions to determine the results of the quantity as well as the characteristics in distribution and penetration of daylight inside buildings, when light from the simulated sky is diffused without direct sun (as under overcast conditions). The results from each variable tested are compared. Testing various sidelighting concepts under overcast conditions help to determine which kinds of sidelighting strategies were function best under predominant cloudy climate-
conditions. The results of the investigation are analyzed to establish a set of daylighting design principles for buildings in the warm-humid climate.

7.2 Methodology and Measurements

Measurements of luminous conditions in an assumed office space were made under a simulated overcast sky condition. With the performance on the “mirror-box” artificial overcast sky, the exterior illuminance of the tested model was held constant. To compare the quantitative result of interior daylight affected by various fenestration designs, “the daylight factor method” is the approach used in this investigation since it can establish a pattern of light distribution throughout a room.

The daylight factor (DF) is defined as the ratio of interior illuminance on a horizontal surface to the exterior illuminance on a horizontal surface simultaneously available outdoors from an overcast sky. Since the DF is expressed as a ratio of the interior and exterior illuminances, it is a relative, not an absolute measure of illuminance. To evaluate the results of the use of the daylight factor method, before and after measuring interior illuminance, one photo sensor must be placed outside the model to measure the absolute value of exterior illuminance on the horizontal plane. Unless the exterior illuminance is known, it is not possible to establish the performance of daylighting systems because no basis for comparison exists without the daylight availability data and it is impossible to convert the absolute illuminance values of the interior into daylight factors.

Collecting data of interior illuminance levels begins by establishing a pattern of illuminance measurements in a model. Line measurement consisted of measuring the absolute illuminance at predetermined reference points in a row perpendicular to the aperture. Reference points were marked at 5 foot increments (to scale, 1" = 1/2") so that 7 readings were recorded as the photo sensor mounted on a stick was drawn through the 40 foot width of the model. The photo sensor measured the horizontal light levels at typical workplane height.
(30" above the floor). This is useful for building types, such as offices, where the standard criterion is the available illuminance at the work surface.

It is necessary to test a model of each variable only once under overcast conditions to represent daylighting characteristics for the entire year, since in the daylight factor for any overcast condition only the absolute illuminance changes. Hence, the testing of each variation may be performed only once under a well controlled condition of the “mirror-box” artificial overcast sky. In addition, the placement of the model was not critical, because the overcast sky produces an even distribution of light from all directions.

7.3 Model Construction and Materials

A model 1/2" = 1'-0" was constructed for studying the distribution and penetration characteristics of sky light. At this scale, the model worked very well with a photocell measuring illuminance level inside the model and a “mirror-box” artificial overcast sky. The model represented a single floor plan with dimensions 18ft.×40ft. with a 10 ft. ceiling height (typical ceiling height is 9-12 ft.). Since the purpose of constructing the model was to test the eleven different fenestration systems (sidelighting strategies), one side of the model wall was designed with an interchangeable wall panel so that the eleven variables could be tested one by one on the same rectangular-box model.

For consistency of testing, ceiling and wall opening sizes were equal, but glazing areas differed. Interior sidewall and floor reflectances were 36 percent matte grey, and ceiling and exterior reflectances were 75 percent matte white. Details of the material used for the model are classified as in the following:

<table>
<thead>
<tr>
<th>Base</th>
<th>: matte grey crescent board # 916 (36% reflectance) adheres on two layers of 3/16&quot; foamboard</th>
</tr>
</thead>
<tbody>
<tr>
<td>Walls</td>
<td>: matte grey crescent board # 916 adheres on two layers of 3/16&quot; foamboard</td>
</tr>
</tbody>
</table>
- outer layer (exterior wall) uses 3/16" matte white foamboard
- inner layer (interior wall) uses matte grey crescent board

Ceiling
: two layers of 3/16" matte white foamboard (75% reflectance) with a sheet of museum board sandwiched between (foamboard is translucent)

Light Shelves & Overhangs
: two layers of matte white museum board (75% reflectance) with a sheet of 1/16" Balsa Wood sandwiched between

The significant concern in building this model was the problem of light leakage. Therefore, all of wall, floor, and roof panels of the model were checked to make sure that they were not translucent. Moreover, all construction joints in the model were taped with black electrical tape to block light from leaking through joints but still allowed the panels, or walls, to be removed easily.

A general rule for daylighting is stated by Moore (1985): "the location of clear glazing within a given fenestration system has a negligible effect on interior illuminance distribution; its use is primarily determined by other considerations (e.g., thermal or aesthetic)." Therefore, apertures of the model used to represent clear glazing were left open and a glazing transmission factor may be applied to the data afterwards.

7.4 Instrumentation

**Photometer**

Two types of photometers were used in the test model for two purposes: (1) to measure reflectance of materials, and (2) to measure interior illuminance levels. To obtain the reflectance of materials used in the model, the Lite Mate Model 501 combined with the Spotmate 1° Spot Model 502 was used to find the reflectance value of each material. Since
the reflectance of material is the value of reflected light (in footlamberts) divided by the value of incident light (in footcandles). **Spotmate 1° Spot Model 502** was applied for measuring reflected light (FL.) and **Lite Mate Model 501** was applied for measuring incident light (fc.).

To measure the interior illuminance level, the type of photometer used was the **21X Micrologger** (Campbell Scientific Data Logger) with five Li-Cor remote photosensors, color and cosine collected. For measuring interior illuminance levels, the remote sensors were mounted on a foamboard stick so that the sensor surface was at workplane height (30” above the floor).

**A “Mirror-Box” Artificial Sky**

This research utilized the mirror-box artificial sky at the University of Washington, Seattle. The mirror-box rectilinear artificial sky has been renovated several times since 1979, when it was first built at University of Washington by Ann Stevens Airy, a master’s student.

