CHAPTER II

LITERATURE REVIEW

2.1 DAYLIGHTING DESIGN AND EVALUATION

The phrase "daylighting design" refers to a process at which daylight concepts such as arrangement and sizing of daylight apertures and arrangement of internal spaces are developed and integrated with other building systems such as electric lighting, lighting control and solar control. Meanwhile, the phrase "daylighting evaluation" refers to a process at which the performance of designed daylighting systems are assessed with some degree of available design information. The following sections discuss daylighting design and evaluation issues and tools.

2.1.1 Daylighting Design Process

In order to use daylighting effectively as a design element and as an environmental system, the designer must incorporate daylighting into the building design process, establishing at what points during the design process decisions about the proposed daylighting concepts or system will be evaluated, and determining at what points these decisions will begin to affect the building's architecture and form and its structure and environmental systems. Many architects and engineers follow a building design process that includes the following five steps:

1) Schematic or conceptual design
2) Design development or final design
3) Documentation or working drawing
4) Bidding
5) Construction

To include daylighting concept in the above general design process, predesign analysis can be added to the beginning of the process and postconstruction evaluation can be added to the end of the process as shown in Figure 2.1.

Most often, the architectural consideration of daylight occurs during the early stages of the design process - predesign analysis and schematic design. The engineering consideration of the daylighting system, which must be included in the early design decisions, begins to predominate as final design process. How daylighting concepts become daylighting systems is established during the final phases of schematic design. The actual details of how the various system interact, how they are sized, and what their actual performance characteristics are can only be determined as the building takes on its final form and as the architecture and the engineering systems of the building are integrated into a building solution that is buildable and economically viable.

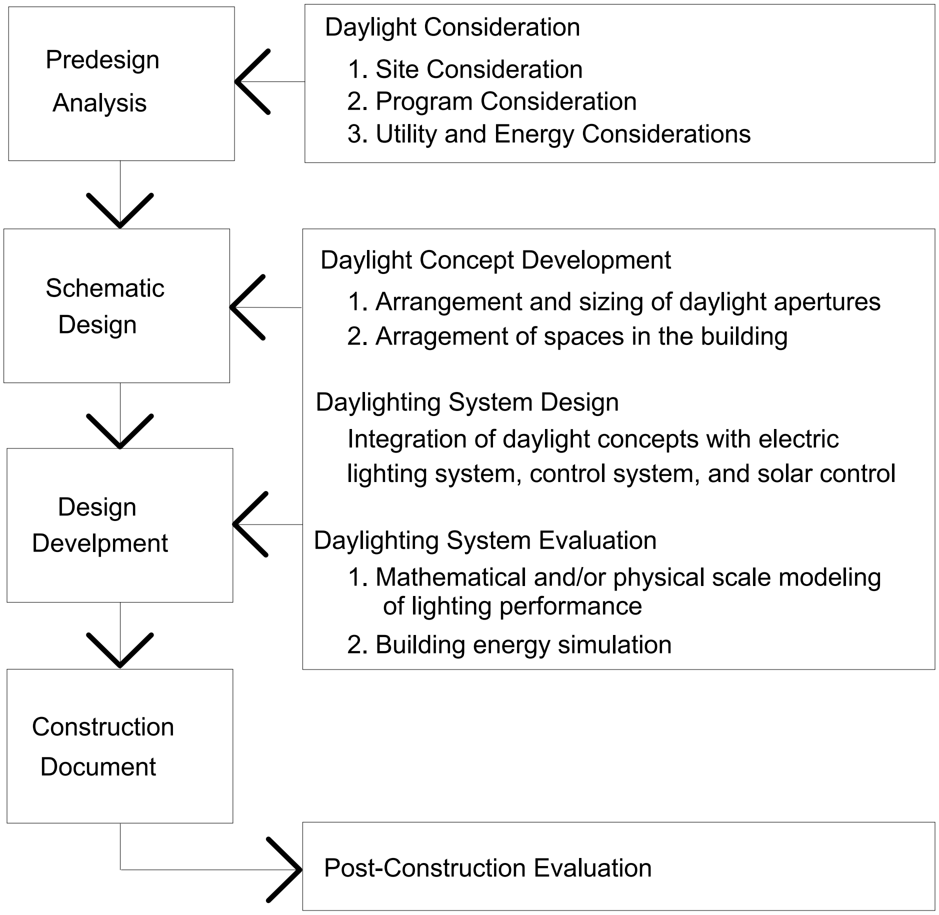


Figure 2.1 Daylighting Design Process

The provision of apertures for daylighting must be considered in conjunction with decisions regarding building economics, architectural composition, thermal control, ventilation, acoustics and other design factors. Even if windows and skylights are provided for amenity lighting only, daylighting effects must be considered in order to avoid glare and thermal problems. A wide range of approaches has been taken to daylighting as a primary means of illuminating spaces. Effective daylighting design requires consideration of the interaction of building systems. For instance, the installation of energy-conserving dimmable lighting systems may provide only minimal savings if heavily tinted glazing, used to control glare, excessively reduces the admission of daylight.

2.1.2 Daylighting Evaluation Issues

Among the numerous ways to evaluate a proposed daylighting design, a logical sequence is the following (IESNA 1993, p. 368):

1) Determine whether sunlight will fall on any areas where it should be excluded, and address any resulting problems by changing the daylighting apertures or providing fixed or movable controls.

2) Determine where sky glare will be a problem, and make adjustments to the design to control glare, or provide fixed or movable controls.

3) Evaluate the performance of the daylighting system acting in concert with any electric lighting, using illuminances and energy use as measures of performance. This includes investigating the pattern of sunlight in spaces where it is being provided as an amenity.

