4 LIGHTING DESIGN CONSIDERATIONS

This chapter, Lighting Design Considerations, and Chapter 5, Applications, discuss the methods and tools needed to produce integrated lighting applications that use advanced sources, luminaires and controls. This chapter reviews the lighting design process, including issues of lighting quality as well as lighting levels (quantity), and presents a series of nineteen guidelines for designing advanced lighting systems. This chapter also reviews advanced tools and computer programs to assist designers. Chapter 5 provides examples of advanced lighting applications for private offices, open offices, executive offices, classrooms, several types of retail spaces, and an outdoor application. These examples demonstrate how advanced technologies can be integrated (with daylighting in some cases) to produce very efficient and quality applications.

4.1 The Lighting Design (and Redesign) Process

"Design" is the science and art of making things useful to humankind, and lighting design is the application of lighting—including daylight when it is specifically used as source of lighting—to human spaces. Like architecture, engineering and other design professions, lighting design relies on a combination of specific scientific principles, established standards and conventions, and a number of aesthetic, cultural and human factors applied in an artful manner.

In recent years, the field of lighting has been struggling with two prominent forces, *energy efficiency* and *lighting quality*. Just as the profession of lighting design began to emerge, in which the quality of lighting is held in high esteem, energy efficiency also became a concern in the design of buildings. Lighting designers initially faced the choice between attractive, well-lighted spaces and spaces that used a minimum of energy. The last quarter century has seen at least some resolution of this dilemma: dramatic improvements in lighting equipment technology, and maturation of the lighting design profession, each permitting better lighting designs that use less energy than previous practices.

The pursuit of more energy-efficient lighting dominated the lighting field from 1975–1990, creating awkward dilemmas for lighting designers. Fueled by utility rebates and commodity pricing, new lighting systems were designed to use minimum power. Existing lighting systems were "retrofitted" to save energy. Lighting installations of inferior quality were the rule, rather than the exception.

Many see the1990s as a period in which the quality of lighting made a significant comeback. This was most evident as the new century approached in a new process for lighting design put forth by the Illuminating Engineering Society of North America (IESNA), the major technical association for lighting in North America. IESNA's recommended procedures for lighting design are described in section **3.3.4**.

The *Advanced Lighting Guidelines'* mission is to describe lighting technology and techniques in order to encourage advanced designs that provide quality lighting with minimum environmental impact. While the IESNA procedure should generally lead to good quality lighting, it doesn't give energy efficiency and environmental impact a priority. The advanced strategies described in this chapter enhance the IESNA procedure so that it may be used to produce designs that minimize energy use and improve the sustainability of projects.

4.2 Lighting Quantity

4.2.1 Setting Criterion Illumination Levels

The IESNA design procedure described in section **3.3.4** is the most widely used and accepted method for determining lighting levels for applications. The method consists of the following:

- Choose an acceptable illuminance according to categories A through G, with A being the lowest and G being the highest. For instance, the illuminance associated with Category D is 30 footcandles.

- Adjust the actual design level according to tasks and human factors. The designer is strongly encouraged to make informed adjustments to the criterion light level. For instance, in Category D, one might choose 20 footcandles for schoolchildren and 50 footcandles for seniors. To make the correct adjustment, the designer should be aware of the occupant's age, the specific tasks to be performed in the space, and the extent to which daylight affects the space. The presence of other tasks, like a computer or adjacent workstation, also needs to be taken into account.

The determination of lighting level is critical. Choose levels too low and the success of the project may be at stake; choose too high, and too much money is spent and energy is used needlessly.

IESNA task illumination recommendations are for the design of lighting under ordinary circumstances, including the assumption that the viewer is "day adapted." The human eye is highly adaptive, so the precise illumination level is not critical. Increasing the illumination level by 100%, either by design or by the addition of daylight, will generally make a small improvement in visual performance. Decreasing the illumination levels will generally cause a reduction in visual performance, but dropping the light level in half will usually not make a big difference as long as the light quality remains good. Small differences (less than 25% difference) in light levels are more or less meaningless with respect to visual performance.

Other factors to take into account include:

- The adaptation level of the viewer. When "night adapted," a person typically will need lower overall light levels than when "day adapted." (See section 2.1.7 for more about day and night adaptation.)
- The viewer's age. The natural aging of the human eye reduces visual acuity and increases sensitivity to glare. Higher light levels greatly help visual acuity, as long as glare is controlled. Choosing light levels at—or sometimes above—the top level in the range is generally called for in designing facilities for seniors. (For more about the aging eye, refer to section 2.1.6.)
- The visual size of the task. Very small tasks, measured in visual angle according to the procedure, may require higher light levels; very large tasks may require lower light levels. (See section 2.1.3 for more about visual size.)
- The interaction of tasks. The specific needs of adjacent tasks may appear to be in conflict, but recognizing that light level recommendations are not absolute can make resolving these issues easier. For instance, many jobs involve computers (Category C) and paper tasks (Category D or E). Designers may use a task-ambient lighting design (see section 4.3.1) or dimming controls (section 8.2) to achieve an acceptable compromise.

Example: Choosing the Lighting Level for a Cafeteria

Consider the lighting for a cafeteria (Category C, 10 footcandles). In a college, the designer might choose Category D (30 footcandles) instead because the cafeteria also serves as a study hall. In a middle school, it would be reasonable to choose 20 footcandles of task illumination because of (generally) youthful eyes. However, in a retirement facility, the designer might choose a light level as high as 50 footcandles after reviewing recommendations for this specific type of facility, especially IESNA RP-28.

Advanced Guideline – Dynamic Light Level Selection

... design lighting systems that are based on a dynamic, rather than a static, model of vision and natural light

Ultimately, the designer chooses an appropriate static light level that does address the potential for varying the light level based on user preference, time of day, weather conditions and other factors. If electric light levels can be varied, there is a significant potential for energy savings as well as other beneficial effects. As an advanced guideline, design lighting systems that are based on a dynamic, rather than static, model of vision and natural light. With the ability to modulate light levels, appropriate electric light energy is used at all times, maintaining a minimum necessary light level and therefore, a minimum necessary lighting energy consumption.

For example, imagine a private office with a south-facing window. Most days, the amount of natural light exceeds the 30 footcandles of task light recommended by IESNA for office paperwork. The office may actually average 100 to 300 footcandles, and electric light may be unnecessary. However, on particularly dark cloudy days and at sunrise and sunset on clear days, it's necessary to maintain these task light levels with electric lighting. Later in the evening, a lower task light level may be acceptable, and by the time people arrive to clean the office, task light probably isn't needed, and the ambient light level may be reduced to 3 footcandles. And most importantly, when the space is vacant, the lights should be turned off. See Chapter 5 for examples of lighting designs in private offices with windows.

Example: A Dynamic Criterion for a School Cafeteria

In the example above (Choosing the Light Level for a Cafeteria), a criterion of 20 footcandles was selected for a school cafeteria.

Taking into account the varying needs of the cafeteria, set the following light levels using dimming and dynamic balancing:

Any occupied use between sunset and sunrise, 3 footcandles (basic orientation) with manual override to 20 footcandles

Between sunrise and sunset, 20 footcandles with electric light dimming and shutoff in daylit zones.

Increased illumination for serving and bussing area during meals, 30 footcandles.

4.2.2 Illumination Levels Based on Light Source Spectrum

Illumination recommendations based on lumens and footcandles don't completely account for certain effects of the spectrum of light sources. There are a number of conditions under which details of the light source spectrum need to be considered to better reflect human vision or perception. This has surfaced as two major concerns, one regarding interior lighting at typical indoor light levels, and the other for low levels of exterior electric lighting at night. They are discussed below.

Advanced Guideline – Interior Lighting Spectrum

The first concern centers on the optics of human vision. It has been demonstrated (Berman 1992) that the diameter of the eye's pupil is set by the response of the rods even at typical interior light levels, rather than the by the cones that are responsible for focal (or foveal) vision. Rod response is generally associated with scotopic vision (night vision), but at the modest levels of light used for interior illumination, it appears that rods remain active and control the size of the optical aperture or pupil. Pupil size affects both visual acuity and depth of focus.

. . . S/P ratios can be used to determine the relative sense of brightness from different sources . . .

The pupil of the eye becomes relatively smaller in response to light sources that are enhanced in bluish-green light, the portion of the spectrum where rods are most responsive. Because the pupil size effect relies on rod response it is referred to as a scotopic effect. A smaller pupil allows vision to have a larger range of focal distance. The increased range of focus also means that less accommodative effort of the eye is needed to bring close objects, such as reading or handwork, into focus.

Visual acuity is improved with a smaller pupil. Although the smaller pupil allows less light into the eye, at typical interior light levels it blocks the aberrant light rays passing through the outer edge of the lens where optical quality is poorer.

Berman's research makes use of factors called Scotopic/Photopic ratios, or S/P ratios. They are independent of light level and express a property of the light or lamp spectrum and express the extent to which a lamp favors scotopic effects. Sources with larger S/P ratios (such as high color temperature fluorescent lamps) can be expected to permit a greater depth of field and better acuity than those with smaller S/P ratios.

Table 4-1 – Scotopic/Photopic ratios for Indoor Lighting Applications
Shows many common light sources. Source: Berman 1992.

Light Source	Scotopic/Photopic Ratio (S/P ratio)	Light Source	Scotopic/Photopic Ratio (S/P ratio)
Low-pressure Sodium	0.20	4100°K Fluorescent (RE741)	1.54
High-pressure Sodium (35W)	0.40	4100°K Fluorescent (RE841)	1.62
High-pressure Sodium (50W)	0.62	5000°K Fluorescent (RE850)	1.96
Clear Mercury Vapor	0.80	Metal Halide (Thallium/Dysprosium/Holmium)	2.10
Warm White Fluorescent	1.00	6500°K Fluorescent (RE865)	2.14
White High-pressure Sodium (50W)	1.14	Daylight Fluorescent	2.22
Incandescent (2850° K)	1.41	Sun (CIE D55 Illuminant)	2.28
Cool White Fluorescent	1.46	Early Sulfur lamp	2.32
Metal Halide (Sodium/Scandium)	1.49	Sun + Sky (CIE D65 Illuminant)	2.47
Quartz Halogen (~3200° K)	1.50	7500°K Fluorescent lamp	2.47

In addition, the apparent brightness of a scene illuminated by white light is influenced by color temperature. Compared to low color temperature sources, high color temperature sources produce spaces that seem brighter. In general, a light source with a high S/P ratio will likely appear brighter for a given foot-candle level than one with a lower level. The S/P ratio of sodium/scandium metal halide, for example, is 1.49. Compared to high-pressure sodium (S/P ratio 0.62), the metal halide lamp could be expected to appear brighter. However, remember that brightness is not a measure of visual acuity or performance, and the effect of a "brighter" source may be undesirable for many reasons.

The primary potential benefit of this work is that we might be able to use spectrally optimized light sources that permit lower energy consumption levels. Because designing interior lighting systems with a low power density generally means using lower general and ambient light levels, use of sources with higher S/P ratio might provide both greater sense of brightness and in some cases better visual acuity and depth of field. However, while there is a growing consensus that scotopic effects are important, scientists and researchers still disagree on the extent to which S/P ratios or other factors might be applied to current standards for proper lighting.

As an advanced guideline, S/P ratios can be used to determine the relative sense of brightness from different sources, and in some cases, to predict acuity and depth of field benefits. But using S/P ratios to justify dramatic differences from conventional practices, such as using them to allow significantly lower light levels than IES recommendations, is currently **not** recommended. From the standpoint of visual acuity and performance, the current system of lumens and footcandles still serves to properly set light levels, and S/P ratios can**not** be used to change design practice in this regard.

Advanced Guideline – Non-Central Vision and Brightness Perception for Large Visual Fields

Consider using a lumen correction factor between 1.2 and 1.4 for modern mercury-arc white light sources . . . as compared to high-pressure sodium

The other primary concern centers on outdoor electric lighting at night. Traditionally, lumens, footcandles and other photopic quantities have been applied to nighttime exterior lighting conditions. This is correct only if the visual task is viewed directly forward. When the visual task is non-central or the perceived brightness of a large field of view is experienced (10 degrees or greater), then both rod and cone responses contribute to vision. Rod related vision (scotopic vision) is significantly more sensitive to blue-green light (507 nm) than yellow-green light (555 nm), the peak sensitivity of day vision (photopic vision). This combination of photopic and scotopic vision, called Mesopic vision, occurs at light levels typically found in outdoor lighting situations such as streets and roadways, parking lots, walkways, and sidewalks. Since the lumen is based on the spectrum of photopic vision, it is now recognized that without a spectral correction factor, lumens and all related factors (footcandles, lux, etc.) at light levels below 1.0 footcandle are not likely to provide a full representation of human perception.

Additionally, it is widely agreed that human peripheral vision at Mesopic light levels has both rod and cone responses. Studies at a luminance level of 0.1 cd/m² (Rea et al. 1996) have shown that the off-axis reaction time to peripheral movement under metal halide light, which has substantial blue content, is 50% faster than under high-pressure sodium light of the same footcandle level. This research, while still controversial, suggests that scotopically efficient sources may be preferred for many outdoor lighting situations, especially where threats from the side are an issue, such as personal security, crossing traffic, or animals crossing a highway at night.