The mirrored box artificial sky with dimensions of 4'W x 5'L x 5'H was used for model testing to hold the sky illuminance constant. With this instrument, different design alternatives were tested and their results when compared with one another were more accurate than results tested under real sky conditions, because the variation of sky light that is unreliable was controlled. A more detailed description about the mirror-box artificial overcast sky is available in Appendix A.
Figure 7.1 Mirror-Box Artificial Sky

Figure 7.2 Lite Mate and Spotmate 1° Spot

Figure 7.3 21X Micrologger Photometer

Figure 7.4 Position Li-Cor Remote Photosensors inside a model
7.5 Tested Variables

The selection of tested variables was based on theory and observation obtained from previous research, case studies, and work experience. The fenestration systems combined with sun control and shade devices analyzed in this chapter are always suitable for aperture design in a warm-humid climate to prevent the impact of direct sunlight. Samples of these systems are opaque overhangs, louvered overhangs, and light-shelves. All have limitations in application as stated in chapter 3 and chapter 6. For instance, horizontal overhangs and light shelves are most suitable for use on the south-facing apertures only to prevent solar heat gain from a high altitude sun. Hence, the parameter for analyzing the variables assumed that the system of horizontal overhangs and light shelves used on the south-facing apertures were designed to exclude all sun rays higher than 45° (as determined by the site's latitude).

For the east and west facade, where the low-angled morning and afternoon sun provides unacceptable heat gain as well as glare, the use of vertical fins or eggcrate systems are appropriate. Therefore, the parameter for analyzing the fenestration systems for the east and west-facing apertures assumed that sunlight could not penetrate an interior space after it reached the window at an angle greater than 25° (assumed from the GSIS Building in case study no. 6). Moreover, as Lechner (1991) suggested vertical fins are most effective to shade east and west windows from direct sun for the whole year between the hours of 7 a.m. and 5 p.m. (solar time), when they are slanted toward the north or south with an appropriate specification of shade line angle. For 24° latitude, the shade line angle for slanted vertical fins is specified at 18°. Therefore, a tested variable of vertical fins in this research followed this shade line angle.

The eleven variables were tested to determine how they affected daylight performance within a room in respect to light penetration, light distribution, and interior illumination level are:
1. Unprotected window wall

2. Unprotected window positioned in the middle of a wall

3. Unprotected window positioned close to a floor
4. Unprotected window positioned close to a ceiling

5. Unprotected window with clerestory

6. High-window with horizontal opaqued overhang
7. High-window with horizontal louvered overhang

8. High-window with intermediate light shelf

9. High-window with vertical slanted fins
10. High-window with horizontal louvers

11. Eggcrate with slanted fins
7.6 Photometric Evaluation and Documentation of the Results

The quantitative data obtained by measuring both exterior and interior illuminance at the reference points of the model were converted into daylight factors and then presented graphically to measure the quality and distribution of light. In this report, the format of “the daylight factor graph/section” presented in a building section cut through the fenestration was selected to express the data. On the daylight factor section, the seven sensor positions are plotted along the base of each graph, and the daylight factor illuminance is shown along the side. The position of highest daylight factor means the position gained the highest illumination.

The average illuminance can be found in the total area under the curve. This allows the designer to compare the total illumination on the workplane. The slope of the curve indicates the amount and rate of illuminance change or “illuminance gradient” along the room’s depth. A rapid change of slope represents the potential for discomfort glare resulting from brightness contrast, and a flatter curve indicates a uniform distribution of daylight. In comparison to different tested variables’ curves, changes in distance between curves, (as well as slope difference) provide an important clue as to which fenestration difference is responsible for the change in illuminance distribution.
Model Data Record Sheet

Condition of Test : Artificial Overcast Sky

Tested Variables :

Part 1 Position of unprotected window

1. Unprotected window wall

2. Window positioned in the middle of a wall

3. Window positioned close to a floor

4. Window positioned close to a ceiling

Part 2 South-window

5. Unprotected window with clerestory

6. High-window with opaque overhang

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7. High-window with horizontal louvered overhang

8. High-window with light shelf

Part 3 East/West Window

9. Window with vertical slanted fins

10. Window with horizontal louvers

11. Eggcrate with slanted fins

Plan of light measurement
<table>
<thead>
<tr>
<th>TEST VARIABLES</th>
<th>EXTERIOR</th>
<th>INTERIOR DAYLIGHT</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>BEF.</td>
<td>AFT.</td>
</tr>
<tr>
<td><strong>PART 1</strong> POSITION OF UNPROTECTED WINDOW</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. Window wall</td>
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<td>907.4</td>
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<tr>
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<td>900.8</td>
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<td>3. Position window sill close to a floor</td>
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<td>4. Position window sill close to a ceiling</td>
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<td>899.3</td>
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<tr>
<td><strong>PART 2</strong> SOUTH-WINDOW</td>
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<td>6. High-window with opaque overhang</td>
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<td>8. High-window with light shelf</td>
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<td><strong>PART 3</strong> EAST/ WEST-WINDOW</td>
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<td>9. Window with vertical slanted fins</td>
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<tr>
<td>10. Window with horizontal louvers</td>
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<tr>
<td>11. Eggcrate with slanted fins</td>
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</table>
Part 1 Position of Unprotected Window
1. Window wall
2. Window positioned in the middle of a wall
3. Window positioned close to a floor
4. Window positioned close to a ceiling

Part 2 South-Window
5. Unprotected window with clerestory
6. High-window with opaque overhang
7. High-window with horizontal louvered overhang
8. High-window with light shelf
Note: Area of Average Required Daylight Factors

Usually, 1.0-2.0% daylight factors (DF) are needed to perform general activity for all public building types. If DF is lower than 1.0%, full electric lighting is required. However, the required daylight factors may vary depending upon building type and activity (see Appendix B).

General Consideration:

1. Area above 2.0% DF, or within a distance of 0-15 feet from aperture, electric light may be turned off (provide only necessary task lighting).

2. Area within a distance of 15-30 feet from aperture, electric light is used to supplement daylight.

3. Area below 1.0% DF, or 30 feet from aperture, electric lighting is required in this area.
7.7 Result and Discussion

Daylight factor graphs of the 11 tested variables reveal significant information about the ability of daylight to penetrate a room using a unilateral sidelighting method under an overcast sky condition. To satisfy for minimum condition of DF = 1, the maximum distance to the source of sidelighting is limited to 30 feet. Within this distance, daylight can be introduced as ambient light inside a building, and as a task light in areas near the window. This result also corresponds to a rule of thumb or theory provided by several authors. For instance, Fuller Moore (1985) said “the 15/30 rule of thumb is a useful guide in the schematic design phase..., a fifteen-foot perimeter zone can be task-lighted primarily by daylight, the next fifteen feet partially daylighted with supplemental electric lighting, with the remainder requiring entirely electric illumination (This guide is based on high windows and a ten-foot floor to ceiling height).” In addition, Claude L. Robbins (1986) stated that daylight penetrates about 2.5 times the head height of the aperture into a room from a window (no specification about sky conditions for this rule). The limited distance of daylight penetration will affect determinants of builtform and daylighting strategy. However, all these statements, including the results from the tests, are only approximate distance for preliminary design.