During the conceptual design stage, serious glare problems must be identified and addressed early in the design process, because fenestration must often be modified to correct problems created by sunlight penetration. For a minimum investigation at the conceptual stage, daylighting should be evaluated with solar altitudes corresponding to the solstices, around December 21 and June 21, and the equinoxes (IESNA 1993, p. 368). A range of sky conditions should be tested, including, at least, the extremes for a particular orientation (such as solar noon and the earliest and darkest hours when daylighting occurs for a south-facing facade). It is also important that designs be checked for critical conditions, when sunlight may enter spaces. During this stage, sun profile angles may be manually plotted on building sections to assess sun penetration. In a more advanced fashion, computers can be used to model complex spaces and determine patterns of sunlight penetration through apertures. Scale models may be used in conjunction with direct sunlight or lamps to simulate conditions of interest. Even though this does not provide accurate estimates of illuminance, it allows the assessment of patterns of sunlight penetration.

During the design development stage, in addition to estimating illuminances, it is often desirable to perform visual assessments of daylighting systems. Scale models and full-scale mockups were, until recently, the sole means of conducting such assessments. Computer-based visualization systems are now offering an alternative means of conducting visual assessments in addition to computing illuminance patterns. During this stage, expected indoor illuminance levels can be determined by manual calculation methods, computer simulation programs, or scale model photometry.

2.1.3 Daylighting Evaluation Methods and Tools

Three main approaches to the evaluation of daylighting systems are illuminance calculation, illuminance measurement, and Glare Index calculation. Another qualifier of a luminous environment is Luminance Ratio (LR) whose maximum allowable values to avoid discomfort glare have been recommended (IESNA 1993, p. 518; Stein and Reynolds 1992, p. 958).

Illumination calculation can be a useful approach to quantitatively compare alternative daylighting systems or consider the limits of daylight utilization for various systems under average lighting conditions. Illuminance calculation involves determination of the sky, sun and interreflected components of daylight. The sky and sun components are due to flux that reaches a point directly. The interreflected component results from sunlight and skylight that have initially reached other surfaces and then been reflected to the point of interest. Computation of the sky, sun and interreflected components may be used to calculate illuminances at points or average illuminances over surfaces. Three main methods in this approach include lumen method, daylight factor method, and flux transfer method. The following statements briefly describe these methods.

1) The lumen method was developed in the early 1950s by Griffith and his associates (Griffith et al. 1957) who developed coefficient of utilization tables from a series of measurements conducted in both experimental rooms and physical models. The procedure was then adopted by the Illumination Engineering Society of North America (IESNA) for its Recommended Practice of Daylighting in 1962. This method, which is primarily used in the United States, can consider both overcast and clear sky conditions. However, it is applicable only for a limited range of window configurations and

calculation points within a room. This method is in large measure parallel to the IES method for calculating artificial lighting, in that it treats the window or toplight as a large area lighting source. It then applies coefficients to the light output of the openings, similar in usage to the familiar coefficient of utilization and light loss factor of electric lighting fixture, and arrives at an interior daylight level. The current issue of IESNA Lighting Handbook (IESNA 1993) presents tables of coefficient of utilizations and equations for both sidelighting and toplighting.

2) The daylight factor method is based on the concept of the Daylight Factor (DF), which was developed in England in the 1920s. This method is widely used in Europe and is recommended by the Commission Internationale de L'Eclairage (CIE). This method is applicable to a wide range of window configurations and can calculate daylighting for any point within a room. However, this method can consider only overcast sky and clear sky conditions without sun. Today, the DF is defined as the ratio between the daylight illuminance at a point in the interior and the simultaneous exterior illuminance available on a horizontal surface from an unobstructed sky (excluding direct sunlight) expressed as a percentage. The light reaching the point of interest is separated into three components: light directly from the sky (Sky Component or SC), light after reflection from external surfaces (Externally Reflected Component or ERC), and light after reflection from internal surfaces (Internally Reflected Component or IRC). The total of these three components gives the Daylight Factor (DF = SC + ERC + IRC). The Building Research Establishment (formerly Building Research Station) of England developed an array of tools for rapid estimation of these three components for overcast sky and clear sky conditions. These tools include protractors, tables, and nomograms. Other simplified tools to calculate the Daylight Factor include: protractors developed by Bryan (1985) for determining the sky components for clear sky conditions, dot charts developed by Pleijel (1954) and Turner (1971) to calculate SC and ERC for overcast sky, another set of dot charts developed by Moore (1985) to calculate SC and ERC for clear skies, and Graphic Daylighting Design Method (GDDM) developed by Millet et al. (1979) which shows the Daylight Factor contours within a room for overcast sky condition.

3) The flux transfer method (or finite surface method) was proposed as early as 1909 as a method of daylighting analysis (Jones 1909). However, it is primarily through the work by Higbie, with Levine (Higbie and Levine 1926) and Randall (Higbie and Randall 1927), in the United States and by Waldram (Waldram and Waldram 1923) in England that the approach has been developed into a major evaluation technique for studying daylight penetration and distribution in rooms and buildings. The flux transfer

method can use the CIE clear or overcast sky without the direct sun illuminating the interior of buildings. It also can work with either illuminance or luminance at the plane of the aperture in determining the illuminance at any point or on any surface of interest in the daylighted room. Work by Dilaura (Dilaura and Hauser 1978) expanded the method to include the direct component of available daylight in a space. In this method the openings and room surfaces are discretized into a number of small zones to more accurately determine the direct and interreflected components by calculating the luminous transfer exchange factors. Since this method requires repetitive calculations with all the combinations between the small zones, it is necessary to use computers.

Illuminance measurement inside scale models or full-scale mockups under real or artificial skies is a useful method not only for determination of sun penetration and illuminances, but also for visual assessments of lighting systems. Especially, photometric measurements in a fully detailed scale model can produce realistic illuminance data. This is because the technique is based on the physical phenomenon that light inside the scale model behaves in the same way as that inside the full-scale structure. For this reason, daylighting studies frequently focus on illuminance measurements in scale models when geometries of room and openings become complex.

Glare Index calculation is an essential approach to the assessment of human visual comfort. This approach requires tools to calculate or measure luminance levels in the visual field. Although glare is a subjective response and cannot be given an absolute value, the Glare Index which is a generalized form of glare quantifier (Hopkinson et al. 1966, Chapter 14) has been accepted by the International Illumination Commission (CIE).