Because of the renewed concern over the different spectral responses of rods and cones, it appears very important to consider the spectrum of the light source in outdoor lighting. As an advanced guideline, when off-axis detection and/or large field brightness perception is the primary concern, consider using a lumen correction factor varying between 1.2 and 1.4 for modern mercury-arc white light sources (metal halide, fluorescent, compact fluorescent, or induction lamps) as compared to high-pressure sodium. In other words, when applied at very low light levels a 10,000-lumen metal halide lamp appears to produce the same effective non-central exterior visibility as a 12,000–14,000-lumen high-pressure sodium lamp.

Researchers and scientists don't yet agree on how to apply spectral factors to outdoor lighting standards. For this reason, it is **not** recommended that lighting level standards or lighting calculations be changed to account for the affects of different light sources. However, if research in spectral response continues on its present course, the impact may be significant. Most importantly, sodium-based light sources, although more "energy efficient" as measured in lumens per watt, might no longer be considered the most "visually" efficient for outdoor lighting. This in turn might result in new lighting systems and light sources for the majority of parking lot, parking garage, industrial, warehousing and roadway applications where high-pressure sodium has been the preferred source for the last few decades.

4.3 Lighting Quality

Lighting profoundly affects many human reactions to the environment. These human reactions range from the obvious, such as the dramatic beauty of an illuminated landmark or the emotional response of a candlelight dinner, to subtle impacts on worker productivity in offices and sales in retail stores. (This range of human reaction is discussed in more detail in chapter 2.) The profession of lighting design, which grew from a mixture of theatrical and architectural methods, is largely valued for its ability to intuitively and artfully provide high quality lighting, at least for projects in which appearance and "mood" are very important.

An important recent trend in lighting philosophy and research is the concept that lighting quality often plays an equal, if not dominant role, to lighting quantity. However, lighting quality is highly elusive. Despite numerous attempts to create metrics of lighting quality, lighting quality remains a combination of measurable physical quantities, placed together in a particular order that is highly dependent on numerous factors involving space, finishes and activities. The current challenge for researchers is to provide more objective metrics of lighting quality to make it possible for more successful projects of all types.

The design procedure recommended in the ninth edition of the *IESNA Lighting Handbook* is based substantially on lighting quality. It embodies the current beliefs and findings about lighting quality in a manner that varies according to building type. Following the IESNA procedure is highly recommended, for at a minimum it helps the designer place the proper priorities on lighting quality as a function of space. But, unfortunately, following the procedure perfectly still cannot guarantee good lighting.

This is the dilemma facing every designer. One can design good quality lighting and yet not achieve "good lighting." Boyce (1996) helps us understand the difference by describing lighting in three quality categories:

- Bad lighting, where the lighting system suffers from a quality defect

- Indifferent lighting, where the lighting system has no quality defects
- Good lighting, where the lighting system is technically correct and excites the spirit of the viewer

A space with "indifferent" lighting quality should be the minimum design criterion for all lighting installations because any of the causes of "bad" lighting can affect worker performance.

This section provides numerous advanced lighting guidelines for the lighting design criteria identified in the *IESNA Lighting Handbook, 9th Edition.* These criteria have been organized in three general categories:

Light Distribution, including:

- Task and ambient lighting
- Daylighting integration
- Light pollution and light trespass

Space and Workplace Considerations, including:

- Flexibility
- Appearance of the space and luminaires
- Color appearance
- Luminance of room surfaces
- Flickering light
- Direct glare
- Reflective glare

Lighting on People and Objects, including:

- Modeling faces and objects
- Surface characteristics
- Points of interest
- Sparkle

4.3.1 Light Distribution

Task and Ambient Lighting Overview

The most common lighting design for commercial spaces has long been general lighting, in which a single type of luminaire is laid out in a more-or-less regular grid or pattern, producing relatively uniform illumination throughout the room. General lighting, however, was developed and promoted in the past based on an office norm of typing pools with no partitions in open office areas. With the advent of systems furniture in the 1970s, task lights became an integral part of the office workstation. By far the most common is a fluorescent luminaire attached to the bottom of a bookcase, binder bin or shelf. Many variations on the concept have evolved since the 1970s, including luminaires with variable screens designed to reduce veiling reflections. This type of task light remains a common part of office workstation design.

Task lighting systems independent from the space's general lighting systems are also found in other building types. For instance, the display lighting in retail stores is a form of task lighting. Similarly, task lights are used in industrial manufacturing and assembly, health care, residential lighting, and many other interior lighting applications.

However, task lights can't light the balance of the room, and thus some other type of lighting system is needed to produce the ambient illumination in the room. There are many options, including indirect luminaires mounted atop cabinetry or workstations, suspended luminaires, and recessed luminaires of the type usually used to produce general light (refer to chapter 7 for detailed information about luminaires). The key difference between general light and ambient light is that ambient light is designed to provide approximately 33%–67% of the illumination level that would have been produced by a general lighting system.

Task-ambient lighting strategies produce energy savings in three ways. First, locating the light source close to the task most efficiently produces the illumination levels needed for the task. Secondly, task illumination levels don't have to be maintained uniformly though out the space, so ambient levels can be lower. And finally, some occupants won't use their task lights, and empty offices or workstations with absent occupants don't have to be fully illuminated, saving even more energy.

Advanced Guideline – Ambient Requirements

Design ambient lighting to illuminate the majority of the space to about one-third the task illumination level

The intent of ambient lighting is to illuminate the majority of the space to about one-third the task illumination level. In reality, this means providing an ambient light level of around 20 footcandles (200 lux). This is enough illumination to permit casual task work in most environments, and relates well to most task types requiring 50–60 footcandles of task illumination.

In spaces that are subdivided by office partitions, store fixtures or other relatively tall elements, it's important to ensure that the effect of the partitions is taken into account. Typical office partitions, for example, employ finishes with around 40% reflectance and stand approximately 55 in. tall. Their net effect is to reduce the average ambient illumination level by about 30%–35%. Thus, an ambient lighting design producing about 30 footcandles average illumination in an empty room is often prudent.

Ambient light shadowing and uniformity are also issues. Using common troffers, a downlighting system producing 30 footcandles, average, will exhibit extremes of light and shadow when used in conjunction with office partitions. Some cubicles will receive over 50 footcandles from the overhead lighting system, and some will receive less than 5 footcandles. A negative result is very bright surfaces within the cubicle having a troffer overhead. An overly lighted office worker, especially one wearing light-colored clothing, can produce severe veiling reflections in the computer screen. Individually dimmable troffers can alleviate this condition. (For more about veiling reflections, see Advanced Guideline – Reflected Glare; for more about downlighting systems, see sections 0 through 7.5.6)

Indirect ambient lighting has often been advocated because of its good uniformity. An indirect lighting system producing an empty room level of 30 footcandles will tend to provide a comfortable light level for a range of workers and tasks. However, indirect lighting systems require higher ceilings than troffers, and suffer other drawbacks including possible additional cost, some lack of flexibility, and limited usability as task lighting. Section 7.5.7 covers indirect lighting in detail.

Other forms of ambient lighting shouldn't be overlooked. Wall-washing and wall slot "grazing" light produce ambient light indirectly from the wall surface (see section 7.5.2). In a gymnasium with a light maple floor, for example, downlight from the overhead lighting system will reflect upwards, illuminating the ceiling and upper walls.

And of course, natural light sources typically produce ambient light, at least for a portion of the space. Daylighting can be an excellent source of ambient light, especially if it's designed to provide balanced, uniform illumination throughout a space. For more about daylighting integration, see Daylighting below.

Advanced Guideline – Task Requirements

Task lighting requires concern for the direction and intensity of the light, as well as the amount of illumination (footcandles). This is because many tasks exhibit specular reflections that can affect contrast. For example, gloss coating on magazines and books or pencil on paper can cause sufficient reflection to make it impossible to distinguish dark areas on a white background. The reader must constantly move the task (or his or her head) to eliminate the veiling reflections.

… provide task lighting that is under the control of each worker

All tasks exhibit some degree of specularity (shininess), and as described in Advanced Guideline – Reflected Glare, the ability to see the task may be dramatically affected by the direction of the incident light. With highly specular tasks, or tasks viewed against a highly specular background material, the geometry of the source/task/eye relationship may be modified to improve visual performance. A typical situation is reading a glossy-page magazine under bright lights or outdoors. At certain angles, the reflected glare of the light source makes the print unreadable. Changing the location of the magazine, the viewing angle of the eye, or other physical movements solve the problem. As an advanced guideline, provide individual task lighting that is under the control of each worker, so that the individual worker can control both when it is used, and its placement, thus source/task/eye geometry.

As a general rule, light to the sides of tasks produces maximum visibility, while light to the front of the task produces maximum reflected glare. This basic axiom suggests orienting luminaires parallel to the direction of view, and to the sides of the viewer. But because not all lighting systems can be moved as desired and not all tasks can be placed where the lighting works best, compromises can be addressed through careful analysis.

As an additional advanced guideline, consider employing computer analysis that predicts visibility using metrics like equivalent spherical illumination (ESI) or relative visual performance (RVP) for fixed tasks under fixed illuminance sources. These metrics were developed specifically to analyze this situation, but unfortunately, are only useful for flat tasks in the horizontal plane, with a fixed viewing position and one of very few printed tasks. Nonetheless, for the design of certain work environments under fixed lighting conditions with demanding tasks, this remains a competent tool.

Some tasks, such as a lifeguard viewing swimmers in a pool, may suffer from serious problems of disability glare caused by windows or skylights at certain times of day. To assess this type of problem, consider using the rendering functions of lighting software tools like Lightscape and Radiance. These programs are capable of dramatically demonstrating reflected glare, and although potentially laborious to do, permit the comparison of alternative lighting systems (including windows and skylights). Computer analysis tools are discussed in section 4.4.

Task Lighting Example

In a private office, providing 50–60 footcandles of general light requires about 1.2 W/ft² of power using modern lighting technology. Providing ambient light of 20 footcandles requires only about 0.4 W/ft². If two task lights employing a 30-W compact fluorescent lamp (CFL) are used in a 100-ft² office, the total load will only be 1.0 W/ft², saving 0.2 W/ft². Moreover, the worker has additional control, and many will choose to turn off the overhead lights, especially if they also have a window, saving another 0.4 W/ft². Yet the worker retains task light levels where needed, sacrificing balanced luminance in favor of a more appealing atmosphere and customized personal space. See chapter 5 for additional task lighting examples.

Advanced Guideline – Light Distribution on Surfaces

Avoid distinct patterns, especially patterns that are irregular or harsh.

Keep most surfaces within a luminance ratio of 3:1

Lighting design ought to consider strategies for illuminating room surfaces, but in the majority of basic lighting installations, luminaires cause light to fall onto room surfaces somewhat randomly. For instance, direct luminaires with sharp cutoff, such as parabolic troffers and specular downlights, create distinctive “scallop” patterns on adjacent walls. Uplights can cast spotty pools of light onto ceilings, especially when luminaires are installed at the minimum suspension length. Track lights and wall-washers, when not uniformly installed, can create hot spots and unusual patterns. (For more about light distribution patterns for specific luminaires, see chapter 7.)

The IESNA procedure suggests that distinct patterns, especially patterns that are irregular or harsh, be avoided. Patterns in general are considered a problem, and keeping surfaces within a brightness ratio of 3:1 is suggested to minimize the impact of patterns of surface luminance.

As an advanced lighting guideline, designers should first review their designs for potential lighting patterns. Clues to potential problems include:

- Directional luminaires such as troffers and downlights that tend to create scallop patterns when near walls
- Uplights within 2 ft of the ceiling (unless specifically designed for a close-to-ceiling application)
- Poor balance of light (ceiling, wall or floor much brighter than each other)
- Walls and ceiling grids that aren’t aligned, with varying spacing of luminaires to walls
- Wall-washing and accent lighting that is improperly located (too close to wall)

Most modern computer programs can reveal potential pattern problems. Should any of these situations occur, study the entire surface of concern with a point-by-point or rendering program. Using aesthetic judgment, correct any problems before completing the design. This may be quite difficult in some cases, such as those using suspended indirect lighting and relatively low ceilings. Be prepared to change the lighting design quite a bit to eliminate this problem. Refer to section 4.4 for information about computer programs for lighting design.

In buildings employing daylighting, use daylight for wall-washing, not just general illumination. Daylight can provide one of the best sources of even, vertical surface illumination. The best way to achieve this is to make sure that any daylight aperture, whether window or skylight, is directly adjacent to a perpendicular surface, as described in Advanced Guideline – Direct Glare. Skylights or windows located next to walls provide a very gentle and attractive wash of light across a large surface, up to three to four times the dimension of the aperture. Roof monitors can provide very even illumination across a sloped ceiling, as can windows that abut the surface of a ceiling. Louvers, blinds or lightshelves can also be designed to help distribute daylight evenly across a surface. For more about daylighting, see Daylighting below, as well as section 7.4.

Advanced Guideline – Light Distribution on Task Place (Uniformity)

Design ambient lighting so it ranges within plus or minus one third of the target level …

Almost no lighting system provides completely uniform, even illumination. Early illumination engineering held out an ideal of perfectly uniform illumination in a space. There was little discussion or appreciation of the variability of lighting within space or time. The establishment of a target average illumination, such as 50 footcandles, was often misinterpreted to mean that a minimum of 50 footcandles would be provided over every square inch of a space.

In the IESNA procedure, the variation of illuminance levels is recognized. For instance, if the target illumination level is 30 footcandles, this is considered essentially met if 67% or more of the task locations have at least 25 footcandles. This will help designers and inspectors better understand the relatively small significance of exact footcandle values.