In the actual process of daylighting design, the characteristics of daylight penetration and distribution as well as illuminance level deriving from the effect of different fenestration systems should be considered in conjunction with the types of activity in a proposed space. Two sources of reference information are:

1. Required Daylight Factors (see Appendix B)
2. IES Recommended Illumination Level (see Table 4.2)

Both sources provide valuable information by giving a range of numbers of required illuminance levels and daylight factors according to activity or function performed under illumination space. Designers may use these reference data to check luminous conditions of their designed daylit-space by using the “Required Daylight Factors” when measuring relative
illuminance and using “IES Recommended Illumination Level” when measuring absolute illuminance.

When review the eleven daylight factor (DF) graphs, note that the penetrated distance of a given DF level of 11 tested variables when compared to one another is not much different (The distance of useful daylight required for general lighting, approximately 1.0 DF (%) or 20-30 footcandles is limited to about 30-foot from aperture to interior), but the illuminance level and distribution at every measured point (7 points) are noticeably different, especially within the first 15-foot from the aperture, because the slope of the curve indicates the amount and rate of illuminance change along the room’s depth. In this case, the rapid change of slope appearing in the first 15-foot from the window represents the potential for discomfort glare resulting from brightness contrast, and a flatter curve appearing inside a room indicates a uniform distribution of daylight. However, each DF graph of the tested variables differing in fenestration design has a comparative difference in its slope individually in response to the change in illuminance distribution. This difference is discussed in the following sections.

Part 1: Position of an Unprotected Window

Under an overcast sky condition, the luminance distribution is about three times brighter at the zenith than at the horizon. The effect inside buildings of this condition can be confirmed by the comparative results of the tested variables No. 2, 3, and 4 in that placing a window high in a wall or close to the sky (DF graph No. 4) provide a higher illuminance level in the interior than placing a window close to a floor (DF graph No. 3). In addition, the size of the window affects the amount of illuminance, penetration, and distribution. As the comparison shown between DF graph No. 1 (window wall) and DF graph No. 2, 3, and 4 (regular size window), the larger window wall of DF graph No. 1 provides higher illumination levels and deeper penetration than the smaller windows of DF graph No. 2, 3, and 4.

However, design consideration in the selection of size and the placement windows must be carefully made, especially on the issue of “brightness contrast.” Normally, large and high window areas appear very bright because of the relatively high illuminance of the exterior
environment. If the window is positioned low in the field of view, this may be a potential source of direct glare (Direct glare results from high luminance or insufficiently shielded light sources in the field of view). Therefore, positioning a window above the field of view (preferably 45 degrees or more above the horizontal) or separating the function between a view window and a daylight window can help prevent direct glare. Additionally, high window locations not only reduce glare from high-brightness exterior areas, but also increase the potential for deep daylight penetration into a room.

Part 2: The South-Window

In this part, variable No. 5, (unprotected high-window with clerestory), was used as a reference model in comparing other variables that were designed with sun protection devices. A high-window variable was investigated after reviewing its advantages for daylighting purposes under an overcast sky-condition. The daylight factor graph (DF) of variable No. 5 represents a higher illuminance and deeper light penetration than DF graphs No. 6, 7, and 8 do. However, in an actual situation, particularly in a warm-humid climate where the effect of heat, glare, and rain are a major problem, the use of an unprotected window is quite rare and not appropriate for this type of climate.

Generally, designing a window for a south orientation is much easier than that for an east-west orientation because of the characteristics of the sun path. During the summer, solar heat gain on a south-facing window is small because of the high midday altitude angle and large azimuth angles in the morning and afternoon. Only a simple system of solid overhangs is needed to shade the window glazing completely during the summer months. However during the winter, when the sun angle is low, the deep penetration of direct sunlight is considered unacceptable for task lighting although the solar gain from low winter sun may be welcome thermally.

Examples of south windows with sun protection devices investigated for their illuminance distribution were: (1) a window with horizontal opaqued overhang, (2) a window with horizontal louvered overhang and (3) a window with an intermediate light shelf. Under
overcast sky testing, the DF graphs of these window systems are almost the same. However there is a small difference on the illuminance level in the area near the window with the highest percent of DF appearing in the system of horizontal louvered overhang (DF graph No. 7) and the lowest percent of DF in the system of light-shelves (DF graph No. 8).

However, these window systems were designed to prevent penetration of solar heat and glare when the sky is bright or when there is direct sunlight. Of course, under an overcast sky, they will obstruct some light penetration, causing a lower illuminance level inside the room. To improve the ability to admit and distribute daylight in the systems of opaque overhangs, louvered overhangs, and light shelves, the quality of materials (i.e. reflectance, surface diffusion), and the geometry of components (i.e. cut-off angle, louver shape, louver slope) are significant, resulting in a change of slope on the DF graph.

Examples for the improvement of overhangs recommended by Fuller Moore (1985) are that "the overhang can be made to transmit diffused light in two ways. The overhang material itself can be translucent (for example, a white fabric awning), or it can be comprised of a series of parallel, opaque white louvers that provide shielding between critical solar profile angles".

The comparative results of the test between white opaque overhangs and sloped white louvers can be used to support the recommendation stated above. The results showed that the angled white louvered overhang (DF graph No. 7) admitted more diffused light into an interior than the white opaque overhang (DF graph No. 6). This is because all light is diffused by a double reflection before reaching the glazed window (i.e. light will be reflected off the top of one louver onto the bottom of the one above, which becomes a secondary source of luminance "seen" in the workplane) (Moore, 1985).

For the performance of intermediate light shelves (DF graph No. 8), this system did not increase illuminance deeper into the room, but its principle advantage was the reduction of glare from the skydome at a location near the window, because light shelves reflect additional
light through the upper glazing, while acting as an overhang for the lower glazing, shading it from the direct sun and obstructing the skydome.