Luminance Ratio (LR) calculation is an alternative approach to the assessment of the visual quality of a space. LR is the ratio of the average luminance value of a visual task area to that of surroundings. By comparing the calculated LR values with the recommended LR values, potentials in discomfort glare can be assessed. In this study, the LR values were determined by the video-based luminance mapping system and used to rank the combinations of canopy systems and atrium well configurations in terms of visual comfort.

2.1.4 Complementary Evaluation Tools

As briefly reviewed in the previous section, existing evaluation methods have limitations due to simplified assumptions behind the development of each method.

The lumen method is accurate, but it is limited to three or five points within a room. The daylight factor method can also be accurate and has been developed into an excellent manual design/evaluation technique. However, these two methods cannot account for direct sunlight in the space at a point or reflected off interior surfaces. These methods cannot account for reflected light in rooms or spaces adjacent to the room with the daylight apertures or for reflected daylight off sloped surfaces in the daylighted room. They also cannot analyze indirect daylighting systems.

The flux transfer method addresses some of these issues and is widely recognized as one of the most comprehensive daylighting evaluation methods. However, this method also has a limitation. The assumption behind this method is that the interior surfaces have a totally diffuse reflection characteristic. However, most atrium spaces have large areas of specular surfaces such as internal windows to admit daylight into adjacent rooms.

On the other hand, scale model photometry may record the illuminance and/or luminance levels at discrete points under the actual lighting conditions, but usually requires a much time to compile large quantities of performance data. In addition, this method cannot explain how daylight is admitted trough the openings and behaves within the room to illuminate a point.

In addition to conventional photometric measurements in scale models, the use of a suitable full-field camera technique permits the measurements of both geometric and photometric daylighting parameters. For this reason, several typical full-field luminance mapping systems which employed photographic or video-based digital image processing techniques were developed as the followings.

The typical full-field luminance mapping systems can be categorized by imaging media and image interpretation methods: 1) those using negative film to capture images and grid diagrams or microdensitometer to interpret the images and 2) those using video camera and digitizing board for image capture and digital image processing techniques for image analysis. Among the systems in the first category are Pleijel's globoscope and Hill's full-field camera, both of which are well explained by Hopkinson et al. (1966, pp. 366-373). Pleijel's globoscope records a stereographic image on negative film and Hill's full-field camera produces an equidistant projection image on a flat photographic plate. Both systems use grid diagrams which are overlaid over the captured images to determine sky factor or configuration factor by manually counting the number of dots (Globoscope) or sectors (Robin Hill camera). Another more advanced system in the first category is the orthographic projection camera developed by Nakamura and Oki (1975). This system (35 mm camera with 10 mm orthographic projection fisheye lens) also records an orthographic projection image on negative film. They used a microdensitometer to measure luminance and luminance distribution by scanning the developed negative film. Computerized luminance mapping systems in the second category are represented by SERI-LM2 (Weaver et al. 1986) developed at the National Renewable Energy Laboratory, Golden, Colorado (formerly Solar Energy Research Institute). This system employs an optical assembly which combines a 10 mm orthographic projection (OP) fisheye lens and a video camera connected to a microcomputer. The captured image is processed by a series of image processing programs to map luminances and to produce isoluminance contour plots.

2.2 OBJECTIVES AND CRITERIA OF ATRIUM DAYLIGHTING

2.2.1 Objectives of Atrium Daylighting

Daylight is distinguished as a light source by its unique, changing spectra and distributions. It can increase occupant satisfaction and conserve energy if considerations such as design for view, glare control, human factors and integration of building systems are properly addressed. In this respect, the atrium concept allows the effective utilization of natural light into the cores of buildings, which are usually the darkest spaces in conventional buildings. Thus, the atrium concept is particularly appropriate in commercial and institutional buildings where high illuminance levels are required during the daytime.

The primary goal in designing an atrium building is to enhance the indoor climate. Among the three major subjects to be considered in achieving the goal are people, indoor plants, and energy. Then, the objectives of atrium daylighting for each subject can be defined as shown in Figure 2.2.

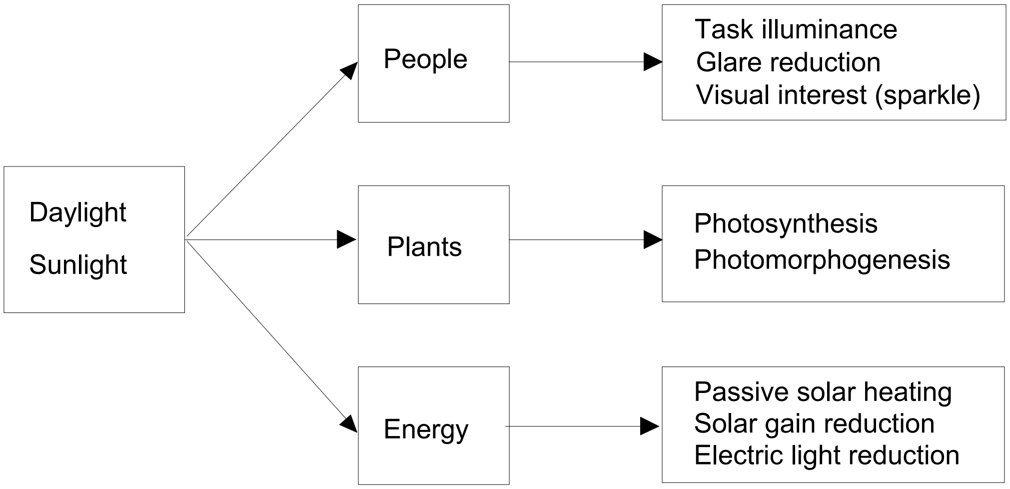


Figure 2.2 Objectives of Atrium Daylighting

As indicated in the figure, light entering the atrium must provide task lighting on the floor of the atrium space and secondary light to adjacent spaces. The recommended luminances and illuminances for various human visual tasks will be discussed in the next section.