As an advanced guideline, it's an essential concept that illuminance levels will vary within a certain range. Overlighting tasks is one of the greatest wastes of lighting energy, and many designers have erroneously sought to achieve the IESNA's recommended illuminance level as the minimum, not the average. Consistent with the IESNA procedure, study all task illuminance values to ensure that they are at least 2/3 of the target value. But likewise, note task locations where illumination is more than 4/3 of the target value. If possible, change lighting until more than 90% of the task locations are within the range of the target, plus or minus one third (range 67%–133%).

As part of this process, it's important to identify the difference between "task" and "ambient" illumination (also see section on task and ambient lighting, above). Providing task level illumination should be limited to actual task locations, not averages throughout a room. The ambient light level should be at least 1/3 of the task level, up to the target illumination level defined for that space. By providing ambient light that is typically between 1/3 and 2/3 of the target level, and task light between 2/3 and 4/3 of the target level, a space generally is using the least amount of electric light energy and still meeting IESNA recommendations.

Example: Uniformity in Small Private Office

This example shows alternative means of providing adequate light levels in a small private office, assuming an office size of 12 ft x 9 ft (108 ft²), 80/50/20 reflectances, illumination from two 2 x 4 lens troffers. Based on a target task illumination of 50 footcandles:

Using the lumen method, a standard design in which each luminaire with two T-8 lamps and standard electronic ballasts produces 45 footcandles, the average throughout the room is 1.11 W/ft².

Using point calculations and maintaining at least 17 footcandles ambient lighting (50 x 1/3) and at least 33 footcandles task lighting (50 x 2/3), the recommended IESNA lighting levels can be provided using tuning (fixed dimming) or reduced ballast factor ballasts (60% ballast factor) at 0.76 W/ft², or 31% less than the standard solution.

Another means of providing adequate light levels would be to employ a single, ceiling mounted indirect luminaire with two T-8 lamps. It will produce a relatively uniform ambient illumination of 18–20 footcandles. Then a task light can be used to provide illumination on the task of 33–66 footcandles, which can be nicely done using a table lamp with a 30-W compact fluorescent source, such as a circline or 2D lamp. The power density of 0.83 W/ft² is still 25% less than the basic, common solution.

Refer to chapter 5 for more office lighting examples.

Daylighting Integration

Daylighting is the practice of using windows, skylights and other forms of fenestration to bring light into the interiors of buildings, using various mechanical means to control the amount of daylight, and employing complementary lighting electric lighting systems (including controls). It is perhaps the most demanding and challenging form of illumination, because of its variability and even more so, because of its impact on many aspects of a building. In traditional modern building design, various disciplines tend to work independently: architects design the mass and fenestration, structural engineers design the structure, mechanical engineers design HVAC and electrical engineers or lighting designers design the lighting. To design daylighting properly, integration of design and coordination among disciplines is essential.

A number of sections of the *Advanced Lighting Guidelines* provide an excellent resource for learning and applying daylighting. Chapter 5 provides example applications employing daylighting design. For details about daylight as a light source, see section 6.3; for daylight systems, see section 7.4. Daylighting controls are discussed extensively in section 8.4.

There are, however, some basic observations that can help lighting designers, architects and engineers begin to understand the potential impact of lighting, and by thinking about daylighting as part of the lighting system, they can encourage the use of daylight in basic building types where the benefits can be realized with relative ease.

The Principal Benefits of Daylight as a Light Source

Recent studies have provided at least some scientific evidence that people respond positively to daylight: they feel better, they work better, they learn better. But even if this were not true, daylight enjoys a significant advantage to electric light. The spectral content of natural light produces about 2.5 times as many lumens per Btu of cooling load. And if introduced through modern high-performance glazing with a low-emissivity ("low-e") coating, which removes some of the infrared energy, natural light can produce almost three times more illumination for the same cooling load of electric light. So if daylight is employed that produces light levels comparable or even higher than electric lighting, and electric lights are extinguished, daylit portions of a day-use building can be illuminated by saving almost all of the electric lighting energy and about half of the energy needed to cool the building load created by the lights. Moreover, the savings tend to coincide with energy peaks on hot summer days.

Daylighting also has many other advantages that augment the lighting quality in a space, as discussed in section 4.3 – Lighting Quality. These include being a flicker-free, scotopically rich, full-spectrum light source, with excellent three-dimensional modeling characteristics. The fact that daylight varies can be an advantage, for adaptation problems in interior spaces are often caused by a person's moving between indoors and outdoors, and the interior ambient level in a daylight space should vary directly with the exterior light levels.

Placing Daylight in Lighting Terms

Daylighting in architecture tends to be employed by architects in pursuit of the aesthetics and human factors of daylight. Just having daylight is not energy efficient, even if electric lights are extinguished (and too often they are not). Like bad electric lighting, daylighting can introduce numerous lighting and energy problems. Lighting designers should at least check proposed daylighting schemes to ensure that the architectural design does not create problems.

The primary energy issue is introducing a controlled amount of daylight such that the additional cooling load of the daylight is less than the cooling load of electric lighting that is turned off or dimmed during daylight periods. As a rule of thumb, the average daylight illumination level under peak conditions should not exceed 3 to 5 times the appropriate electric lighting level for the space. Excessive daylight increases the cooling load for the space and requires larger more expensive heating, ventilating and air-conditioning (HVAC) equipment. In other words, in a space where an appropriate electric light level is 50 footcandles, having average daylight levels in excess of 250 footcandles is probably inefficient design. The point at which daylighting becomes an energy problem varies considerably depending on climate, architecture, and other factors, but designers should be aware of the potential problem.

It's also important to consider the quality of daylighting. Like electric illumination, daylight can cause disability glare, discomfort glare, and other problems. For instance, a skylight should be shielded, just as if one were using a downlight. A standard, commercial skylight 4 ft x 8 ft introduces more average lumens than a 1000-W metal halide lamp. Think of the skylight well as the shielding of an electric luminaire. Likewise, employ a refracting lens or diffuser in the skylight to prevent hot spots of light in the room from direct sun. Remember that daylight control on the east, south and west exposures is critically important in controlling daily and seasonal light changes, especially the potential for glare. For more about shielding strategies for daylight systems, see section 7.4.

Advanced Guideline – Daylighting Integration and Control

Most buildings have some windows and other potential forms of daylighting. For example, classrooms can easily be designed to provide adequate daylight throughout most of the year. Winter mornings, rainy or snowy winter days, and evenings are the only time most electric lights should be needed in the average classroom (see examples in chapter 5). Similarly, most single-story commercial buildings could easily be daylit through the use of skylights. These daylight strategies can save substantial amounts of energy during peak daylight periods if the electric lights are reliably turned off. Occupants have been observed (Lowe, Rubinstein) to leave the electric lights off or choose lower output options if there is sufficient daylight in the space *when they enter* the room. However, for truly predictable energy savings from daylighting, the use of automatic photocontrols is needed. The presence of daylight does not deter the occupant of a space from turning on lights and defeating the system.

No energy codes in the United States currently require automatic daylighting controls, although buildings are required by most energy codes to provide separate switches for “daylit zones” to encourage occupants to harvest the savings. To date, photocontrols have not been considered sufficiently cost effective in all cases to make them a code requirement. However, the cost of dimming ballasts and photocontrols has been dropping rapidly in the past few years, making their use ever more attractive. Dimming ballasts offer the opportunity of other control strategies as well. There are a number of simple strategies that can be pursued now that will make daylight integration more widely successful. Future energy codes are expected to require dimming ballasts and automatic daylighting controls.

… for daylit workplaces with fluorescent lighting … equip every luminaire with a dimming ballast … or multilamp switching

Circuiting should follow the contours of daylight illumination in the space

As an advanced guideline for daylit offices and other workplaces with fluorescent lighting, the designer might begin by equipping every luminaire with a dimming ballast. Ballast costs are sufficiently low to make this worth pursuing, since daylighting, tuning (fixed light maximum) and dimming (adjustable light levels) are then possible. Any of the modern dimming ballast systems are probably acceptable if implemented with sensors and control circuits. However, if designing the building for future controls circuits, as in a tenant-occupied building, consider using the 0–10 volt dimming ballast as it presently permits the widest range of sensors from a variety of manufacturers.

As a budget option, at least consider using multilevel electronic ballasts that permit switching light levels using a simple switch circuit. Using multiple lamp luminaires and switching them to provide variable light levels is an excellent and cost-effective design strategy for many space types, especially large areas without stationary tasks. For instance, instead of HID industrial downlights in a daylit retail store, consider using downlights with multiple CFLs having separate ballasts.

The most important basic step toward daylight integration is to make sure that branch circuit wiring be designed to provide independent switch legs for each daylit zone. Circuiting should follow the contours of daylight illumination in the space. This will enable daylighting control to be provided at the lowest cost regardless of when the actual controls are added. See section 8.4.3 for more information.

For each project, seek out additional cost-effective and reliable ways to harvest daylighting savings. The key to success is designing a system that is reliable, simple and effective. A system requiring minimum commissioning is probably best, preferably a system that will work well right out of the box and will even improve if properly commissioned. Improvements to daylighting controls are rapidly evolving, and the advanced designer needs to stay abreast of the latest developments. Meanwhile, don’t be afraid to have a system that is not optimized—if it has the potential to be saving 70% but it is only saving 50%, use it anyway.

Advanced Guideline – Light Pollution and Light Trespass

Use night lighting only when and where necessary …

Use the minimum amount of light needed rather than the maximum …

Use sources with cutoff optics that restrict light to the intended area of illumination …

In outdoor lighting, an electric light usually illuminates more than just the intended area. Through lack of optical control or overlighting, stray light also illuminates adjacent properties. This light can become offensive if unwanted, and it has become known as light trespass. Once believed to be a minor problem usually involving tennis courts and commercial establishments in expensive neighborhoods, light trespass has become recognized as an area of significant concern and perhaps even future regulation.

In a related problem, electric lights emitting light upward or reflecting light upward cause a condition called light pollution. Light pollution causes moisture and particles in the air to glow at night. It creates the unfortunate sky glow of cities, obscuring the stars from view. See sections 3.2.4 and 3.2.5 for an overview of the environmental impacts of light trespass and light pollution, respectively. For a discussion of advanced outdoor luminaires, see section 7.6.

In the IESNA procedure, both light trespass and light pollution are recommended concerns for the lighting designer. As an advanced guideline, it's important to realize that both problems involve energy, and directly or indirectly pollute in a number of ways. Several steps should be taken to avoid or minimize light trespass and light pollution:

- Use night lighting only when and where necessary. Design exterior lighting to meet, but not exceed, the IESNA design guide. Overlighting directly contributes to light pollution and is often related to light trespass.
- Use the minimum amount of light needed rather than the maximum. Provide uniform lighting with good distribution that avoids wasteful "hot spots." Design for the lowest maintained illuminances that will produce the desired effects.
- Use sources with cutoff optics that restrict light to the intended area of illumination.
- In many cases, use more sources, each of lower wattage, to improve uniformity in the intended illumination area and minimize trespass into adjacent areas.
- Use sharp cutoff light sources and other means to eliminate light directed upwards or sideways. Consider "full cutoff" luminaires that emit no light above 90 degrees (horizontal). (It may be possible to reduce light pollution by using cutoff or semi-cutoff luminaires spaced farther apart than full cutoff luminaires can be spaced to achieve the same uniformity. This is controversial but deserving of analysis.)
- Use lighting strategies that allow nighttime adaptation of the eye to very low light levels. Unless security is an issue, focus on wayfinding with very small points of light, rather than illumination of large areas. In signage and retail, use color contrast to attract attention, rather than high levels of illumination.
- Use timers and occupancy sensors to limit the use of outdoor lighting to only the minimum time required for the purpose. Most outdoor lighting can be shut off or switched to a minimum level after 10 PM or 11 PM. Use astronomical time clocks or energy management system (EMS) controls to switch lights off, rather than simpler photocells that only switch lights on at dusk and off at dawn (see chapter **8**).
- Consider a "layered" approach. This might involve one set of full cutoff luminaires that provides the low-level utilitarian lighting (for example, street lighting from tall poles spaced 120 ft apart), and another set of luminaires that produces more decorative effects or provides pedestrian-scale light (for example, traditional-style glowing post-top luminaires on 12 ft poles). The second set of luminaires can use low-wattage lamps, and can also be shut off at 11 PM, leaving the utilitarian lighting burning all night for security purposes.

- Avoid development near existing astronomical observatories; when outdoor lighting is unavoidable, apply rigid controls. Consult with the observatory on needs for specific spectral control and shielding.
- Locate outdoor lighting below tree canopies, not above. The leaves of the trees then shield the light from the sky.
- Provide reflective surfaces for lettering or other elements that need to be illuminated at night. Illuminate only the lettering, not the background.
- Light from the top down, rather than from the bottom up. In signage lighting and building facade lighting, consider lighting from the top to reduce stray uplight. Spilled light is at least reduced by reflection from the ground before it is directed to the sky.

Many cities have light pole height ordinances designed to prevent light trespass. In general, pole height is not the primary issue; rather, cutoff and shielding determine the quality and control of light. Avoid purely ornamental exterior luminaires, ordinary floodlights, and similar light sources that have a minimum of optical control.

4.3.2 Space and Workplace Considerations

Advanced Guideline – Flexibility

The preservation of lighting and daylighting systems throughout their useful life is an important measure of sustainability. The ability to rewire or reconfigure an office building as easily as a living room is often viewed as ideal. Furthermore, an advanced perspective recognizes that the "one-size-fits-all" approach to lighting can be very wasteful. Redundant systems that allow different uses of the space may save energy and materials over the long run.