Similar to the effect of opaque and louvered overhangs, improving the reflectance and surface diffusion of materials used for light shelves can enhance illuminance level and daylight distribution into an interior. The design consideration for an overcast condition is that the use of reflective materials or white color on the upper part of the shelves will reflect the light onto the ceiling and then redirect it into the workplane. This design increases interior light level more than the use of reflecting materials on the lower part of the shelves. Under overcast conditions, diffused light from the sky has a more direct effect than reflected light from the ground. In addition, the contribution of light shelves on interior illuminance is directly affected by ceiling reflectance and glazing type.

Part 3: The East/West Window

The comparative performance data of variable No. 9 (vertical slanted fins), No. 10 (horizontal louvers), and No. 11 (eggcrate system) are presented in the form of daylight factor graphs to illustrate that the change in fenestration geometry affects interior illumination levels and light distribution. Among the three variables tested, the system of fixed vertical slanted fins provided a higher illuminance level near the window and a deeper illuminance into a room than the system of horizontal louvers and eggcrates. This is due to its geometry. White vertical fins angled at 45 degrees toward the north with a 90 degree cut off angle, allow sky light to enter directly while diffusing direct sunlight by a double reflection.

After the first 15 feet from aperture, the illuminance level and illuminance distribution of the vertical slanted fins (DF graph No. 9) are similar to those of the horizontal louvers (DF graph No. 10) with a slightly higher illuminance level appearing in the vertical slanted fins. In contrast, the lowest illuminance level and light distribution appeared in the system of the eggcrate (DF graph No. 11). Although, the solid eggcrate system composed of slanted vertical fins and horizontal louvers is best for sun protection, it is not as appropriate to use for daylighting purposes when the sky is dominated by overcast condition.
Generally, it is more difficult to obtain desirable results when designing a window with an east-west orientation, than for a south orientation because east-west orientation has solar exposure characteristics that differ from that of the south. Normally, window sunlight exposure occurs in east in the morning and in the west in the afternoon.

To increase illuminance levels for both east/west windows and south windows, the system of adjustable vertical fins and horizontal louvers may include retractable shading devices applicable to these window orientations. However, a greater effect will occur, especially at east/west exposures, because the louvers can be set perpendicular or retracted for the half day when no sunlight shielding is required. Moreover, the adjustable shading devices can allow a larger range of view that cannot be obtained from fixed shading devices.
Chapter 8: Conclusion: The Alternative Approaches and Design Principles for Daylighted Commercial Buildings in a Warm-Humid Climate

The use of daylight in commercial buildings in a warm-humid climate has great potential, especially when it is integrated with artificial light, to provide both energy-efficiency and a pleasant environment, located as they are in latitudes with abundant daylight. Moreover, the sky (a major source of daylight) of this climate is predominately partly cloudy, a condition that often produces the highest level of illumination when compared with the illumination of an overcast sky or clear sky without direct sun.

To design with daylight for a building in this climate, light should be admitted into a building under sufficient control so that only a modest amount of natural light is allowed to illuminate the building. Additionally, sunlight’s thermal effect and excessive brightness must be avoided by means of a variety of control devices and by the building design itself. Such limitations will directly influence the design of the envelope and optimal orientation of the building. A design principle that is always appropriate for a building in a warm-humid climate is that the longer side of a rectangular building should be oriented along an east-west axis to allow desirable daylight penetration into the interior as much as possible. At the same time, the strong solar radiation on the shorter east and west facades needs to be mitigated with various strategies of control, including the use of shading devices and positioning of service cores, as well as optimizing of glazing on all sides of the building.

The limited distance of daylight penetration, will partially affect design consideration of forms and proportions of the building in that the building form needs to be adjusted by increasing its perimeter to access daylight or creating a narrower floor plan. However, in the actual design process, the form of the building does not derive its shape from daylighting considerations alone. The B.C. Hydro group, discussed in chapter 3, studied the effect of form and energy cost and pointed out that the form of a building is determined in conjunction
with many other constraints. It is up to the designer to choose the most appropriate method for achieving energy savings. Moreover, the analyses of case study buildings in chapter 5 has lead to the understanding that no matter what the form of the building is, daylight can provide many benefits if proper methods in the use and control of daylight are introduced into the design. Each different form and orientation of a building has its own method for accessing daylight. With this in mind, according to fundamentals of generating architectural form, the building’s mass or builtform may be classified into three groups: (1) block form, (2) slab form, and (3) tower form. A detailed discussion of daylighting strategy and builtform follows.

Even with the extensive possibilities of architectural design (i.e., builtform and orientation, geometry of space, fenestration design) to create a good lighting environment in buildings, daylighting cannot entirely replace electric lighting. A comprehensive approach to lighting design is needed not only in architectural design, but in interior design (i.e. space planning, reflectance of material) and artificial lighting design (i.e. lamp and luminaire, lighting control system) as well. Consequently, the alternative approaches and design principles for daylit commercial buildings in a warm-humid climate can be made following the three groups of considerations that follow.
(1) Consideration of Builtform

How each builtform is adjusted to access daylight, and which daylighting strategy is appropriate for manipulating the form and envelope of a building have been discussed in chapters 3, 5 and 6. When analyzed for possible use in daylighting design, the following conclusions were arrived at for each builtform:

1. Block Building

A block building is a large square-shaped building. The compact or block form allows more natural light to enter a building by manipulating forms such as an atrium, light court, or reentrant (the directing inward of a building’s perimeter design to optimize daylight penetration, such as C, U, E forms and stepped-back forms) to reduce the core area where...
daylight cannot reach. These methods can be used together with methods of manipulating the building envelope which are composed of: (1) sidelighting strategies, and (2) toplighting strategies. Especially, toplighting strategies (skylight, sawtooth, monitor), are appropriate in this building form because they function very well in single-story or low-rise buildings.

2. Slab Building

A slab building is a rectangular building having relatively less width compared to its length and height. Generally, the slab or extended form of the maximized perimeter in a horizontal direction provides more natural light than a block form. Sometimes, when this building form has a narrow floor plan, only sidelighting strategies (window, clerestory) may be sufficient to provide natural light inside the building. However, for more natural light when a deep floor plan occurs, both sidelighting and toplighting strategies may be applied.