Problems with daylight and/or sunlight glare are most often caused by sidelighting windows that allow direct view to the sky and/or sunlight. In this context, toplighting concepts of atria can be considered effective ways to control visual glare by separating the daylight apertures from the direct line of sight at the floor level. However, some cases, such as shallow atria with horizontal glazing or south-facing sawtooth canopies, may have glare potential if beam sunlight is admitted into the atrium space and occupants are allowed to view the sky through the fenestration. Reflected glare may occur when the admitted beam sunlight is reflected from specular surfaces such as interior windows toward the occupants. Discomfort glare may be caused by an extreme brightness contrast between the canopy opening and structure. The recommended maximum luminance ratio to create comfortable luminous environment will also be discussed in the next section.

Besides the glare control, another qualitative lighting objective in atria is to create sparkle which is visual interest of a sunlit outdoor scene. To achieve this esthetic objective, some direct sunlight should be allowed to hit the architectural surfaces to create sharp shadow lines (Lam 1986, p. 162). The atrium roof can make use of toplighting or clerestory sidelighting concepts to admit not only daylight, but also direct sunlight of controlled intensity and incident angle into the building.

The most stringent quantitative objective is to optimize growing conditions for trees and plants (Lam 1986, p. 162). The intensity of the light entering the atrium space mainly controls the growth of interior plants. Sufficient light to promote growth must reach not only the trees, but also the ground-cover planting below them. The way daylight enters the atrium will affect the growth pattern of plants, because the photomorphogenesis effect makes plants grow towards light. Therefore, toplight concepts are more desirable for plants as a direction-giver (Saxson 1987, p. 150).

Another important issue to be addressed in the earliest design stage is the thermal energy balance strategy of the atrium building with respect to site climate. The atrium affects the overall thermal energy balance of the building in many ways by means of its heat loss characteristics, its solar gain property, and its natural convection which causes the stack effect (Navvab and Selkowitz 1984). Three types of atria in connection with the thermal energy balance strategy include warming atrium to collect heat, cooling atrium to reject heat, and convertible atrium to collect and reject heat as required at different seasons (Saxon 1987, p. 84). As both the thermal and lighting conditions in the atrium building primarily depend upon the sun, daylighting should be designed to admit natural light in a way compatible with the thermal strategy.

2.2.2 Lighting Quantity Criteria

As discussed in the precious section, in general, successful daylighting in atria means adequate illuminance for visual task and interior plants, smooth luminance distribution to minimize glare problems, and visual interest created by sparkling sunlit patches, and proper control of incoming light to save energy.

In 1979 the Illuminating Engineering Society of North America established a procedure for selecting illuminances, based upon factors important to visual performance. The factors that a designer needs to assess in selecting target illuminance include (IESNA 1993, p. 459):

1) type of activity within a space,
2) characteristics of the visual task,
3) age of occupant,
4) importance of visual performance in terms of speed and accuracy,
5) and reflectance.

Then, consideration of these factors were systematized into the following four steps.

1) Define the visual task: The type of activity for which the illuminance is being selected is defined. At the same time, the plane in which the visual task will be performed is determined.

2) Select the illuminance category: Nine illuminance categories (designated A through I) were established by IESNA. Each of these nine categories is associated with a range of three target illuminances as shown in Table 2.1.

3) Determine the illuminance range: Every illuminance category has a corresponding range of three target illuminances as also shown in Table 2.1.

4) Establish target illuminance: Target illuminances are established differently for the established illuminance categories by considering room surface reflectance and occupant ages. Then the designer determines weighting factors and finally selects the target illuminance from the illuminance ranges by considering the sum of the weighting factors.

Further detailed description and examples can be found in IESNA Lighting Handbook (1993, pp. 459-478).

TABLE 2.1
Illuminance Categories and Illuminance Values
for Generic Types of Activities in Interiors
(IESNA 1993, p. 460)

Type of Activity	Illuminance Category	Ranges of Illuminances [lux]	Reference Work-Plane
Public spaces with dark surroundings	A	20-30-50	General lighting throughout spaces
Simple orientation for short temporary visits	B	50-75-100	
Working spaces where visual task are only occasionally performed	C	100-150-200	
Performance of visual tasks of high contrast or large size	D	200-300-500	Illuminance on task
Performance of visual tasks of medium contrast or small size	E	500-750-1000	
Performance of visual tasks of low contrast or very small size	F	1000-1500-2000	
Performance of visual tasks of low contrast and very small size over a prolonged period	G	2000-3000-5000	Illuminance on task, obtained by a combination of general and local supplementary lighting
Performance of very prolonged and exacting visual task	H	5000-7500-10000	
Performance of very special visual tasks of extremely low contrast and small size	I	10000-15000-20000	

As discussed in the previous section, the more important subject in atrium daylighting design is interior trees and plants. The energy needs of most plants are equivalent to at least the supply of 700 to 1000 lux for 12 hours per day (Saxson 1987, p. 150). The Illuminating Engineering Society of North America (IESNA 1981, pp. 19-32) recommended illuminance between 1000 lux and 2000 lux for at least 12 hours per day for interior trees and plants.

Since the human eye can adapt to a wide range of illuminances, the illuminance of 1000 lux for interior plants was selected as target illuminance in this study.

2.2.3 Lighting Quality Criteria

Quality of lighting is a term used to describe all of the factors in a luminous environment not directly connected with quantity of light. Excessive luminances and excessive Luminance Ratios in the visual field are commonly referred to as glare. When glare is caused by light sources in the field of vision, it is known as direct or discomfort glare. When glare is caused by reflection of a light source in a viewed surface, it is known as reflected glare or veiling reflection. As discussed earlier, both Glare Index and Luminance Ratio (LR) can be used to assess the quality of lighting. In this study, LR values were used to compare the effects of canopy systems on lighting quality. Recommendations for maximum luminance ratios to achieve a comfortable luminous environment are presented in Table 2.2.