Consider use of:

Easily re-configured controls
Portable luminaires
Modular wiring
Lighting tracks
Lightweight suspended luminaires

Advanced lighting designs should be flexible enough to ensure that:

- Lights operate where needed, and are off where not needed, as people move around within a space and use rooms in different ways. Lighting designs employing occupancy sensors and other methods of ensuring this flexibility are the most sustainable. Also, ensure that changes in tasks can be accommodated with changes in light level, through dimming, for example. Controls are discussed in detail in chapter 8.
- Spaces used for "hoteling"—the occasional or transient use of a workspace—remain dark unless needed. Hoteling requires lighting and controls that permit these workspaces to function independently of the remainder of the space, and generally requires a combination of control flexibility and design in which dark areas do not negatively influence ambient light quality in general.
- The lighting system can be rapidly reconfigured to match a changed floor plan or accommodate a different space use, and still operate at maximum energy efficiency. This philosophy suggests mechanical and electrical flexibility. Consider modular wiring and re-mountable lighting systems to attain this flexibility. Many manufacturers are developing "plug and play" lighting systems that feature this ease of reconfiguration. Also, consider using lighting systems that serve reasonably well in all anticipated uses so as to reduce the likelihood of needing a different type of luminaire when the reconfiguration occurs. Common troffers (lens and parabolic) are among these "jacks of all trades."
- The lighting system permits multiple uses and on-demand flexibility in multiple-use spaces such as conference rooms and modern A/V classrooms. Multiple separately controlled or dimmed circuits can allow sufficient flexibility to meet the room's various arrangements.

Most modern lighting systems intended for commercial use are designed to be as flexible as conventional lay-in ceilings and common wiring permit. Far too many luminaires are installed in inappropriate locations because they are perceived to be immovable or too expensive to move, when in fact the luminaire is wired by a flexible “whip” permitting relocation in a few minutes. Even track luminaires are usually not moved once installed. For more information about specific luminaires, see chapter 7.

To design lighting systems that achieve the desired flexibility, consider these options in selecting lighting systems:

- Employ a control system that is easily reconfigured and commissioned
- Use portable lighting equipped with a cord and plug
- Use a modular wiring system
- Use a lighting track or busway
- Use lightweight luminaires suspended from the ceiling

Advanced Guideline – Appearance of Space and Luminaires

In the IESNA design procedure, the appearance and style of the luminaire play a major role. Throughout the history of lighting, thousands of different types and styles of luminaires have been built. Architectural, interior design or landscape architecture issues typically limit luminaire choices to a particular style that is suitable for the project. Some lighting equipment has been utilitarian (like the keyless socket) but until the era of the recessed luminaire, most lighting equipment complied with the architectural style of the building. Modern projects may permit the designer greater latitude in selecting among recessed luminaires as well as more traditional luminaires.

… find lighting systems that embody the project’s style or aesthetic … while using high-efficacy sources and efficient principles

Luminaire efficiency and the ability to use efficacious sources have become increasingly important criteria for selecting luminaires. Once seen as a tradeoff between aesthetics and appearance, attractive traditional and contemporary luminaires are available at many price levels.

As an advanced guideline, the designer should be constantly challenged to find lighting systems that embody the project’s style or aesthetic, but to do so using high-efficacy sources and efficient principles. For instance, choose among decorative luminaires that “hide” the light source, such as a diffusing bowl. Avoid luminaires such as crystal chandeliers that require lamps with bare incandescent filaments—unless, of course, a replacement in appearance for the bare filament can be employed, such as an LED.

See chapter 7 for an in-depth discussion of luminaires.

Advanced Guideline – Color Appearance

The appearance of color, both in terms of chromaticity (color temperature or degrees Kelvin) and color rendition (CRI), are important in the overall feeling of the space, and in some instances can have a dramatic effect on visual tasks. The IESNA design procedure requires the designer to consider both chromaticity and CRI as key components of a design. Section 6.2.4 covers chromaticity and CRI in detail; below is brief overview of design considerations related to color appearance.

… use light sources of CRI 80, or better…

… employ color balanced efficient alternatives to eliminate incandescent lamps

… work with higher color temperature and higher CRI sources to produce beneficial vision effects …

Chromaticity

A preference for a narrow range of source color temperature has been established and appears to coincide with design practice. Known as Kruitof's Curve, in general the lower the ambient light level, the lower the preferred color temperature range. Most commercial illumination levels coincide with an acceptable color temperature range of 3000K to 4500K.

Color temperature preference may be affected by latitude. The color temperature of light can affect perceptions of thermal comfort. Modern practice in commercial settings in the United States, such as offices and grocery stores, appears to favor a cooler source (4100K) in the southernmost U.S., an intermediate source (3500K) in the majority of the country, and a warmer source (3000K) in northern states. By volume in T-8 lamps, the most popular color temperature is 3500K throughout the U.S.

This does not eliminate consideration of other color temperature lamps. As noted in section 4.2.2, high color temperature lamps tend to add "scotopic" benefits, and T-8 lamp products are available at 5000K and 6500K. In addition to scotopic effects, high color temperature lamps tend to better match natural daylight, which varies between 4000K and 7500K for most of the day. When used in a daylit space, warm color temperature lamps can appear noticeably pinkish or yellow in comparison to the daylight. But at night, the cool lamps may appear unnatural; this factor should be taken into consideration in the design.

Because fluorescent and CFLs can be obtained in matching colors, it's good practice to match light color whenever possible. This is generally extended to include 3000K halogen and metal halide lamps and 4100K metal halide lamps, which can generally be matched to fluorescent lamps of corresponding color temperature.

Color Rendering

Color quality is generally assessed using Color Rendering Index (CRI), a scale having a maximum rating of 100 for reference sources like natural daylight and laboratory-quality incandescent light (see section 6.2.4 for more about color rendering). Ordinary incandescent and halogen sources and unfiltered natural daylight are often CRI 100 (or extremely close). Designers should be aware that modern "high performance" windows modify the color of daylight, and both correlated color temperature and CRI can be affected. Specially tinted glazing such as green or bronze can produce dramatic color change with comparatively lower CRI. (See section 7.4.2 for more about tinted glazing.)

Most other electric light sources, especially energy-efficient sources, have CRI that is lower than 100. Current practice is to employ sources having CRI of at least 70 for most applications. Recent advances in fluorescent and HID technology make light sources of CRI over 80 quite practical; these should be employed whenever possible.

There are specific lamp products that produce light of extremely high CRI, in the range of 90–100. These lamps tend to be more expensive and have lower lumen output than 80–89 CRI lamps, so the relative benefit of their use is limited to special applications where critical color discrimination is required, such as fine art and graphics art studios, textile mills, etc.

Design Considerations

As a basic concept in energy-effective lighting, the designer should use efficacious sources in as many applications as possible. Color appearance has long been a major issue, as most people still associate fluorescent light with the unfortunate cool and greenish hue of “cool white” lamps. The key to more energy-effective design is to employ efficient full-size fluorescent, compact fluorescent, and HID lamps to create spaces balanced at various color temperatures in order to eliminate incandescent lamps. Whenever possible, however, a higher color temperature such as 4100K or even 5000K will permit realization of the scotopic effects.

Use Table 4-2 as a guide to color temperature selection for lighting designs using high efficacy lamps.

Table 4-2 – Preferred Color Temperature Ranges

Lamp CCT (Kelvin)	Applications
<2500	Bulk industrial and security (HPS) lighting
2500–3000 “Warm”	Low light levels in most spaces (<10 footcandles). General residential lighting. Hotels, fine dining and family restaurants, theme parks. Suitable high-efficacy sources include fluorescent and compact fluorescent, 2700K or 3000K and halogen IR lamps.
2950–3500 “Neutral”	Display lighting in retail and galleries; feature lighting. Suitable high-efficacy sources include halogen IR, white sodium, and ceramic metal halide.
3500–4100 “Cool”	General lighting in offices, schools, stores, industry, medicine; display lighting; sports lighting. Suitable high-efficacy sources include induction, fluorescent, compact fluorescent and metal halide.
4100–5000 “Very cool”	General lighting in offices, schools, stores, industry, medicine, and sports lighting. Also special application lighting where color discrimination is very important. Suitable high-efficacy sources include induction, fluorescent, compact fluorescent and metal halide.
5000–7500 “Cold”	Special application lighting where color discrimination is critical; uncommon for general lighting, Suitable high-efficacy sources include fluorescent, compact fluorescent and metal halide.

As an advanced concept, designers can work with higher color temperature and higher CRI to produce beneficial vision effects, which, in turn, may permit the selection of a lower overall illuminance level. But this must be carried out in a manner that does not destroy the ambience of the space. Using 4100K instead of 3000K or 3500K, for instance, will appear brighter and may produce slightly higher visibility, especially if the source is a rare-earth fluorescent or metal halide with significant blue output.

Ideally, although it is presently difficult to achieve, the color of electric light, as well as its intensity, would shift in a natural manner, following the patterns of daylight. The highest light levels would be provided by day at 5000K, dimming at dawn and dusk continuously down to 2500K or less before taking on a nighttime appearance. At low light levels, low color temperature sources appear most natural, especially for interior residential and hospitality spaces, but higher color temperature sources, like moonlight, offer better visibility.

Advanced Guideline – Luminance of Room Surfaces

... use light colored room surfaces and minimize the use of dark surfaces

... ensure that the average room surface luminance is at least 10% of the task background

Technically, luminance thoroughly describes the visual scene and should be the primary design metric. The problem is, luminance is not easily measured and calculations are complex and time consuming. Because luminance depends on the reflectance of the surface, it’s highly dependent on exact knowledge of architectural and interior finishes. Most footcandle-based standards are simplifications and approximations of true luminance-based design and analysis.

The IESNA design procedure recommends that luminance be considered as part of the design. As a basic premise, the design criteria suggest that wall and ceiling luminance be close to task luminance. The luminance of the task background—typically white paper—should be used as the basis and in general, room surfaces should be between 1/10 and 10 times this level, preferably less than the task.

Luminance, being a quality of the room surface as well as light, places critical elements outside of the lighting designer's hands. Periodic trends in interior design introduce dark paints and finishes. These trends contribute to difficulty in producing energy-effective design by increasing lighting requirements to raise surface luminance into the comfortable range.

As an advanced guideline, the lighting designer should:

- Encourage the use of high diffuse reflectivity (light colored) surfaces and minimize the use of dark surfaces. Work with building owners, architects and interior designers on this key issue to improve the efficiency and cost-effectiveness of the building.
- Use computer modeling to ensure that the average room surface luminance is at least 10% of the task background. See section 4.4 for information about computer modeling.
- With indirect lighting systems, use computer calculations to check for uniformity, and try to maintain 10:1 luminance ratio or better.

Example: Back Wall Illumination in Open Office

In open-office lighting design, the illumination of the interior or core walls is critical in producing balanced luminance. A typical off-white wall (70% reflectance) can be washed to a vertical illumination level of about 20 footcandles and will achieve a luminance level of about 1/3 the task luminance for ordinary paper tasks. However, if the wall were to be painted a saturated blue (7% reflectance), achieving the same level of luminance would require 10 times as much electric light energy.

For more examples of office lighting design, see chapter 5.

Luminance is also a concern with respect to computer screens. Extremely bright or unevenly lighted surfaces can cause unwanted reflections in CRT-type (cathode ray tube) computer screens. As with paint, the best solutions—flat-faced CRT screens or flat active matrix screens—are beyond the control of the lighting designer. For average situations with undefined monitors, a sufficiently bright wall can easily be a reflected veiling image in a computer screen. For this reason, wall luminance and uniformity can be an issue in the computer work environment. As a general rule, the upper wall luminance should match the ceiling luminance, or at least not be significantly different. See Advanced Guideline – Reflected Glare for more strategies for reducing reflected veiling images.

Light-colored walls and room surfaces greatly improve the efficiency of every lighting system, including daylighting. Luminous ratios between windows and walls can be greatly reduced through the use of light-colored walls, and by making sure that the window abuts a perpendicular wall. Windows that create a “punched hole” in a wall are the worst offenders of luminance ratios, and often require non-efficient measures to correct the poor lighting quality. The Daylight Systems section (7.4) discusses this issue in greater depth.

Advanced Guideline – Flicker and Strobe

The visual system has a range of sensitivities to flickering light, depending on illumination levels and the size of the flickering object. Above a certain frequency flickering light is perceived as steady. The focal system can detect flicker up to about 60 Hz (the critical fusion frequency), but the peripheral system can only detect flicker up to about 18 Hz, with a peak sensitivity at 15 Hz (IESNA 2000, 3-20).

Flicker becomes the most troublesome when two cycling systems interact with each other to produce light modulations at frequencies approaching 15 Hz. This can happen with the interaction of computer screens or rotating equipment with electric lights that also have a strong oscillating light output. Oscillating light levels from a single fluorescent or HID lamp is most likely to be associated with these problems.

… eliminate from consideration any light source that does not operate on DC, high frequency AC (greater than 30 kilohertz), or AC square wave

The degree of oscillation from a lamp is a function of lamp type, type of phosphor coating, lamp configuration, type of circuit, and type of ballast. Fluorescent and HID lamps on magnetic ballasts flicker at a rate that is twice the line frequency (120 Hz in the United States and 100 Hz in Europe and southeast Asia). Recent studies comparing office worker performance under various fluorescent lighting systems have found a small but noticeable improvement in performance under electronic ballasts over magnetic ballasts (Veitch 1998). This finding is consistent with the theory that a reduction in flicker, such as occurs with electronic ballasts operating at 20kHz or more, should improve performance.