3. Tower Building

Since a tower form maximizes its perimeter in the vertical direction, it can provide more natural light than the block form. Although this building form has a larger total area to access daylight, it also experiences more impact from solar heat and glare than the block or slab building. Therefore, designers should be as concerned about the proportion and type of glazing used for tower buildings as they are about the design of shading devices. Similar to the methods used for block and slab buildings when the building's floor plan is deep, toplighting concepts, (especially skylight strategies) and the methods of manipulating form (such as atrium, and reentrant) can be appropriately used for the tower building.

(2) Consideration of Orientation

Along with manipulating forms (i.e., atrium, skylight, reentrant, and narrow plan) and manipulating envelope (i.e., toplighting, sidelighting) which aim to maximize daylight into the building, the methods of sun control and aperture shading are also important for good daylighting because they can prevent overheating of the building while still permitting daylight to enter the interior. The methods of sun control and aperture shading that are
always applied together with toplighting and sidelighting strategies will create optimum results only when devices are selected and oriented properly. Here, daylighting design, type of shading devices, type of daylighting strategy, and orientation of the building must be considered together to achieve the desirable results appropriate for specific climatic conditions. The design considerations for glazing different orientations or facades of a building are the same for each orientation. These principles can be applied to the scale of all buildings, no matter what the form is. The design consideration and daylighting methods for designing window glazing for each orientation are:

2.1 South Orientation

Windows, clerestories, or monitors oriented toward the south provide the easiest opportunity for controlling solar heat gain while permitting access to sunlight during most of the day. For best results, roof overhangs and horizontal overhangs should be constructed of permeable louvers oriented to transmit diffuse daylight while providing shade from direct sunlight. The utilization of light shelves is appropriate for this orientation because the shelves reduce the contrast between glazing windows and interior surfaces, minimizing glare and providing visual comfort as well as uniform light distribution.

2.2 East or West Orientation

East or west oriented glazing has access to sunlight for half a day. To prevent solar heat gain, glazing requires a combination of horizontal and vertical shading. But such combinations will obstruct some light penetrating the building, especially when the sky is overcast. One of the best solutions is orienting fins or louvers towards the south (toward the southwest when on the west and the southeast when on the east side). Otherwise, fins or louvers may be oriented toward the north (toward the northwest when on the west and the northeast when on the east side). But designers should be careful that orienting fins or louvers toward the north allows direct sunlight during the clear sky of summer. However, when possible, the utilization of adjustable or automatic shading systems can provide the best results for east/west orientations.
2.3 North Orientation

Usually, glazing oriented toward the north does not receive the strong effect of direct sunlight which causes severe problems in other orientations. Consequently, sun control and shading devices may be eliminated from this orientation. However, if shading is required, widely spaced perpendicular fixed vertical louvers will be sufficient.

Daylighting design in a warm-humid climate, where the sky presents the characteristics of both overcast and clear conditions, is very complicated because the design must ensure an adequate amount of illuminance inside a room when outside condition is overcast, while preventing solar heat and excessive brightness during overheated periods or when there is undesirable direct sunlight from the clear sky. Hence, designing horizontal oriented glazing, for example, horizontal skylights for buildings in this climate, should be combined with shading devices or diffusers designed to control the problem of imbalance of illumination between winter and summer days. This is due to the fact that on sunny days of summer, skylights permit too much sunlight into building’s interior, and too little in the winter. Roof monitors or sawtooth clerestories oriented north or south can be another solution in the design of an overhead light source.

(3) Design Principles

The following design principles for daylighting design in a warm-humid climate are classified in three parts: architectural design, interior design, and electric lighting. A detailed explanation and the design method of daylighting as well as electric lighting are available in chapters 3 and 4. The design principles that are appropriate for daylighting design are:

3.1 Architectural Design

1. Orient the building with major facades or glazings facing north and south
2. Size windows according to use and orientation
3. Consider characteristics of site climate
4. Design fenestration with the purpose of maximizing view, daylight, ventilation, and winter sunlight while minimizing glare, summer heat gain, and direct sunlight on critical visual task areas.

5. Maximize floor to ceiling height and place fenestration high on the wall to increase daylight penetration (however, for multistory buildings, this principle should be evaluated with construction economy).

6. Increase perimeter daylight zones.

7. Admit daylight on more than one side of a room to avoid a sharp contrast between daylight and adjacent wall surfaces.

8. Avoid sharp rectangled jamb-corners that cause high brightness ratios and glare by using, for example, sloped jambs or sloped light wells to lower brightness ratios.

9. Baffle daylighting openings by using exterior or interior devices so that the view of the sky is shielded from occupants in most viewing positions.

10. Filter daylight to soften and distribute light more uniformly.

11. Integrate with other environmental control systems (HVAC, view, ventilation, acoustics, and electric lighting).

12. Select proper glazing materials needed to provide more light gain per unit of heat gain.

3.2 Interior Design

1. Consider interior space planning, for example, locate work stations near windows when designing office.

2. Consider reflectance of interior surfaces, including furniture. For example, use high-reflectance matte finishes on interior surfaces to maximize effectiveness of both daylighting and electric lighting and to soften contrast with the sky.

3. Use open space planning with minimum interior partitions. Otherwise, use transparent interior partitions (or upper parts of partitions) to transmit daylight into interior.

4. Use interior control devices like blinds, drapes, etc. to respond to changing diffuse and clear sky conditions.
3.3 Electric Lighting

1. Complement daylighting with electric lighting
2. Switch or dim lighting fixtures to lower illumination levels or turn them off when daylight is sufficient
3. Consider color-rendering capabilities of electric light sources and interior surfaces
4. Use automatic lighting control systems
5. Use indirect lighting systems to minimize occupant perception of lighting control systems and to increase lighting quality
6. Use high-efficiency fixtures and lamps
7. Use nonuniform lighting designs to match occupancy needs by varying light intensity

Along with the principles stated above, another important design principle in all areas (architecture, interior, and electric lighting design) is "maintenance". Maintenance should be done regularly to maintain or enhance the quality of reflectance surfaces (i.e., shading devices and reflecting walls), and the efficacy of lamps and luminaires in electric lighting.

The purpose of this research was to understand the potential of daylight as an energy-efficient approach integrated with the use of artificial light for the design of commercial buildings. The information related to daylighting was presented in this research in a step-by-step approach beginning with the study of the characteristics of a warm-humid climate. Knowledge of site climate helped to consolidate the scope of daylighting design. The study of daylighting and electric lighting as well as the six case study buildings were analyzed to determine principles and design methods appropriate for commercial buildings in a warm-humid climate. As reported in chapter 7, selected variables of fenestration design used in a warm-humid climate were investigated through physical model testing under an overcast sky.