TABLE 2.2

Recommended Maximum Luminance Ratios

(Stein and Reynolds 1992, p. 958)

1 to 1/3	Between task and adjacent surroundings
1 to 1/10	Between task and more remote darker surfaces
1 to 10	Between task and more remote lighter surfaces
20 to 1	Between luminaires (or fenestration) and surfaces adjacent to them
40 to 1	Anywhere within the normal field of view

Another qualifier of atrium daylighting is the geometric properties (locations and sizes) of sunlight patches which can add liveliness and visually interesting sparkles to the atrium space, if the admitted sunlight is not accompanied by excessive solar heating and direct or indirect glare. In this study, the Sunlight Patch Locations (SPL, elevation angles) and Sunlight Patch Sizes (SPS, Configuration Factors) on the atrium walls were determined from captured video images. Previous studies (Boubekri et al. 1991) found the size of sunlight patch area from 15 % to 25 % of total floor area as optimal for occupants' environmental satisfaction and 40 % as maximum. Even though the previous study dealt with a sidelighted room and sunlight patch areas on the room floor, the criterion might be applied to sunlight patches on the atrium wall areas.

2.3 CONCEPTS OF ATRIUM DAYLIGHTING SYSTEMS

In order to use daylight and sunlight effectively in atrium spaces, it is necessary to understand how the exterior daylight and sunlight conditions are given, how the light is admitted into the atrium, how it is distributed within the atrium space, and how it is finally reaches on atrium floor level and collected and delivered to the adjacent spaces. In conjunction with these lighting functions, four major daylighting systems can be listed as: 1) light source, 2) light admitting system, 3) light guiding system, and 4) light collecting system. The following statements discuss the functional roles and impacts of the major daylighting systems on the daylighting performances in atria and related architectural design elements.

1) Light source provides the atrium with ample natural light. It determines the primary quantity and quality of the light, which vary with weather condition, site location, time of the day, day of the year, and building orientation. The daily and seasonal movements of the sun with respect to a particular geographic location produce a predictable pattern of amount and direction of potentially available daylight and sunlight. Related design elements are daylight and sunlight.

2) Light admitting system admits daylight and/or sunlight into the atrium. The incident light is blocked, redirected and filtered by the structural system and glazing material of this system. It has major impact on light intensity and spatial distribution of the admitted light. The key design elements related to this system are geometric and photometric properties of canopy structure, glazing, and shading device.

3) Light guiding system distributes the admitted daylight and/or sunlight within the atrium space. The admitted natural light is reflected at the atrium surfaces before it illuminates a target point. Related design elements are geometry and surface treatment of the atrium well. The geometry of atrium well determines the sky area seen from a target point and the location of sunlit area. The surface reflectance and specularity, then, determine the intensity and directional characteristics of reflected light.

4) Light collecting system collects the admitted light and delivers it into the adjacent spaces. The light incident on the upper surface of the system is reflected onto the ceiling of the adjacent space and illuminates the working plane. Related design elements are geometry and surface treatment of an optional light shelf attached to the opening of adjacent spaces and/or interior balconies used for occupant circulation.

Figure 2.3 shows the factors in the lighting systems which control the daylighting performances in the atrium and adjacent spaces. Key design parameters associated with the lighting systems and design elements were identified from the previous studies (Boyer 1990; Boyer and Oh 1988; Gillette and Treado 1988; Kim and Boyer 1988; Navvab and Selkowitz 1984) and shown in Table 2.3.

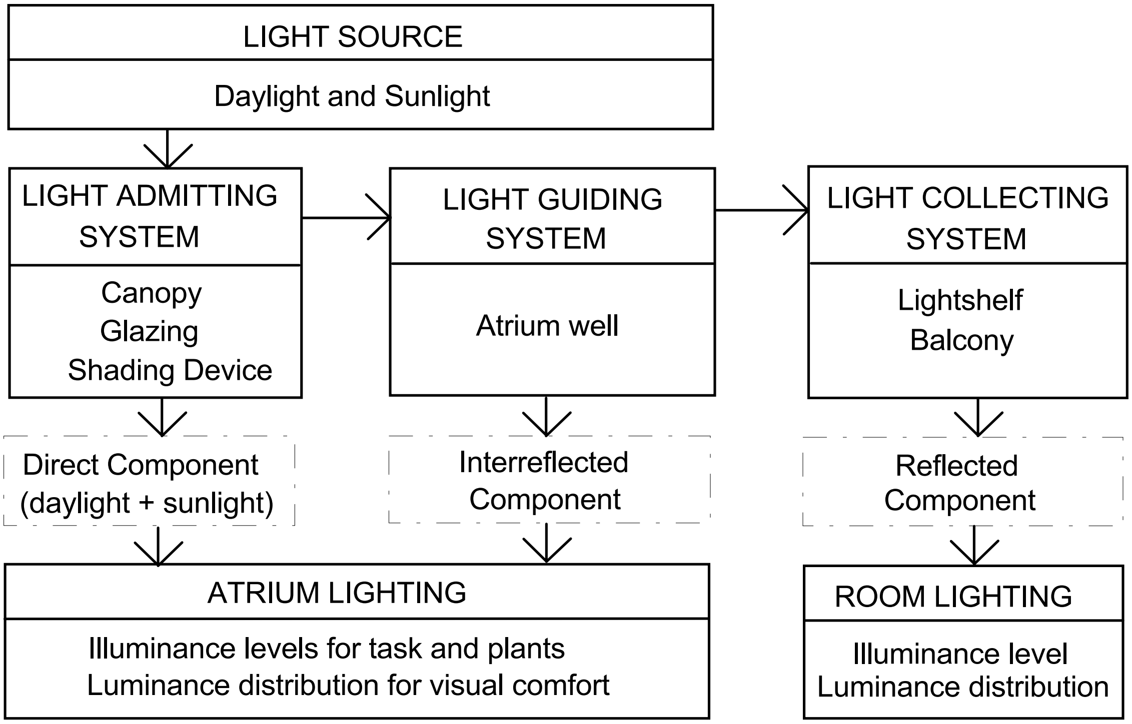


Figure 2.3 Factors Controlling Atrium Daylighting Performance

TABLE 2.3

Key Parameters in Atrium Daylighting Design

Daylighting Systems	Design Elements	Design Parameters
Light Source	Daylight availability	daylight illuminance, sunlight illuminance, sky luminance distribution
Light Admitting System	a) Canopy structure b) Glazing c) Shading device	a) structural system; area, orientation and tilt angle of opening b) transmittance, transparency c) size, orientation, tilt angle, reflectance, transmittance, and specularity
Light Guiding System	a) Well geometry b) Wall surface	a) plan aspect ratio, section aspect ratio, well index b) reflectance, specularity
Light Collecting System	a) Light shelf and balcony geometry b) Light shelf and balcony surface	a) location, area, tilt angle b) reflectance, specularity