There is some evidence that flickering lights can cause headaches and other problems in sensitive individuals (for more about possible health effects, see section 2.2.6). In some applications, flickering lights can cause dangerous conditions in work areas with rotating or moving parts. The *IESNA Lighting Handbook* makes a relatively broad condemnation of flickering lights.

As an advanced guideline, consider every possible way to eliminate flickering electric lights (except of course for signs and glittering lights, such as in casinos). For instance, eliminate from consideration any lamp or light source (other than incandescent) that does not operate on DC, high frequency AC (greater than 30 kilohertz), or AC square wave.

See sections 6.5 and 6.6 for more information about flicker and strobe effects associated with fluorescent and HID sources, respectively.

Advanced Guideline – Direct Glare

Direct glare is caused by a view of the light source, often with high contrast to the surroundings. While the bare light bulb is technically the most efficient "luminaire" because it has no internal losses, it's a poor choice in almost every application because the glare from the bulb walls is visually disabling. Thus, the control and distribution of light from a source is an essential characteristic of its visual efficiency. Glare is associated not just with lamps, but also with daylight, especially when one is exposed to low angle, direct sunlight. Any excessively bright source, not just electric lamps, but also low-angle sunlight or overly bright luminance, can cause glare from windows or skylight diffusers. IESNA design guides promote modest ratios of brightness.

Be the most concerned about sources of glare in relation to stationary tasks …

As an advanced guideline, it's important to understand that there is not a clear-cut line between comfort and glare. For instance, many people will happily work away in a daylit space with a window, turning their backs to the sun and avoiding the glare while generally enjoying a cheerful space. In other cases, people will tolerate some glare as long as it contributes to an overall impact of sparkle or a festive mood. Yet a modest difference in brightness caused by an unattractive source like a lens troffer is often deemed too much glare.

In other words, there is acceptable glare and unacceptable glare, and the definition is not quantitative but qualitative. In general, be more concerned about glare caused by fluorescent lamps, lenses, and other overly bright sources of manmade light. (Chapter 7 provides more information about glare issues related to specific types of luminaires.) Be less concerned about the glare of sunlight and small point sources like incandescent filaments. Be the most concerned about sources of glare in relation to stationary tasks when the building occupants cannot easily relocate themselves or their task.

The first most important step to avoiding glare in daylighting applications is to always arrange for a window or skylight to be next to a surface that will diffuse its light. Avoid "punched holes" in walls or ceilings. A window next to a wall will balance luminance ratios between indoors and out. A splayed skylight well will balance luminance ratios between the ceiling and the skylight.

… always arrange for a window or skylight to be next to a surface that will diffuse its light

Avoid "punched holes" in walls or ceilings

Balance the daylight illumination levels in the space with a source of daylight from at least two directions

The second most important step to avoiding glare in daylighting applications is to balance the illumination levels in the space with a source of daylight from at least two directions. Very bright illumination from a window can be balanced by daylight from a window or skylight on the other side of the room. Redirecting daylight, through the use of blinds, lightshelves, or special glazings can also help to balance luminance ratios, and thus reduce glare. For further discussion of glare and daylighting, see section 7.4.

Occupant control of light sources is also an important strategy in reducing the impact of glare. Adjustable task lights and individually dimming ceiling luminaires provide control over glare conditions from electric lighting. Individually controllable window blinds and curtains provide occupants with the opportunity to adjust lighting conditions to their particular needs and wants. When feasible, such personal control of lights will greatly reduce the negative impacts of potentially glaring sources. For more about controls, refer to chapter **8**.

Advanced Guideline – Reflected Glare

… modify the task to eliminate glare problems

Use a flat adjustable computer screen to eliminate specular reflections …

Disability glare and veiling reflections have long been associated with gloss-coated paper, pencil paperwork and the computer CRT (cathode ray tube) screen. All can create specular reflections that can cause glare, either reducing comfort or disabling the worker's vision in particular areas.

Indirect lighting, by creating a diffuse and uniform illumination, has been advocated as a solution to preventing reflected glare in workplaces. However, if properly located and shielded, direct lighting systems and especially, two-component lighting systems (see task and ambient lighting discussion in 4.3.1) may provide the best overall results in preventing reflected glare. Direct and indirect luminaires are discussed extensively in section 7.5.

As an advanced lighting guideline, after the lighting system has been optimized to minimize glare, consider modifying the task to eliminate any remaining glare problems. The computer CRT screen, for example, can be changed to a flat screen, either CRT or active matrix, to minimize or eliminate specular reflections from ceilings and upper walls. The angle of the screen can be adjusted to further minimize these problems (see sidebar below, Veiling Reflections in Computer Screens). Use of ink, rather than pencil, virtually eliminates reflected glare problems with paperwork. Use of matte-coated or uncoated paper, rather than gloss-coated paper, prevents glare reflections in printed material. Similarly, reflected glare from polished floors or shiny conference room tables can be avoided by changing the finish.

Lacking these options, the designer should utilize source/task/eye geometry studies to eliminate or minimize the impact of reflected glare (see Advanced Guideline – Task Requirements). In addition, pay close attention to room surfaces and finishes and either design light accordingly or change the finish (see Advanced Guideline – Luminance of Room Surfaces). For instance, unfinished or matte-finished wood can be wall-washed using relatively generic equipment, but if a satin or gloss finish is applied, a more sophisticated and (probably) less energy-efficient grazing light technique must be used to avoid a harsh reflection to the viewer.

The reflection of interior lights and objects in selectively coated glazing can produce another type of glare. Designers should consider optical coatings that minimize these reflections, especially if there is a desire to “see through” windows at night.

VEILING REFLECTIONS IN COMPUTER SCREENS

The lighting industry has given much attention to the problem of avoiding veiling reflections in computer screens. This was a dramatic problem with the advent of the early black-screened monitors, where a reflection of a bright luminaire against the dark background could make large areas of information difficult or impossible to see. With the introduction of white-based screens, with flatter and diffusing glass, this problem is somewhat ameliorated, but remains an important concern. Standards for designing office space appropriate for white cathode ray tube screens are addressed in the *IESNA Lighting Handbook’s* recommended practice RP-1.

The computer industry continues to advance at a rapid pace. Many current innovations are directed at developing smaller, flatter, higher resolution and lighter weight display devices to make viewing information easier under all kinds of conditions. With laptop computers came the introduction of liquid crystal display (LCD) screens, which are now spreading to standard desktop applications. Features such as easy adjustability of the angle of view, a matte surface and a flat screen make veiling reflections easier to avoid.

Computer users now also have the option of ever larger display screens and higher resolution to solve visibility problems. (A side benefit of flat screen LCD screens is that they consume much less power than conventional CRT screens, thus saving energy as well.) Speaking computers are also giving visually impaired users more access to computer technology. Simultaneously, an ever-expanding array of handheld devices is bringing numerous LCD micro-screens into the workplace, on telephones, watches, calculators and personal digital assistants (PDAs), adding another visual challenge. The technology of computer-based tasks promises to continue to evolve faster than the lighting industry can develop generalized illumination guidelines in response to these new technologies.

Figure 4-1 – LCD Screens in the Workplace

There have always been at least three ways to solve a visibility issue: enhance the illuminance conditions (with more appropriate light), enhance the vision of the viewer (with corrective lenses), or improve the visibility of the task. The computer industry itself has been the major source of innovations to resolve visibility issues and making computers as easy and trouble free as possible.

4.3.3 Lighting People and Objects

Advanced Guideline – Modeling of Faces or Objects

In human vision, shadows and highlights enhance the perception of three dimensions. Both are the products of directional light sources. The sun and the moon produce well-defined shadows, and are considered dramatic and attractive light sources.

Diffuse light, like the light from a cloudy sky, produces an even light that is relatively shadow-free. Once considered desirable, it is now realized that shadow-free light can fail to render changes in surfaces making a space or task less visible. To model a surface for better recognition of its shape and features, in general some percentage of directional light is considered important.

… blend direct and indirect lighting to provide a combination of comfort and modeling …

the direct component should be at least 20–25% of the total illumination …

As an advanced guideline, designers are encouraged to consider using a blend of direct and indirect lighting in most designs to provide a combination of comfort and modeling. The percentage of direct component will vary according to the project requirements, but to achieve a minimum of modeling, directional light for an object or area of interest should be at least 20–25% of the total illumination. Section 7.5 provides specific information about direct and indirect lighting systems.

Daylighting in buildings often provides a highly directional source of light, and excellent three-dimensional modeling. The provision of a window within a space will create highlights on three-dimensional surfaces. A skylight overhead provides a very natural sparkle on the tops of objects. Since light from a window is primarily traveling in a horizontal direction, it can provide excellent facial modeling. For more about daylight as a light source, refer to section 6.3; for information about daylight systems, see section 7.4.

Daylighting often provides a highly directional source of light, and excellent three-dimensional modeling

Shadows are particularly important in rendering three-dimensional forms in space. For instance, in designing facilities for care of the aging, shadows are essential in revealing steps and grade changes, wall edges, and other basic building elements that the younger eye has less difficulty seeing with ordinary lighting. In such cases, contrast can definitely improve visibility. (See The Aging Eye, section 2.1.6, for more about special visibility needs for the aging.)

Advanced Guideline – Surface Characteristics

In recognizing the benefit of surface revelation, the new IESNA procedure demonstrates a modern view of the role of lighting design in architecture. Once limited to special buildings and projects, lighting techniques that reveal architectural nuance like texture enhance visual perception, and have become more commonly requested by building owners and architects.

Use lighting techniques that reveal texture to enhance visual perception …

As an advanced guideline, employ light rendering programs like Radiance or Lightscape to confirm the effect of lighting designs in rendering building surfaces and other surface characteristics. This is where the power of these tools is unmatched in the profession. The ability to illustrate the revelation of texture, specularity, color and pattern is a compelling tool in studying and presenting these lighting techniques. These tools are described in section 4.4.

Advanced Guideline – Points of Interest

It has been long recognized in retail and museum lighting design that the human eye is attracted to the brightest points, and in comparison, dark areas are hardly looked at. As a primary design tool in these types of spaces, designers use highlights of up to 10 times the ambient light level to draw attention to key displays.

Less recognized but equally important, most award-winning lighting designs employ contrast and non-uniform illumination in an artful manner to achieve aesthetic purposes. Techniques range from the illumination of room surfaces or objects, as in wall-washing or cove lighting, to the use of bright sparkling elements, such as crystal chandeliers.

As an advanced lighting guideline, recognize that it's wasteful to create more lighting than is needed. Carefully select highlights, and use a minimum effective highlight level. Strategies include creating highlights in contrast to lower ambient illumination levels and creating highlights with efficient sources as close to the object or surfaces as possible. Small points of light from fiber optic sources or LEDs may offer efficient ways to create highlights or attract attention where specifically desired.

… create highlights in contrast to lower ambient illumination levels

… create highlights with efficient sources as close to the object as possible

The high levels of illumination that are easily achievable from daylighting are a very energy efficient way to provide highlights and focus attention. For example, the center of a store can be daylit with skylights, pulling customers deeper into the store, or central circulation areas can receive high illumination levels from daylight, emphasizing their central importance in the building. Such designs should carefully consider alternative nighttime illumination strategies from electric sources that do not try to duplicate the high level of illumination available from daylight.

In chapter 5, the grocery store and specialty retail store applications provide examples of the use of highlights in lighting design.

Advanced Guideline – Sparkle/Desirable Reflected Highlights

Sparkle and related reflected highlights have recently been recognized as essential elements of lighting design. These issues are often very similar to those discussed in Advanced Guideline – Points of Interest.

However, there are many commercial and industrial tasks where highlights are critical to the work. Workers often use specular highlights to judge workmanship, assess surface quality, and evaluate the quality of materials. As an advanced guideline, assess these nuances of task work and employ lighting systems that enhance, or in some cases conceal these effects. Computer modeling using Radiance or Lightscape can prove to be an exceptional tool. See section 4.4 for more about computer modeling tools.

4.4 Implementation

This section describes tools and methods for making lighting calculations (4.4.1 and 4.4.2) and evaluating the cost effectiveness of design alternatives (4.4.3).

4.4.1 Lighting Analysis Tools

Introduction

Lighting calculations have always been part of the basic practice of illuminating engineering. Calculations using a simple hand calculator (or slide rule) were once common, but the results of this type of calculation are limited to broad generalizations and averages. These days, computer calculations, requiring merely a modest personal computer and relatively low-cost software, are the standard for virtually every lighting practitioner.

This section provides an overview of lighting design analysis tools, including calculation methods and software programs. Section 4.4.2 describes design analysis tools for daylighting in more detail.

Hand Calculations

The Lumen Method

The lumen method, also known as zonal cavity calculation, is a quick and simple technique for predicting the average illuminance level in a room. The lumen method's major drawbacks are that it determines neither the range of light intensity in a room nor where differences in light intensity levels occur, and it can't provide information about lighting quality, visual performance or lighting patterns in the room. This method is especially inaccurate for non-uniform lighting systems.

The lumen method still has its place, however. It permits reasonably effective comparisons of competing general lighting systems, and it lends itself quite well to the lighting retrofit market. Because of the wealth of product data, simplicity of the formula and the ease of incorporating it into spreadsheets, the lumen method continues to play an important role in everyday lighting design. Lumen method calculations are described in more detail below.