Since the experiment of parametric analysis was conducted in a given condition (an overcast sky), the results of this testing cannot be generalized. They can be used only to evaluate the design that is encountered in a minimum sky condition (when the sky condition
is low in illumination level). To ensure the full effect of the proposed design elements or
daylit space in a warm-humid region with partly cloudy sky, it is recommended that those
design elements or spaces should be tested under both overcast sky conditions and clear skies
with direct sunlight. Under clear skies, the result of a test may differ from the results
obtained from the overcast sky because on the clear day, the effect of direct sunlight will play
a major role, especially in designing shading devices. Sunlight’s effects may be considered
on a variation of shade and shadow patterns and the penetration of direct sunlight inside a
room. Generally, direct sunlight in the workplane or on critical visual surface is
unacceptable. Therefore, use of a scaled physical model, constructed with reasonable
accuracy, tested under both clear and overcast conditions, is useful and effective to check
qualitative and quantitative design characteristics.

For the next step of study, especially when a fenestration design is selected or when there
are few tested variables, the process of physical model testing may be done with greater detail
and accuracy. Of course, it will take more time to obtain test results. The extended process
of a daylighting study should focus on “qualitative observations” as well as on “quantitative
tests” that were done by measuring illumination levels with the line measurement method and
interpreting test results with a daylight factor graph as performed in this research.
Observations on qualitative characteristics of light may be performed by either viewing or
photographing, or both through viewing ports. Direct observation may suggest alternative
adjustments to the model. Photographing the different schemes and the different time-of-day
and seasons will facilitate direct comparison. Questions that may arise when considering the
qualitative characteristics of daylight in the model are: Are there distracting shadow or dim
areas? or How will artificial lighting be integrated?

To achieve an optimal utilization of integrating daylight with artificial light in a deep
interior, particularly when there is a design scheme that uses multilateral illumination, the
pattern of illumination measurement and the graphic method of presenting data need to be
changed. “Iso-lux contour graphs” generated by measuring illumination in a grid pattern over
a plan view, should be used to present the data instead of a one axis of “daylight factor
graph/section” generated by measuring illumination in a single line pattern. This Iso-lux graph is similar to a survey map; it shows changes in level through the use of contour lines (fig. 8.1). Data from the Iso-lux graph can be used to determine which method should be used with artificial lighting, or to divide the zone of artificial lighting installation. If daylighting is not sufficient, artificial lighting will be turned on. If use of artificial lighting can be predicted, an aspect of how daylight will save energy can be quantified.

In addition, possible future technology may result in the ability to down size lamps and luminaires. If these scaled-down lamps and luminaires are available with the same quality as they are in normal sizes, designers may test the efficiency of their designs in integrating daylight with artificial light with the use of a small scaled physical model. This technology will allow designers to observe and analyze how their light interacts with daylight, and how the quality of light within a space will eliminate glare or distort color rendering.

In conclusion, it is hoped that the design principles and methods contained in this research will be useful in warm-humid regions for designers who want to take advantage of daylight in designing their buildings. However, although daylighting is proposed here as an optimum approach to achieve energy cost-savings. When it is integrated with artificial lighting, it should be evaluated with other design alternatives to determine if cost-effective design economics and life-cycle cost savings will occur after implementing daylight principles. Moreover, the most appropriate strategy resulting from the evaluation should be in response to the two main goals of daylighting design; first, promote energy-efficiency and cost savings, and second, promote a pleasant lighting environment which responds to occupants’ needs.
Figure 8.1 Plan and Iso-lux graph; contour lines and shading show different levels of illumination.

Source: Lam, William M. C., *Sunlighting as Formgiver for Architecture*, 1986
APPENDIX A: “MIRROR-BOX” ARTIFICIAL SKY

History and Luminance Distribution

In an attempting to test daylighting models outdoors under “overcast” conditions that provide rapid and unpredictable shifts in luminance patterns and illumination levels as well as difficulties with delicate measuring instruments, various types of facilities that simulate the sky were designed and built with different limited capabilities. One is a “mirror-box” or rectilinear artificial sky. It was first designed and used by The British Research Station in England. The mirrored box was developed for use in conjunction with building models to simulate and predict the quantity and quality of daylight in a building under real sky conditions. It provides a means to examine and compare the effects that various design elements, such as fenestration patterns or ceiling sloping patterns, can have on the amount, distribution and character of daylight in a proposed space or building.

Since low light levels can result in unreliable instrument readings, the desirable characteristics of an artificial sky instrument is to provide a high level of illumination as well as a luminance distribution which closely approximates that of the real sky. One criterion widely accepted as critical in judging artificial sky validity is the luminance distribution pattern (LDP). Since the natural sky is a fluctuating light source, a reference formula describing the LDP was developed in 1955 by the Commission Internationale d’Eclairage (CIE), the international lighting standards association, as the C.I.E Standard Overcast Sky (Fig. A-1). The equation that describes the luminance distribution of this sky is:

\[ B(\alpha) = \left\{ B(\theta) \right\} \times \frac{1 + 2 \sin(\theta)}{3} \]

where, \( B(\alpha) \) is the luminance of the altitude angle \( \theta \)
B (theta) is the luminance of the zenith, that defines a sky three times brighter at the zenith than at the horizon, with a gradation of brightness values at the intervening altitudes.

![Figure A-1 CIE Standard Overcast Sky](image)

Loveland and Naavab (N.D.) believe this equation in Simulating Daylight with Architectural Models (N.D.) leads to the concept of relative brightness. The brightness at angle alpha is a direct function of the zenith brightness, B (theta). Thus the brightness at angle theta is expressed as a decimal fraction of the zenith brightness. Through this equation, the sky's luminance at any one point can be compared to the reference sky without concern for the actual levels of illumination. From this, one can develop plots of sky points of equal luminance or logarithmic curves that can be easily compared to the given standards. The methods and procedures of luminance measurement is available with a more detailed explanation in the above stated book. The CIE Standard Overcast Sky has been used since then by daylighting designers and researchers as a general worst-case condition for building daylighting.