2.4 TAXONOMY OF ATRIUM AND CANOPY SYSTEMS

2.4.1 Taxonomy of Atrium

The older forms of atrium buildings were court houses in Greece, North Africa and Middle East functioned as a grand entrance space, focal courtyard, and semi-public area. The courtyard was built without covered roof and worked well in the hot-dry climatic zones. In summer, the walls that surround the courtyard shade the adjacent spaces. The masonry walls around the courtyard are cooled by night air and absorb heat from adjacent spaces during the daytime. In winter, the masonry walls store the solar heat brought through the opening to the sky during the daytime and emits longwave radiation to the adjacent spaces at nighttime. Rapoport (1969) viewed this house form from the point of view of socio-cultural impacts. He maintained that the need for family privacy leaded to this form of house. Now, atrium is, by definition, a centroidal, interior, daylit space between occupied blocks of building (Bednar 1986, p. 63; Saxon 1987, p. 113). It provides horizontal and vertical circulations and improved thermal and visual environments.

Most atrium sections are uniform from top to bottom with visual relief created on the interior facade by projections and setbacks. But, the section can be progressively narrower from top to bottom and vice versa. Most atrium plans are square or rectangular. But, circular, triangular, or any irregular plans can be designed. In general, when the type of an atrium space is defined, the proportions in plan and section are considered. The plan proportion is termed Plan Aspect Ratio (PAR = width / length), while the section proportion is termed Section Aspect Ratio (SAR = height / width). An atrium with a PAR of less than 0.4 can be considered linear. An atrium with a PAR between 0.4 and 0.9 can be considered rectangular, and between 0.9 and 1 square. An atrium with a SAR of less than 1.0 can be considered shallow, whereas an SAR above 2.0 yields a tall and/or narrow proportion. The large majority of SAR figures are between 1.0 and 2.0, a reasonable proportion for effective daylight penetration (Bednar 1986, p. 66). Various atrium types can be categorized by the geometric configurations as follows:

1) Four-sided atrium: This is the most common atrium type surrounded by occupied zones on all sides (Figure 2.4.a). The only source of daylight and view is the skylight. The representative buildings include Philadelphia Stock Exchange Building in Philadelphia, Pennsylvania; Erie County Community College in Buffalo, New York;

Hyatt Regency hotel in San Francisco, California; and World Trade Center in Dallas, Texas.

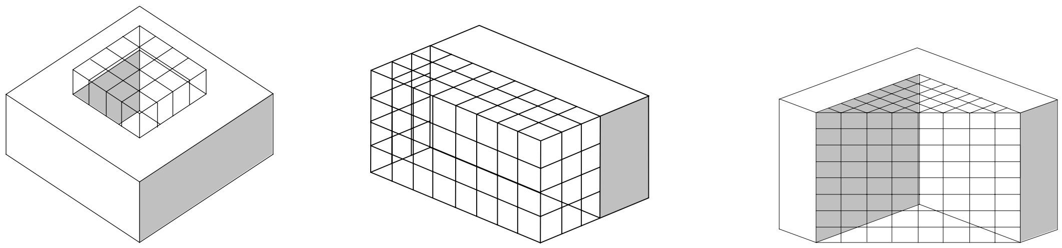
2) One-, two-, and three-sided atria: This is atrium subtypes blocked by occupied zones on one (Figure 2.4.b), two (Figure 2.4.c), or three (Figure 2.4.d) sides, respectively. The roof may or may not be glazed. The glazed sides are very sensitive to manipulation of view, daylight/sunlight and solar radiation. The representative buildings include Ford Foundation in New York, New York; Hercules Plaza in Wilmington, Delaware; One West Loop Plaza in Houston, Texas; John F. Kennedy Library in Boston, Massachusetts; Hyatt Regency hotels in Houston, Dallas and San Antonio, all in Texas.

3) Linear atrium: This is an atrium subtype with occupied zones on opposite sides of the atrium and circulation connections across (Figure 2.4.e). It usually has an elongated rectangle in plan. The ends may be glazed or defined by building elements. Skylight or roof clerestory is the major source of daylight and view. The representative buildings are Tennessee Valley Authority - Chattanooga Office Complex, Chattanooga, Tennessee; Dallas City Hall in Dallas, Texas; Galleria II shopping mall in Houston, Texas.

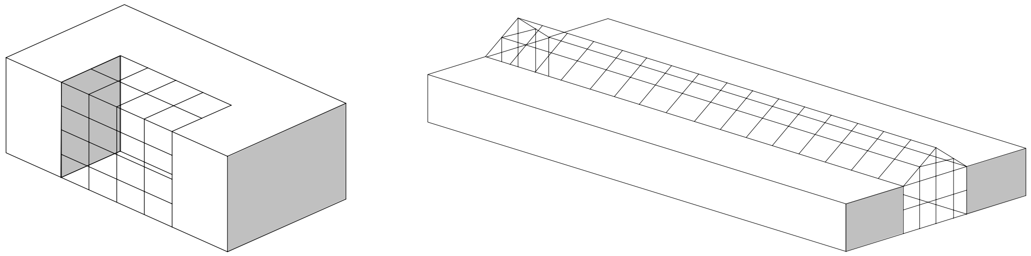
4) Multiple lateral atrium: This subtype contains more than one atrium disposed laterally within a building (Figure 2.4.f). Each one is usually a complete atrium type in its form. Two atria with circulation elements between them is common. The representative buildings include New Thomas Jefferson University Hospital in Philadelphia, Pennsylvania; National Gallery of Art East Building in Washington, D.C.; Lowes Anatole Hotel in Dallas, Texas; and Antoine Graves Homes in Atlanta, Georgia.