Lumen method calculations are typically templates for spreadsheet programs or short routines built into handheld computers. Calculations have simple input requirements:

- Physical characteristics of the room, including length, width and height
- Ceiling, wall and floor reflectance (% of light reflected by the room surfaces)
- Work plane height (that is, desk height or height above the floor at which the visual work is to be performed)
- Distance from the work plane to the luminaires
- Coefficient of utilization (CU) for the luminaire: the percentage of initial lamp lumens that are delivered to the work plane. This value depends on the luminaire design and the characteristics of the space where the luminaire is located (see above bullets).
- Number of lamps per luminaire and initial lumen output of each lamp
- Light Loss Factors (LLFs): scalar multipliers that account for the degradation of rated initial lamp lumens. Light loss factors may be either recoverable due to maintenance of the lighting system and room, or non-recoverable and constant. Light loss factors include dirt accumulation on luminaires and room surfaces, lamp depreciation, ballast factors and thermal application effects.

The lumen method can be used to calculate the average illuminance incident on the work plane once the lighting system has been designed. Alternatively, the method may be used to calculate the number of luminaires required to produce a desired light level. While the method is most commonly used with direct lighting systems, it can also be used with indirect and direct-indirect lighting systems.

While the method easily lends itself to hand calculations, spreadsheets and personal handheld computers, obtaining manufacturers' data is still required. The more powerful programs require complete photometric data, but basic CU data is available on many product "cut" sheets, and generic data can often be substituted with only a modest loss of accuracy. Some spreadsheets combine the lumen method calculation with an economic analysis program, especially for evaluating lighting retrofits.

Basic Point-by-point Lighting Programs

These programs determine light levels at specific locations in a space. They can predict the brightness of room surfaces and give the patterns of light on the ceiling, walls and floor. Some programs calculate special figures of merit such as equivalent sphere illumination (ESI) and relative visual performance (RVP), metrics of lighting quality and visual performance. Other programs can address glare issues through calculation of uniform glare rating (UGR) and visual comfort probability (VCP). The sidebar, Common Lighting Performance Terms, describes these concepts in more detail.

Graphically enhanced point calculations go beyond these capabilities by providing graphic representations of the results. These may include color or gray-scale plots and isolux (isofootcandle) plots for either interior or exterior lighting, and three-dimensional perspective renderings of an interior space with its lighting system.

These programs are useful for interior electric lighting and daylighting, and can also be used for exterior lighting calculations requiring consideration of reflected light such as from canopies or walls. All modern programs run in Microsoft Windows and can obtain input space geometry from user input or from a .DXF or .DWG file.

Virtually all modern programs designed for everyday use in lighting design employ “radiosity,” a modern form of radiative-transfer calculations that have been used in point calculations since the 1970s. These programs are more precise in their calculation abilities, and thus require more detailed input, including:

- Room dimensions, work plane height, and luminaire mounting height (for pendant mounted luminaires).
- Room surface reflectance, including "inserts"—portions of room surfaces that may have different reflectance.
- Detailed luminaire photometric data in IESNA format.
- Precise location and orientation of luminaires using x, y, z coordinates, or using an interface with CAD programs.
- Light loss factors and any other multiplying factors to adjust the lamp and ballast output from the assumptions used in the luminaire photometry.

Point calculation programs calculate the lighting effects caused by specific luminaires in specific rooms. They cannot choose an appropriate lighting system given the designer's requirements. Most programs can only analyze an empty rectangular space lighted with electric lights and will provide the following output:

- Illuminance (lux or footcandles) on a horizontal work plane at selected points in the room, as well as summary statistics such as average, maximum, minimum, and standard deviation of illuminance values.
- Room surface luminance (candelas per unit surface area) or exitance (lumens per unit surface area). These results are based on the assumption that room surfaces have a matte, not shiny, finish.
- Lighting power density (W/m^2 or W/ft^2).

Point calculation programs may also have some or all of the following capabilities:

- Daylighting analysis. Calculated illuminance values and light patterns include daylight contributions through windows and skylights as well as contributions from the electric lighting system. Consideration of daylighting generally requires that outdoor illumination conditions be specified along with details about the orientation and transmission characteristics of the building's fenestration.
- Partition analysis. The effect on interior partitions or other light-blocking objects in the room is considered.
- Calculations and analysis taking into account furniture, partitions, and interior elements like columns and pilasters. These and other “objects in space” increase the realistic quality of renderings, but can add considerable computational time.
- Visibility and visual comfort metrics. UGR (uniform glare rating), ESI (equivalent sphere illumination), RVP (relative visual performance) and VCP (visual comfort probability) are the principal metrics computed by these programs. They are calculated for a specific location in the room and for a specific viewing direction.

Output from these programs is usually a chart of calculated values, an isolux (isofootcandle) plot, or a shaded plan with gray scales representing a range of light levels. All programs print results, and some will display the results directly on the screen. Most programs offer three-dimensional, black-and-white or color-shaded perspective views of the room showing light patterns produced on the room surfaces by the lighting system.

Modern point calculation software requires Pentium-class or greater computing power; exact requirements vary with the capabilities and design of a specific program. The run time for point calculations can range between several seconds to several hours, depending on the software and hardware used. Calculation complexities, especially rooms of unusual shape, many internal objects, or those with a large number of luminaires, increase calculation time dramatically. For instance, a simple box room with four luminaires can be completely analyzed (including daylighting) on a Pentium II class machine in about 30 seconds; adding a single desk in the middle of the room can double or triple execution time.

Programs for general use will range in cost between $100 and $900, depending on features and capabilities. Some manufacturers offer software for free or a nominal price (less than $100), but these programs are generally limited to a stripped down version of the “real” program.

Advanced Lighting Programs

Advanced programs include both radiosity and ray-tracing programs. They are capable of extreme accuracy in spaces of complex geometry. Most generate high quality, semi-photorealistic images depicting interior and exterior lighting, including daylight.

Because ray tracing is significantly more computationally intensive than radiosity, ray-tracing programs are much less common. Ray-tracing programs require considerably more computer time, data entry time, and operator expertise. However, ray-tracing programs generally produce superior visual results, often making them worth the time and expense for critical lighting designs and evaluations. Ray-tracing programs are uniquely capable of demonstrating effects and issues caused by specular surfaces, and are the only programs that render highlights such as reflections in polished surfaces or glass. Some programs combine the computational speed of radiosity with the accuracy and realism of ray tracing, permitting a practical program for common use.

Advanced radiosity programs have greater capabilities than basic programs, including:

- Analysis of rooms of any shape
- Rooms can have sloping and complex ceilings
- Realistic objects in space
- Faster execution time
- Much more realistic renderings

Advanced ray-tracing programs are the most accurate means of computing lighting effects. By tracing each "ray" of light, extremely complex visual scenes, including furniture, artwork and windows, can be analyzed exactly. Difficulty notwithstanding, ray-tracing programs display lighted rooms in full color, with accurate light patterns on room surfaces and partitions, and realistic shadows from realistic furniture. Fine details, such as the specular reflection from a window or shiny metal, enhance the sense of realism to levels unattainable with radiosity software alone. Some programs, such as Lightscape, use radiosity for most calculations, then add a ray-tracing “layer” for realism of specular reflections and highlights.

Pentium III-class computers with advanced graphics cards are generally needed to obtain satisfactory results with Windows-based programs. In general, the computer model is created in a 3-D visualization program, an arduous task requiring input details for every object and material to be rendered. The lighting program imports this data, lighting data is added, and the analysis performed. Depending on the complexity of the design and the computer power available, program run time can be minutes or even hours.

For people with access to a Unix-class graphics workstation, the public domain program Radiance is perhaps the most powerful. Specialists with high-powered graphics workstations have used Radiance to produce unprecedented real-time walkthroughs of spaces. However, the program was not originally developed for commercial use, and the learning curve is very steep, requiring a very large investment in time, computer power, and patience. A Microsoft Windows version of Radiance has recently been introduced; there is no experience data yet.

Rendering add-ins to AutoCAD and 3D Visual Studio/3D Viz are also available. Rendering add-ins are a relatively new phenomenon, as they take advantage of lighting algorithms to illustrate games and architectural programs with considerable realism. However, because most of these programs are illustrator's tools and not necessarily professional lighting programs, it is probably a good idea to determine the accuracy and features of the program with respect to lighting and daylighting.

Specialty Calculations

There are several lighting calculations that are best performed using a program specifically designed for them. In particular:

- Most exterior lighting calculations don't require calculations involving reflecting surfaces such as ceilings and walls, so faster, simpler programs have been written for this task.
- The unique nature of theatrical and performance lighting equipment is best served by an application-specific user interface, although the calculations may be very similar otherwise.
- Easy-to-use programs and templates have been developed as aids for common lighting problems, including skylight design (see section 4.4.2) and display lighting design.

Exterior Lighting Calculations

Exterior lighting programs are used for parking lots, roadways, pedestrian paths, and special situations such as airport aprons, car sales lots and sports fields. Exterior lighting calculations are very similar to interior calculations, except that they are simpler, since no light reflectance from room surfaces are calculated. Exterior programs generally allow the user to aim the luminaire (interior programs usually assume the luminaire will be parallel to the floor). Input data typically include the following:

- Plan dimensions of the site to be studied, usually entered in x, y coordinates or through a CAD interface
- Points on the site where illuminance is to be calculated. Some programs permit blocking out the printing of light levels on areas of the site where light levels are not critical, or where buildings or trees would block the light.
- Luminaire photometry
- Mounting heights, site locations, orientations, and tilt of luminaires
- Lumen output of the specified lamp
- Light loss factors due to lamp aging, ballast factor, and luminaire dirt accumulation

As with interior programs, photometric data files for exterior luminaires are generally supplied by manufacturers on data disks in IESNA format. Or, if a data disk is not available, the candlepower data may be keyed in by hand from the manufacturer's photometric report.

The most common form of exterior lighting analysis is the calculation of illuminance on horizontal and vertical planes. Horizontal planes usually are used for roadways, pathways and parking lots, while vertical planes are typically used for parking lots, sports fields and automobile display areas. Exterior lighting programs are also very useful in calculating light trespass onto adjacent properties, the lighting of adjacent building facades, and evaluating a lighting system for the use of exterior closed circuit television cameras. Advanced tools including the calculation of veiling luminance are available when using some programs.

Because the results of roadway and parking lot calculations lend themselves well to graphic presentation, output from most of these programs is provided as a grid of illuminance levels, gray-scale tones, and/or isolux (isofootcandle) plots. Most programs will limit analysis to areas of the site where illumination is important, such as between the curb lines in roadway analysis. No analysis is performed (or at least not printed) for areas of the site where light levels are not critical. Many programs can take into account the shadowing from buildings. Most exterior lighting programs are designed to run on Windows-based computers.

Many exterior lighting programs are designed to work with CAD programs. CAD interface capabilities allow rapid data input and layout using a mouse or digitizer. This type of drawing and computing relationship accelerates and improves the accuracy of site and roadway lighting design. Locations of luminaires can be determined from CAD data, and output information such as isolux/isofootcandle plots can be entered directly onto the base civil engineering or site plan. Enhanced screen and printer images include three-dimensional representations, such as perspective-isolux drawings.

Exterior programs for general use cost $200 to $1500. Several outdoor luminaire manufacturers will supply software to specifiers for a nominal fee ($0–$100), but these programs may only analyze that particular manufacturer's luminaires. For most commercially available lighting software, a reasonably current office computer is generally all that is needed.

General Purpose Energy Simulation Programs

Energy simulation programs such as DOE-2, BLAST and EnergyPlus are not really lighting programs, but they do simulate the energy used by lighting systems and are useful in evaluating the interactions between lighting system improvements and HVAC systems. The programs enable one or more lighting systems to be modeled in each space. The peak power is defined for each system and an operation schedule is assigned. The operation schedule indicates the percent of the lights that are operating for each hour of the year. Most of the programs can do basic daylighting calculations for a single lighting reference point.

Application Guidelines

Approaches to Lighting Design

Lighting design strategy often determines the appropriate type of lighting calculation. Two design approaches are discussed here: general lighting approaches and task-ambient lighting approaches.

General Lighting

The general lighting design approach is a common strategy used to provide a fairly uniform amount of light throughout a room. If the task location in a room is likely to vary widely, or if the space is likely to be frequently reconfigured to accommodate changes in work groups (such as adding staff and moving workstations around a couple of times per year), then it may be advisable to design for task levels of illuminance everywhere in the room.

The general lighting system is usually a regular pattern of luminaires that produces very even light levels, slightly higher than the average value in the center of the room, and slightly lower in the outer corners of the room. Lumen method calculations are appropriate for the design of general lighting systems.

Multicomponent Lighting Design

Task-ambient lighting and other multicomponent design approaches tend to be non-uniform, with lower ambient light levels surrounding brighter task areas. For example, in a task-ambient design, luminaires might be concentrated primarily over work areas, while an indirect lighting system provides relatively low levels of general (ambient) illuminance. This design strategy usually requires point calculations to ensure that luminaires are correctly located to produce the lighting level and quality necessary for performing visual tasks at the needed locations.

The skilled application of computerized point lighting calculations can optimize lighting levels in both the task and ambient domains in order to minimize energy consumption. The lighting professional should consider the use of point lighting calculations, both to design more energy-efficient spaces, and to create spaces with more drama and visual interest.

Point calculations are an exceptionally accurate way to compare general lighting systems. While the easier lumen method allows the comparison of average illuminance, point calculations permit the comparison of uniformity of light on the work plane, the patterns of light produced on ceilings and walls, and task contrast rendering. More specifically, point calculations allow consideration of the effects listed below.