As described by Cooksy (1990), the attraction of this sky pattern for sky simulators is apparent. It is an unvarying condition (unlike the clear sky model, with a LPD that varies according to the sun's position) and it allows designers' working to a minimum daylight factor to assume that tests under the Standard Overcast will provide an indeed minimum-based information.
The artificial skies using the Standard Overcast LDP ideal have been built since the 1940’s. The form used has consisted of a rectangular box of varying sizes (from 4’x4’ to more than 15’ on a side) with mirrored walls and a diffused light luminous ceiling (fig. A-2). This arrangement is described by Walsh in The Science of Daylight (1961). He used an 85% mirror reflectance to demonstrate how the Standard Overcast LDP can be created in an environment through the increasing absorption of light over multiple reflections at a lower angle (fig. A-3).

![Figure A-2 Mirror Box Artificial Sky](Source: Cooksy, Christopher, *The Limits of The Sky*, 1990)

<table>
<thead>
<tr>
<th>Line Angle</th>
<th>Reflections</th>
<th>Relative Luminance</th>
</tr>
</thead>
<tbody>
<tr>
<td>16°</td>
<td>4</td>
<td>.52</td>
</tr>
<tr>
<td>25°</td>
<td>3</td>
<td>.61</td>
</tr>
<tr>
<td>35°</td>
<td>2</td>
<td>.72</td>
</tr>
<tr>
<td>51°</td>
<td>1</td>
<td>.85</td>
</tr>
</tbody>
</table>

![Figure A-3 Walsh Diagram](Source: Cooksy, Christopher, *The Limits of The Sky*, 1990)
Besides the natural tendency for decreasing luminance at lower angles is simulated by the mirror box, its additional advantage is the infinite reflection to the horizon. This characteristic allows for any observation point to see the horizon as it should be, at an infinite distance and at eye level. This capability eliminates the problem called “horizon error” found in a hemispherical or artificial dome sky. The horizon error occurs because the dome’s horizon is only a few feet away rather than infinitely distant, so the angle of depression from the top of a window to the horizon may be several degrees, when it should be practically zero. The result is that the model window “sees” more sky than it should, and thus, the ceiling and deeper reaches of a room are rendered too bright. Another advantage of the mirror-box sky is that it provides a good “overcast” sky luminance distribution of a bright zenith and darkened horizon. This occurs because of the cumulative absorption of repeated reflections provided by a luminous ceiling at the top of the box.

Figure A-4 Horizon Error in A Dome Sky

For reasons of its accuracy, ease of construction and the comparatively inexpensive material costs, the mirrored box skies based on the CIE Standard Overcast Condition as an ideal LDP have been built for use as research and teaching tools by a number of universities in the United States. At the University of Washington, master student, Ann Stevens Airy built a mirror-box sky from which information was gathered and was later used as a guideline and reference for mirror-box skies at other universities. Her experience and observation about the mirrored box skies proposed her thesis was built on the suggestions of Hopkinson
et al. (Hopkinson, 1961) at the British Research Station. Airy (1979) described the design, construction, and calibration of a “mirror-box” artificial overcast sky built at the University of Washington, Seattle. A summary of her studies follows.

**Design and Construction**

While in principle the design of an artificial sky is quite simple, there are few guidelines available for proportioning the various elements. Published descriptions and illustrations suggest vastly different designs from tall enclosures to very flat boxes with plan dimensions nearly three times their height. For the artificial sky at the University of Washington, Seattle, a shape between these extremes was chosen: a box of near-cubic proportions, whose over-all size was determined by the research model and cost limitations, measuring 4 feet by 5 feet in plan, with the upper 12 inches reserved for the lamp housing. The basic construction is 3/8-inch plywood, framed at the edges for stiffness. To attain the infinite horizon, the inner vertical surfaces of the box are mirrored. This is most easily accomplished by gluing the mirrors on the walls in small squares of 12“x12”. The mirror squares line all four walls including the wall that acts as the model access. The front access door slides open.

The light source consists of twenty-four 4-foot, 40-watt Vita-Lite fluorescent lamps, chosen specifically for their close approximation to the natural daylight spectrum. They are arranged in parallel on 12 ballasted fixtures and spaced to provide an even output distribution. Eight inches below the lamps, an acrylic diffuser (1/8-inch Plexiglas white # 2067) rests on right-angled aluminum extrusions at the edges and is supported at the one-third and two-thirds span points by suspended transparent buttons. Although fluorescent lamps are comparatively cool in operation, this arrangement generates 960 watts in a close space, and thus overheating (with reduced lamp efficiency) is a potential problem. To prevent this, several small vent holes are drilled in the plywood roof panel near the heat-generating ballasts, and two 5-inch propeller-type “boxer” fans are mounted in the back panel of the lamp enclosure. The floor of the box is painted a neutral gray so as to simulate natural ground reflectance values. Since there are too many variables in an artificial sky (degree of light absorption by mirrors, rate of hot-air evacuation, etc.) to design any of the elements with
precision, and most of mirrored box skies have been designed and built without preliminary
testing for LDP. To meet the experimental quality, the recommendation for construction of a
mirrored box artificial sky is the established process of testing, calibration, and adjustment
prior to being used with assurance for actual daylighting studies.

Calibration of The University of Washington Sky

If an artificial sky is intended for research, calibration is absolutely necessary. The two
most important concerns when calibrating are: (1) a high level of illumination to provide
sufficient instrument gauge deflection for accurate readings inside models, and (2) a realistic
luminance distribution (a simulation of the CIE Standard Overcast Sky in the case of the
mirrored box). Full overcast skies give up to 2000 footcandles of illumination, and Walsh
(1961) recommends that artificial skies provide at least 500 footcandles because:

(1) the accuracy of instrument readings when placed in daylighting models can be
negatively affected at extremely low illuminance levels.

(2) the artificial sky light source, the lamps, will lose lumen output with age, thus,
possibly affecting the accuracy of readings.

(3) the lumen output of the lamps will fluctuate relative to their operating temperature or
warm-up time.

Therefore, the lumen output of the sky should be checked regularly. In the University of
Washington Sky, initial tests of horizontal illumination showed values of about 1500
footcandles. Even though lamp output diminished, a high level of illumination was
maintained.