5) Partial atrium: This type of atrium spatially organizes only a part of a building. It can be a tower base form with the atrium in the base (Figure 2.4.g); or, it can be a vertically stacked form with multiple atria in a high-rise building (Figure 2.4.h), each one relating only a set number of floors. Representative buildings include Chicago Board of Trade Addition in Chicago, Illinois; SOM Office Building in Chicago, Illinois.

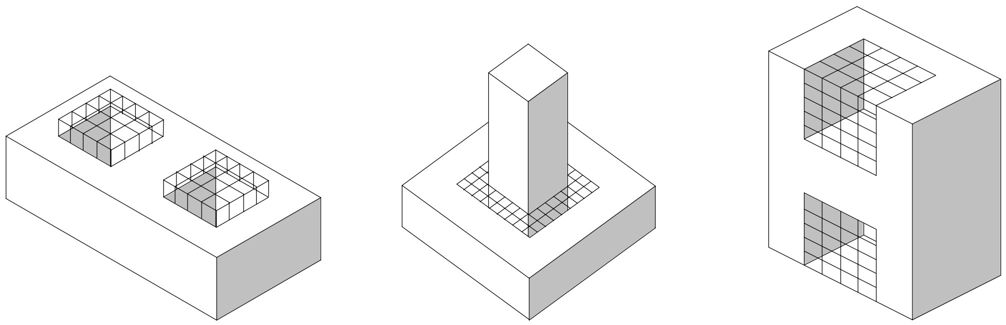
In this study, the four-sided atrium with square plan was selected as the target atrium type.



a. Four-Sided b. One-Sided c. Two-Sided



d. Three-Sided e. Linear



f. Multiple Lateral g. Tower-Based Partial h. Vertically Stacked Partial

Figure 2.4 Generic Atrium Well Types

2.4.2 Taxonomy of Canopy System

Atrium canopy systems are integrated assemblies of structure, metal frames, and glazing materials. The canopy systems can be categorized into horizontal, vertical, and sloped systems by considering the slope of the atrium opening to be covered. The three basic types can be further distinguished by the overall canopy forms which have specific geometrical and structural characteristics. Such form types are described as follows and illustrated in Figure 2.5.

1) Multiple linear canopy (Figure 2.5.a and Figure 2.5.b): This type of canopy system is characterized by the multiple units of either sawtoothed, vaulted, or ridged canopy system supported by an independent, long-span structural system.

2) Pyramid skylight (Figure 2.5.c): This type consists of plane glazed surfaces triangular in shape and bounded on each side by a sloping ridge forming the intersection of the adjacent planes and culminating in a common vertex. Pyramidal forms are adjustable to different spans and geometries. Glazing is integrated with the structural system.

3) Barrel vault skylight (Figure 2.5.d): This type has round glazing area treated by either a smoothly curved plastic material or flat plane glass segments. It is a usual practice to integrate the glazing material with the repetitive metal frame which can stand without support from supplementary truss structure below.

4) Multiple unit skylight (Figure 2.5.e): This type is characterized by an independent long-span, two-way structural system. The openings between the structural members can be covered by either pyramidal or domed, of either plastic or glass materials.

5) Ridge skylight (Figure 2.5.f): This type has a gable form that can span wide distances with integrated trusses. The glazing area can be treated by either flat plane plastic or glass integrated with the metal frame.

6) Glazed wall (Figure 2.5.g): This type is used to cover the vertical opening of 1, 2, or 3-sided atrium. The glazing panes, which are usually flat planes, are supported by a structural diaphragm braced against the building. Shading device is required for non-north-facing openings.

7) Sloped systems: This type is considered a sloping skylight (Figure 2.5.h) when it spans an opening, whereas it is considered a sloping wall (Figure 2.5.i) when it is braced against other building elements. It is usually treated with integrated structure and glazing.

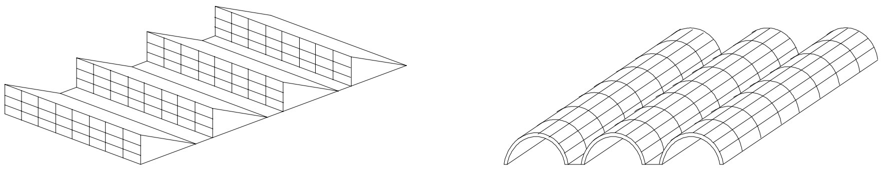
In designing a canopy system, a basic form type must be selected before a structural system can be designed. Structural supports are usually more complex for horizontal and sloped systems than they are of vertical systems. The degree of complexity depends upon the opening spans to be covered and the loads to be carried (snow, wind, mechanical equipment, walkways, washing equipment, and lights). In most atria, steel is usually used for the structural supports because of its strength, ease of fabrication, and visual lightness. The steel is often painted white to reflect light and to soften its appearance against the sky.

For a horizontal atrium opening, many different types of the canopy systems can be selected. A barrel vault skylight and a ridge skylight provide simple weathering and drainage. A multiple linear skylight system with sawtooth pattern is useful both in admitting light selectively and in allowing weather-tight louvers for ventilation. A more common current approach is to use the multiple unit skylights with pyramidal or domed roof-lights supported by two-way of beams. Another common form is steel space-frames with pyramidal skylight modules.

For a vertical atrium opening, a vertical glazed wall with two different types of structural systems can be used. The first type extends the frame of the occupied building across the atrium wall. An advantage of this approach is that the consistency of the building facade can be achieved, while the space inside the building can be freely arranged and an irregular atrium volume can be designed within a regular massing. The second type adopts a separate curtain-wall approach which uses a trussed metal frame structure.

For a sloping atrium opening, similar approaches can be used as for vertical glazing. Many designers use rolled steel to avoid the visual complexity involved in trusses (Saxon 1987, p. 115). Arch forms are attractive shapes, because they have similar shape and efficiency to those of barrel vault skylight systems. Another common type is space-frame which creates regular pattern of shadows and silhouettes rather than a clear view through.