- *Effects on Room Surfaces.* By evaluating the patterns of light on a wall caused by a row of compact fluorescent downlights, an aesthetic evaluation can be made. Artwork locations may be selected or lighting may be designed to highlight artwork. It may also be possible to determine whether the pattern created on a wall will produce luminance extremes that will cause glare or reflections in VDT screens.
- *Indirect Lighting Effects on Ceiling.* When they are too close to the ceiling, indirect lighting systems may create definite stripes or pools of light on the ceiling that are distracting and that may image in VDT screens. Careful ceiling luminance calculations can help identify the problem, and allow comparison of lighting products with various optical distributions and suspension lengths to reduce the effect. Gray-scale printouts or shaded VDT screen output of luminance make visual assessments possible.
- *Interior Task-Ambient Lighting.* Point calculations should be used for any type of lighting design where the task locations and types are well known and are unlikely to move without a lighting redesign. They may also be used for lighting designs where tasks that move end up in predefined locations.

Cautions for Point Calculations

In the case where a task light is used, or where an indirect luminaire is mounted within 12 in. of the ceiling, point calculations aren't always appropriate. In general, if the luminaire is close to the surface where lighting patterns are to be evaluated, a *near-field* situation exists. A shortcoming of the mathematics used in point calculations is that these near-field calculations are comparatively inaccurate unless near-field photometric data is available from the luminaire manufacturer, or the computer program is capable of adjusting the luminaires' characteristics to improve the accuracy of the results. Otherwise, it may be more accurate to evaluate the light patterns from the task light or indirect luminaire empirically.

Common Lighting Performance Terms

Luminous Flux, measured in lumens, refers to the gross amount of light generated by a source, irrespective of the intensity of the light in a given direction.

Candlepower is the measure of the intensity of a light source in a given direction, measured in candelas (cd). Candlepower distribution curves describe the direction and intensity of light radiation by a luminaire or a light source.

Illuminance describes the amount of light falling on a surface. If the surface is horizontal, light striking it is known as horizontal illuminance; if the surface is vertical, it is called vertical illuminance. The average illuminance on a surface may be calculated by dividing the number of lumens falling on the surface by the area of the surface. Or, the illuminance incident at a point may be calculated as the candlepower of the light ray from the light source to the point, divided by the square of the linear distance between them, times the cosine of the angle between the light ray and the normal to the surface. Both methods result in "footcandles" if the area or distance is measured in square feet, or in "lux" if the area or distance is measured in square meters (1 footcandles =10.16 lx). Illuminance can be measured with an inexpensive meter. This value is still used as a measure of lighting quantity and as a standards value.

Equivalent Sphere Illuminance (ESI) is a measure of how visible a specific target is under a proposed lighting system, as compared to the same target illuminated by a uniformly bright hemisphere, expressed as the illuminance created by the hemisphere. ESI can be a powerful design tool in evaluating performance of competing lighting systems. In simple terms, ESI indicates how much illuminance on the task actually aids visibility, as opposed to causing veiling glare. This metric is very difficult to measure in the field or calculate by hand; however, available computer programs are able to compute it easily and can be an aid to understanding basic principles of lighting quality.

Relative Visual Performance (RVP). Based on experimental measurements made at the National Research Council of Canada, this is a metric describing the potential of performing a visual task accurately under a very specific set of conditions. RVP is an important tool for comparing lighting systems. It is expressed as a percentage that predicts the probability of successfully performing a task where speed and accuracy are important by measuring how well the lighting system renders the target's contrast. User age, precise reflectance characteristics of the task, distribution of the light approaching the task, viewing location, and orientation with respect to the task and lighting system must be known to compute RVP at a point. This does not diminish its utility when comparing lighting systems. RVP for an existing task, user, and lighting system may be determined using an instrument designed for this purpose. RVP is considered an important tool for comparing lighting systems, but it has been slow to gain widespread acceptance, because it is generally limited to those who comprehend how it is calculated and understand its limitations and narrow application.

Visual Comfort Probability (VCP) is a calculation taking into account the relative brightness of a lighting system from a given viewing angle, resulting in the likelihood (as a percent) that a lighting system will be visually comfortable. VCP data were confirmed experimentally using uniform layouts of lensed fluorescent luminaires. While it is typical practice to extrapolate the VCP concept to apply it to various size louvers and luminous ceilings, it should be noted that VCP data have not been experimentally confirmed using these systems. As such, one should be cautious in using VCP to evaluate the potential visual comfort of lighting systems using other than lensed luminaires.

Exitance, Luminance, and Brightness are properties describing how light is reflected from or transmitted through a real (or imaginary) surface. **Exitance** is the total quantity of light emitted by, reflected from, and transmitted through a surface into a complete hemisphere. It is expressed in units of lumens per unit surface area. **Luminance** is a very important concept in lighting, since luminance is what we actually see. Rigorously, luminance is defined to be the ratio of the intensity of light produced by a surface in a given direction to the projected area of the emitting surface. In SI units, luminance is generally expressed as candelas/meter^2. In English units, luminance should generally be expressed in candelas/ft^2. The foot-lambert unit for luminance that has been used in the past has been deprecated and should be avoided. **Brightness** is used to describe the strength of the physical sensation caused by viewing surfaces (or volumes). Brightness is related to luminance, but takes account of the fact that a surface with a luminance of, for instance, 100 cd/m^2 will not appear twice as bright as a surface of 50 cd/m^2.

Spacing to Mounting Height Ratios and **Spacing Criterion** (S/MH and SC) refer to the maximum recommended spacing between luminaires to achieve uniform general lighting. S/MH is often expressed as "parallel" or "perpendicular," and refers to the ratio of the center-to-center distance between luminaires to their mounting height above the work plane in the direction either parallel or perpendicular to the length of the lamps. Current luminaire photometry uses the term "spacing criterion" (SC) instead. While these metrics are useful for lumen method general lighting calculations, neither S/MH nor SC is applicable in spaces with workstation partitions or where task-ambient design is appropriate. Spacing criterion is described further in section **7.3.2**.

Resources

Each year, the Illuminating Engineering Society of North America (IESNA) publishes a lighting software survey in *Lighting Design + Application.* Products are surveyed in many areas, including hardware requirements, analysis features, applications, types of output, user features, and price. At the time of the printing of the *Advanced Lighting Guidelines,* the IESNA survey was the most up to date and complete source of information on lighting software on the market. The following are some of the more readily available and recognized software available at the time of this document's development.

Table 4-3 – Lighting Software Programs

Category	Program	Manufacturer	Description
General Purpose Programs and AutoCAD Extensions	CALCU-LITE 5	The ScreenMaker Williamstown, NJ	Basic lighting program
	AGI	Lighting Analysts, Inc. Littleton, CO	Advanced radiosity lighting program with rendering
	LUMINAIRE GLOBAL ILLUMINATION TOOLS	Jissai Graphics	Radiosity add-in to 3D Viz with rendering
	LUMEN-MICRO 2000	Lighting Technologies, Inc. Boulder, CO	Advanced radiosity lighting program with rendering; also, Simply Lighting basic lighting programs
	LITE-PRO	Columbia Prescolite Spokane, WA	Radiosity lighting program with rendering
	LUXICON	Cooper Lighting Peachtree City, GA	Radiosity lighting program
	VISUAL	Lithonia Lighting Group Conyers, GA	Advanced radiosity lighting program
Radiosity and Ray Tracing Program	LIGHTSCAPE 3.2	Autodesk San Rafael, CA	Combines radiosity with ray tracing for rendering accuracy
Ray-tracing Program	RADIANCE (Unix) and Desktop RADIANCE (Windows— AutoCAD 14)	Lawrence Berkeley National Laboratory University of California, Berkeley, CA	Ray-tracing program that is computationally intensive but produces the most realistic renderings

Note: These listings are not exhaustive and do not imply applicability or endorsement. Additional programs are available. Refer to the annual lighting software survey in *Lighting Design + Application* magazine and http://www.lightsearch.com for additional sources of software and comparative analyses.

4.4.2 Daylighting Design Analysis Tools

Unlike electric luminaires, daylight apertures are not routinely tested for their photometric performance. The evaluation of an advanced daylight luminaire usually involves one or more of the following specialized analysis tools.

Manual Calculations

Several methods have been developed for manual calculation of interior daylight levels. Most notable among these are the lumen method of toplighting and sidelighting and the Lune Method (see *IESNA Lighting Handbook*). Because of the dynamic nature and complexity of daylight and the plethora of potential apertures, these techniques are quite time consuming and provide only a rough estimate of performance. They have substantially been replaced by scale model and computer simulation techniques.

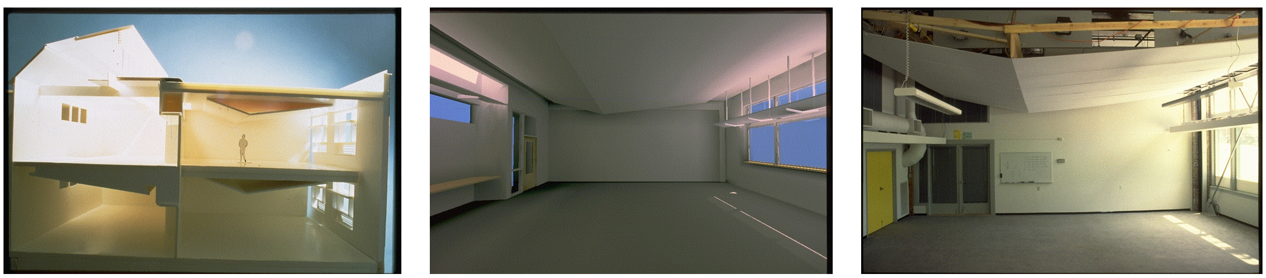
Scale Models

When constructed appropriately, a daylighting scale model provides accurate qualitative and quantitative evaluations of daylight performance. Scale models (from 1/8 in. = 1 ft to over 2 in = 1 ft) furnish information about shading patterns, direct sun penetration, daylight distribution and glare conditions. Smaller models are used for site analysis; larger models, for evaluation of interior spaces. Models must be light tight and constructed with appropriate dimensions and surface reflectance. Larger models may use actual building components (glazing, surface treatments, etc.) to improve accuracy of the model.

Scale models are relatively easy and inexpensive to construct, but testing is time consuming and may require access to an artificial sun and sky facility (known as a heliodon) for accurate studies of multiple scenarios. These facilities are available at some university and utility laboratories. Model studies are conducted for both direct sun and overcast sky conditions. Light level measurements are recorded with small photosensors placed in the model or documented with photographs or videos.

If well built, the quantitative accuracy of scale models can be higher than most current computer simulations. The Lighting Design Lab in Seattle, Washington, has developed a training video on the construction and testing of models in an artificial sun and sky.

The ultimate model study is a full-scale mock-up of the space. Though expensive, these studies can give the most accurate qualitative and quantitative information about the daylight and electric light and allow the designers and clients to experience being in the space. They are usually only constructed for a small representative portion of a larger extended building. Some utility-funded lighting facilities have large spaces with movable ceilings and window walls which may be used to construct the interior of a full scale space.



(a) scale model (b) Lightscape computer simulation (c) full-scale mock-up of classroom

Figure 4-2 – North Clackamas High School Classroom Study Tools
Photographs of North Clackamas High School, Portland, Oregon, courtesy BOORA and LDL.

Computer Simulations

An increasing number of computer programs are available to simulate quantitative daylight levels and qualitative renderings of architectural space. The programs vary in their ability to represent complex architectural spaces (sloped and curved walls, for example) and handle specular reflections. The most sophisticated programs take architectural information from the designer's CAD file, add detail, and generate rendered, textured, color images with specular reflections for a particular location, day and time. They can include the effect of both the daylight and electric light in the space and can generate an automated "walkthrough" of the space for a particular day and time.

The quantitative accuracy of these programs is inherently constrained by the current lack of photometric data for glazing and fenestration products and the dynamic range to qualitatively represent glare conditions. However, use of the daylighting analysis features of either radiosity or ray-tracing programs can be extremely useful, if not perfectly accurate. Simulations for simple spaces that don't require a refined rendering can be accomplished quickly (frequently faster than scale models) and with quite reasonable accuracy. More refined simulations require technical expertise and extensive modeling time. This time is abbreviated if the designer has already constructed an appropriate CAD file. Repetitive parametric runs are easily accomplished.

Daylighting Control Simulation Tools

Some of the common daylight control simulation programs used in the United States are listed in Table 4-4. A more comprehensive list can be found in Daylighting Performance & Design (Ander 1997). None of these tools includes the ability to evaluate savings due to lumen maintenance strategies, lengthening of relamping schedules, and any productivity improvements that may result from the daylight and increased flexibility of the controls. These will need to be calculated separately.

Table 4-4 – Daylighting Control System Simulation Tools

Program Tool	Description	Cost and Availability
DOE-2	Hourly building energy simulation tool developed by LBNL. Commercially available from a variety of suppliers Models both windows and skylights. Evaluates impact on HVAC and savings from lighting controls.	Cost: $400–$1,400 Availability: For a list of commercial versions, go to http://gundog.lbl.gov/dirsoft/d2vendors.html
Energy 10	Hourly building energy simulation tool developed jointly by NREL and PSIC. Limited to buildings less than 10,000 ft². Models both windows and skylights. Evaluates impact on HVAC and savings from lighting controls.	Cost: $250 Availability: Contact Passive Solar Industries Council (PSIC) at (202) 628-7400 X210 or online at http://www.nrel.gov/buildings/energy10
Adeline	Electric and daylight design tool linking a selection of lighting (Superlite and Radiance) and energy software tools with a CAD program to evaluate the HVAC and lighting performance of windows and skylights.	Cost: $450 Availability: Order online at http://radsite.lbl.gov/adeline or contact LBNL Building Technologies Program
SkyCalc	Microsoft Excel-based spreadsheet program (originally derived from DOE-2 runs) that predicts lighting and energy outcomes of a given skylighting system over a range of skylight-to-floor ratios. Includes estimates of energy impacts due to lighting, heating, cooling and controls. Skylights only.	Free Availability: Download free online at http://www.energydesignresources.com or http://www.h-m-g.com

4.4.3 Economic Analysis of Lighting Systems

Some advanced lighting systems increase construction costs. Designers need to know when these additional costs can be justified through future energy savings or other benefits. As discussed in section 2.3, many of the benefits of efficient lighting systems—such as productivity gains—are difficult to quantify. Environmental impacts are also elusive and are often called externalities because they are external to most analyses of economic performance.