Since the natural sky is a fluctuating light source, the formula for the CIE Standard
Overcast Sky was adopted as a stable reference:

\[ \text{Be} = \frac{\text{Bz} \cdot (1+2 \sin \phi)}{3} \]

where \( \text{Be} \) is the luminance at altitude angle \( \phi \), and
\( \text{Bz} \) is the zenith luminance.
The luminance calibration measurement was obtained, using a hand-held Minolta 1° Spotmeter (a luminance meter), with an "angle-finder" level mounted on top for reading elevation angles. The luminance tests generally showed good results with some variation according to test height and azimuth direction.

Figure A-5  Luminance Distribution of The University of Washington

Details of Construction

The following description and graphic details of mirrored box skies is based on a document by Moore (1985). His document clarified and followed the construction methods and lessons learned in the building of the mirrored box sky at the University of Washington as documented by Ann Airy.

The entire sky box is elevated and mounted on a three-foot platform with a trapdoor (opening downward) to allow the experimenter to get inside the sky chamber to move photocells or alter the model without opening the large front door panel and removing the model. The base (floor) of the sky is extended beyond the confine of the chamber to form a five-inch ledge. A small element of this edge slides out to provide a recessed channel for instrument leads (fig. A-10).

The front access door is a vertical slider mounted on wooden tracks and hung from pulleys with counterweights so that the door can easily be pushed out of the way for placing
or removing test models. The vertical edges of the door panel each have two small doweled pins to guide the door in the vertical tracks. The tracks are designed and placed so that the door slides 3/8" away from the sky's wall (to protect the mirror) until it is in the fully closed position. Then, the door's pins are secured into their seats in the door's light-tight position with simple casement window latches.

Figure A-6 Left- Isometric Cutaway Drawing
Figure A-7 Right- (a) Front View, (b) Side View
Source: Moore, Fuller, Concepts and Practices of Architectural Daylighting. 1985

Figure A-8 (a) Front Section, (b) Plan
Source: Moore, Fuller, Concepts and Practices of Architectural Daylighting. 1985
Figure A-9  Movable Door and Tracks: (a) Front View, (b) Side View

Figure A-10 A recessed channel for instrument leads on the extended floor
### APPENDIX B : REQUIRED DAYLIGHT FACTORS FOR VARIOUS FUNCTIONS

<table>
<thead>
<tr>
<th>Building Type</th>
<th>Activity</th>
<th>DF (%)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>All public buildings</td>
<td>Circulation</td>
<td>0.5-3.0</td>
<td>Minimum is sufficient, higher levels only as transition from adjacent areas at higher levels</td>
</tr>
<tr>
<td></td>
<td>Lobbies, Foyers, Lounges</td>
<td>1.0</td>
<td>Individual task lighting may be necessary for reading</td>
</tr>
<tr>
<td></td>
<td>Reception Desks</td>
<td>1.0-2.0</td>
<td>Depending on difficulty of task involved</td>
</tr>
<tr>
<td></td>
<td>Restroom</td>
<td>0.0-1.0</td>
<td>Need not be daylit</td>
</tr>
<tr>
<td>Assembly, Concert Halls</td>
<td>General</td>
<td>0.0-1.0</td>
<td>May be undesirable to daylight without good controls capable of blacking out for media presentations</td>
</tr>
<tr>
<td>Banks</td>
<td>General</td>
<td>2.0</td>
<td></td>
</tr>
<tr>
<td>Churches</td>
<td>Congregation</td>
<td>1.0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Pulpit, etc.</td>
<td>1.5-4.0</td>
<td></td>
</tr>
<tr>
<td>Hospitals</td>
<td>Wards, Public</td>
<td>1.0</td>
<td>Individual task lighting for reading</td>
</tr>
<tr>
<td></td>
<td>Laboratories</td>
<td>3.0</td>
<td>Provide task lighting</td>
</tr>
<tr>
<td></td>
<td>Operating Room, Examining Room</td>
<td>3.0-5.0</td>
<td>Privacy and thermal considerations may override</td>
</tr>
<tr>
<td>Industrial</td>
<td>High Resolution Work</td>
<td>5.0</td>
<td>Top lighting recommended</td>
</tr>
<tr>
<td></td>
<td>Other Works</td>
<td>2.0-3.0</td>
<td>Provide task lighting where suitable</td>
</tr>
<tr>
<td>Libraries</td>
<td>Stacks</td>
<td>1.0</td>
<td>Additional artificial light required</td>
</tr>
<tr>
<td></td>
<td>Reading Areas</td>
<td>1.0</td>
<td>Provide individual controlled task lighting</td>
</tr>
<tr>
<td>Museums, Galleries</td>
<td>General</td>
<td>1.0</td>
<td>Additional artificial lighting may be required for emphasis, daylighting may be inadvisable where light-sensitive materials are displayed</td>
</tr>
</tbody>
</table>

212
<table>
<thead>
<tr>
<th>Category</th>
<th>Task</th>
<th>DF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Offices</td>
<td>General</td>
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</tr>
<tr>
<td></td>
<td>Typing</td>
<td>4.0</td>
</tr>
<tr>
<td></td>
<td>Drafting</td>
<td>5.0</td>
</tr>
<tr>
<td>Residential</td>
<td>Kitchens</td>
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<tr>
<td></td>
<td>Living Rooms</td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td>Bedrooms</td>
<td>0.5</td>
</tr>
<tr>
<td>Schools</td>
<td>Assemblies</td>
<td>2.0</td>
</tr>
<tr>
<td></td>
<td>Classrooms</td>
<td>2.0</td>
</tr>
<tr>
<td></td>
<td>Art Rooms</td>
<td>4.0</td>
</tr>
<tr>
<td></td>
<td>Laboratories</td>
<td>3.0</td>
</tr>
<tr>
<td></td>
<td>Staff Areas</td>
<td>1.0</td>
</tr>
<tr>
<td>Sports</td>
<td>Playing</td>
<td>2.0</td>
</tr>
<tr>
<td>Swimming</td>
<td>Water</td>
<td>2.0</td>
</tr>
<tr>
<td></td>
<td>Deck</td>
<td>1.0</td>
</tr>
</tbody>
</table>

Provide task lights, or lower DF plus full electric lighting on photocontrols. May require task lighting, be careful of reflected glare on video displays. May be difficult to provide uniform high level with only side lighting.

Source: Schiler, Marc. *Simulating Daylight with Architectural Models*
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