In this study, among the enlisted canopy types, sawtooth, single-unit barrel vault, single-unit pyramid, and multiple-unit skylights with waffle structure were dealt with. In addition, a flat horizontal skylight with space-frame structure was included. More detailed geometric and photometric properties of the canopy systems will be discussed in Chapter 4.

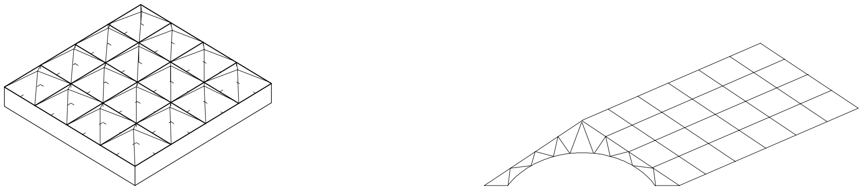


a. Multiple Linear Canopy
(Sawtooth)

b. Multiple Linear Skylight
(Barrel Vault)

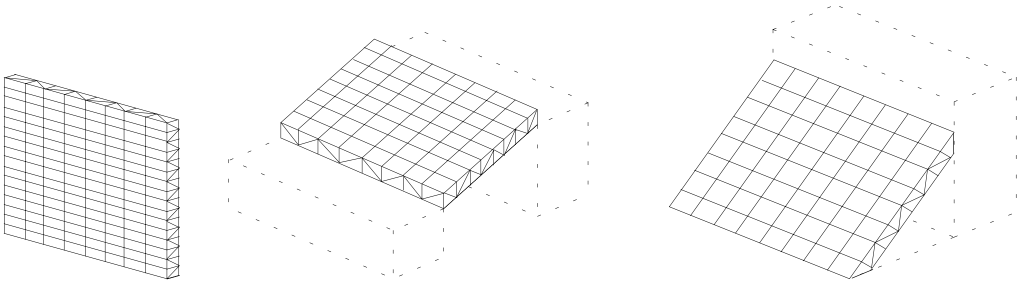
c. Pyramid Skylight

d. Barrel Vault Skylight



e. Multiple Unit Skylight
(Waffle)

f. Ridge Skylight



g. Glazed Wall

h. Sloping Skylight

i. Sloping Wall

Figure 2.5 Generic Canopy Configuration Types

2.4.3 Glazing Materials

Choice of glazing material to cover the opening of a canopy system has greatly expanded in recent years. However, base materials for a variety of atrium glazing products are glass and plastic with different properties of strength, transmittance, and thermal resistance.

When selecting a glazing material for a large-scale canopy system, a great concern must be given to safety for the occupants below when the glazing breaks and/or falls. In the past, wired glass was used, but it is not as resistant to breakage or fire as annealed, heat-strengthened, or tempered glass. The safest skylight is laminated glass formed by two layers of tempered, annealed, or heat-strengthened glass bonded to a polyvinyl butyral interlayer which keeps the pieces from falling when broken. Acrylic or polycarbonate plastic has great resistance to breakage but the disadvantage of combustibility and deformation under heat. If a sprinkler system is provided, this may not be a problem. Acrylic has fifteen to thirty times the impact strength of normal glass, and polycarbonate is even stronger. However, plastic materials have disadvantage of discoloration with aging, abrasion, and reaction to certain chemical compounds. The most notable advantages of plastics are light weight and can be easily formed into bubbles, pyramids or curves.

The glazing materials can be characterized by the following properties: transmittance, absorption, reflection, diffusion, refraction, cost, thermal properties and appearance. The following statements discuss photometric characteristics of typical glazing materials and approximate light transmittance data for several materials are provided in Table 2.4. It should be noted that the transmittance of materials is a function of the incident angle of the light.

1) High-transmittance materials: These transmit light without greatly changing its direction or color. These materials are image preserving. Common types are sheet, polished plate, and float and molded glass as well as some rigid plastic materials and formed panels.

2) Low-transmittance materials: Low-transmittance glasses and plastics offer a measure of reduction in the intensity of transmitted light. Glazing materials with transmittance below 0.5 can give a gloomy appearance to outdoor views.

3) Diffusing materials: The amount of diffusion in glazing materials varies over a wide range, depending upon the material and its surface treatment. Generally,

transmittance and luminance decrease as diffusion increases. The luminance of highly diffusing materials is nearly constant from all viewing angles. Diffusing materials include translucent and surface-coated or patterned glass, plastics, translucent sandwich panels with fiberglass reinforced polymer faces.

4) High-reflectance, Low-transmittance materials: Reflective glasses and plastics provide luminance control by having high exterior reflectances. These materials perform as one-way mirrors, depending upon the ratio of indoor to outdoor illuminance.

5) Directional transmitting materials: These glazing materials include glasses and plastics with prismatic surfaces that are used to obtain the desired directional control of light and luminance. They are used in either horizontal or vertical panels.

6) Specularly selective transmitting materials: These include the various heat-absorbing and reflecting materials that are designed to pass most visible spectra, but absorb or reflect a portion of the infrared radiation, which would otherwise contribute to cooling loads. Absorbed heat is reradiated indoors and outdoors in approximately equal proportions.

TABLE 2.4

Approximate Light Transmittance Data of Glass and Plastic Materials

(IESNA 1993, p. 371)

Material	Transmittance [%]
Polished Plate / Float Glass	80 - 90
Sheet Glass	85 - 91
Heat Absorbing Plate Glass	70 - 80
Heat Absorbing Sheet Glass	70 - 85
Tinted Polished Plate	40 - 50
Figure Glass	70 - 90
Corrugated Glass	80 - 85
Glass Block	60 - 80
Clear Plastic Sheet	80 - 92
Tinted Plastic Sheet	42 - 92
Colorless Patterned Plastic	80 - 90
White Translucent Plastic	10 - 80
Glass Fiber Reinforced Plastic	5 - 80
Translucent Sandwich Panels	2 - 67
Double Glazed - 2 Lights Clear Glass	77
Tinted Plus Clear	37 - 45
Reflective Glass	5 - 60

Note: For glazing materials used in this study see Table 4.7.