The construction or initial costs of lighting systems are a key concern to all players. To be successful, an advanced lighting system must also meet the economic criteria of the building owner. These criteria may not appear immediately rational to the outside observer, as discussed in Economic Limitations below. Comparison of alternative lighting systems should include all relevant costs associated with a lighting system, and use an appropriate analysis tool, as discussed in Economic Decision-Making below. Lighting retrofit projects should start with a screening of all possible projects for those that have the greatest potential, a quick scoping study, and then if warranted, an investment grade audit should be performed, as described below in Retrofit Assessment and Lighting Audits.

Economic Limitations

Energy efficiency advocates have long thought that if only they could prove the economic rationality of efficiency improvements, then surely reasonable decision-makers would choose the more efficient strategies. This has repeatedly proved a much more difficult sell than originally thought. Lighting systems in commercial buildings have been greatly undervalued and often are of much poorer quality than could be easily justified economically. Reasons for underinvestment in lighting systems include:

- Last-minute changes to the lighting specifications that allow the substitution of inferior products.
- Decision-making based on initial installation costs, rather than long-term operating costs.
- A market culture that is driven by the sense that "what everyone else is doing" must be right.
- A deep-seated belief that lighting doesn't really affect worker performance (see the sidebar **There's No Such Thing as the Hawthorne Effect** in chapter 2.)

Substitutions

Lighting installations in commercial buildings often suffer by being the last major system to be installed in a building, and are perhaps therefore the most susceptible to last-minute cuts to the construction budget. Lighting designers complain that their designs are frequently changed without their review by a "value engineering" process where contractors recommend that specified items be replaced with lower quality products. Construction scheduling is also often used to "break the spec" by claiming that the specified product is not readily available and that waiting for it will slow down construction. Building owners who called for high quality lighting during the design process may discover after occupancy that they received only mediocre lighting systems as a result of decisions made during construction.

Importance of Initial Costs

Like it or not, initial cost is the prime criterion for evaluating most construction decisions. Construction budgets are extremely sensitive to a system's first cost, and are much less sensitive to a system's life-cycle costs. Construction and renovation projects are seen as one-time expenses with pre-set budgets, managed independently from other business expenses. Design teams are tasked with meeting the budget as their primary objective. Furthermore, most private sector companies must borrow money for building projects. With financing, the time value of money puts even more pressure to keep the construction budget as low as possible. Businesses must prove to the bank that their building is worth the investment. Prudent risk management generally suggests keeping that investment as low as possible, putting even more pressure on keeping the construction budget as low as possible.

Government agencies have tried to change this "initial cost" culture by insisting that all public building projects be evaluated using life-cycle cost criterion. Clear rules and procedures have been developed, evaluations are dutifully performed and recommendations made. However, even in these situations, the construction budget and schedule often become the final criterion in decision making. Recommendations can be ignored, but budgets must be met. Thus there is enormous pressure to reduce the initial cost of lighting systems. Any increase in cost must be convincingly justified; and even then, it's likely to be ignored when the project team is confronted with the final budget.

Market Culture

It's also important to understand the "market culture" involved in lighting decisions. Both developers and government agencies often want to be doing what everyone else is doing; they don't necessarily want their buildings to be exceptional. Once a particular lighting system is accepted as "standard practice" or as "modern," many people assume that it's "better" and use the system indiscriminately in every application. A recent example of this mentality is the pervasive use of parabolic luminaires whether they are needed for glare cutoff or not. This market culture is not economically rational, but it can be influenced by leaders in the field who make thoughtful decisions.

The key to greater investment in lighting systems will ultimately depend on a widespread understanding that quality lighting makes an important contribution to worker performance. Efforts are underway to quantify these benefits, as discussed in section 2.3 – Light and Productivity.

Economic Decision-Making

Most companies spend very little time assessing the economic value of lighting alternatives. The easiest path is to do "the same thing we did last time." Some companies may do a quick payback check, which may be no more than a "back of the envelope" calculation. However, without more careful financial assessment, many of the advantages of advanced lighting systems will be ignored or undervalued.

There are a variety of methods to evaluate costs and benefits of lighting alternatives and put them into an economic equation. These include:

- Simple payback, which compares installation costs to the expected first-year savings from the new system, usually just energy savings. It's expressed as the amount of time required to pay for the incremental cost of the system with increased savings, in terms of months or years. Simple payback always underestimates the value of energy and maintenance savings because it doesn't consider the time value of money.
- Life-cycle cost analysis (LCA), which considers all the costs over the life of a system, including energy, maintenance, disposal, and the time value of money based on expected inflation rates or standard interest rates. It's very useful when comparing systems with different life span and period costs, like maintenance, that occur on different schedules. Different systems are compared by their annualized cost of ownership.
- Return on investment (ROI), which can consider as many or as few factors as the analyst wishes. The final answer is expressed in terms of the value of the investment in the system, compared to the value of any other investment.

Publications are available that thoroughly detail how to perform these economic analyses.[26] There is a basic trade-off between simplicity and accuracy in choosing which method to use. Software tools have made the more sophisticated economic analysis methods within reach of anyone with a computer. The Federal Energy Management Program (FEMP) has developed a series of software tools to facilitate life-cycle cost analysis of energy related projects.[27] Many private-sector lighting programs also include a variety of financial analysis options.

The key to any economic analysis will always be the accuracy and completeness of the information inputs. Simple analysis based on rough guesses or defaults provide "ballpark" estimates. This level of analysis is usually appropriate at the initial states of a project. Sophisticated analysis considers more detailed data from documented and updated sources. Such careful analysis is highly appropriate to any major investment or policy-level decision.

All of the costs and benefits associated with a lighting project should be considered in a careful economic evaluation of a lighting system. These include:

- Installation costs
- Financing costs
- Design and management costs
- Energy costs
- Maintenance costs
- Human factors
- Environmental benefits (externalities)

These costs and benefits are described below.

Installation Costs

Installation costs, also called first costs or initial costs, are all the costs to purchase and install a fully functioning system in a building. They properly include:

- *Equipment cost*, including distributor's and contractor's mark-up, and shipping charges

[26] See the lighting economic analysis information included in the *IESNA Lighting Handbook, 9th Edition*, EPRI's *Lighting Fundamentals Handbook*, and various publications and software available from the Federal Energy Management Program's Web site, http://www.eren.doe.gov/femp/ordermaterials.html.

[27] For more information on federal economic analysis tools, go to http://www.eren.doe.gov/femp/techassist/softwaretools/softwaretools.html.

- *Labor to install equipment*, including placement, wiring, cleaning and contractors' mark-up
- *Labor to commission* and train building employees in proper operation of the system
- *Any discounts*, rebates, or incentive payments

There are often trade-offs between equipment and labor. Reduction in wiring and installation costs can often counterbalance more expensive equipment. For example, linear pendant luminaires can sometimes reduce costs over recessed troffer alternatives by reducing the number and complexity of wiring connections between luminaires.

Similarly, any project involving moving parts or adjustable settings needs to be commissioned on-site to be sure that it is functioning as intended. Commissioning costs should be included in any budget allowance. A construction budget should also include an allowance for the contractor to train building employees in the proper maintenance and operation of systems.

Any discounts, rebates or incentive payments should also be factored into installation costs. Utility companies have often tried to encourage the installation of more efficient systems by helping to "buy down" the installation cost with incentive payments or rebates to the building owner. These programs change, so check current program rules and availability with your local utility representative rather than assuming that such incentives will be available for a given project.

Financing and Appraised Value

As discussed above, the cost of financing construction projects is considerable and becomes a motivator to keep the project "on time and on budget." Any increase in initial cost or extension of the construction finance period multiplies the final cost of a project. Depending on the specific terms, financing costs can easily equal or exceed the installation costs of a project.

Whenever possible for private-sector projects, managers should try to take advantage of the reduced operation costs and improvement in overall building value of a new lighting installation to help leverage the financing limits for a project. Banks typically determine their financing allowance based on expected income from tenants less all operating costs, times a capitalization rate. For example, with a 10% capitalization rate, which is fairly typical in the construction industry, a $0.20/ft² reduction in yearly energy costs translates into an increased total building value of $2.00/ft², which would likely cover the additional costs for a state-of-the-art lighting system.

Similarly, many people are looking for ways to help appraisers recognize the value of such energy savings when they assess the value of a commercial building for resale. If appraisers assigned an increase in value to a building with improved energy efficiency or enhanced lighting quality, it would provide a major incentive for developers to invest in those features since it would add to the building's permanent valuation. Essential to achieving this goal is an objective measure of building performance that appraisers can easily reference and compare to an industry standard. Since appraisers only compare projects within small geographic areas, typically on the scale of a city or even neighborhoods, this information must be available at a similar geographic level. One effort in this direction is the Energy Star Building program initiated by the U.S. Environmental Protection Agency (EPA).[28] Another is an ongoing project in California to develop a statewide database of building characteristics that might be used to establish industry norms by building type and age. Developed by investor-owned California utilities, this database currently resides at the California Energy Commission.

Many large institutions and governments have a difficult time financing lighting renovations, even when the financial analysis clearly shows that it would be a wise investment. To help these organizations, a new industry has evolved that essentially finances projects by taking a share of the energy savings. This approach is often referred to as "energy cost sharing," and companies that provide this service as "energy savings companies" (ESCOs). The federal government has created a new form of contracting called

[28] For more information, go to http://www.energystar.gov.

"energy services performance contracting" (ESPC) to enable federal agencies to take advantage of this financing mode.[29]

Design and Management Costs

Many analysts forget to include the cost of design services and time spent managing a project in their calculations of cost effectiveness. People often make subconscious choices here, deciding to go with a "quick and dirty" approach that can get a job done quickly, but may not optimize its quality and cost effectiveness.

Professional design services do add to a project's real cost, as does the time to manage those design services. However, an experienced and qualified practitioner knows how to optimize a lighting system for the owner's needs and can greatly improve the economic value of a project. National Council on the Qualifications of the Lighting Professions (NCQLP) requires that practitioners who have earned the designation LC (Lighting Certified) have knowledge of economic analysis and can perform this function for their clients (see section 3.3.4).

Lighting design practitioners who are asked to perform careful economic analyses or create alternative scenarios for comparison will expect to be paid for additional services. A number of utility programs recognize this increased cost and help to reimburse the designers for these services.[30]

Managing a lighting project also involves time on the building owner's end. Building owners generally prefer making quick, well-informed decisions rather than spending a great deal of time considering alternatives and approving design changes. Thus, simple proven design strategies have a decided economic advantage. Participating in special programs, such as government certification programs or utility incentive programs, can also involve considerable administrative time, especially if eligibility must be certified with much paperwork or with on-site audits. Program designers must be sensitive to this issue, or they will find the "transaction costs" will discourage participants from joining the program.

Energy Costs

A full assessment of energy costs should include:

- Per-unit energy charges
- Demand charges
- Fixed charges
- Escalation rates
- Discounts and other benefits

These factors are discussed below.

Per-unit Energy Charges. Calculating energy costs used to be relatively straightforward once you knew total wattage and hours of operation of a lighting system. Most lighting energy analysis assumed an average cost per kilowatt hour[31] and used the simple equation:

Energy cost per year = Connected load in kilowatts x Hours of operation per year x $/kWh

Equation 4-1

Per-unit energy charges become more complex when they vary by time of use. For example, some utilities charge more for electricity used during the day than at night. The average cost per kilowatt hour

[29] For more information on financing options for federal projects, go to http://www.eren.doe.gov/femp/financealt.html.

[30] For example, in California, the statewide *Savings by Design* program offers payment to design teams, as does the *Design 2000* program from National Grid serving areas of New England.

[31] *Energy User News* publishes average costs of electricity by sector and utility.

can still be calculated based on total energy bills for one year divided by total energy use for the same period. However, a better understanding of the cost savings due to an energy efficiency measure will involve knowing the time of use for different systems and the load profile for the building. (See discussion of lighting load profiles in section 3.1.4.)

Demand Charges. A more sophisticated analysis also looks at peak demand and associated demand charges. In some regions of the country, peak demand charges can become more costly than overall per unit energy charges. By reducing connected load with lower power densities, or peak demand with controls that reduce use during peak periods, building owners might save more money than the value of the straight energy savings.

Considering demand impacts makes the equation much more complex, because now you must know when particular watts are used, by season or time of day, and even how lighting loads relate to other loads in the building. Does peak lighting use coincide with peak periods defined by the utility? And do those lighting peak loads also coincide with other peak loads in the building? Such an analysis requires not only more information, but also a program that can simulate building energy use hour by hour.

Demand savings are also rarely certain, and difficult to attribute to one building system over another. Some utilities shift demand periods by weather conditions, and most buildings have different peak demands as weather changes. Some lighting strategies, like using photocontrols in conjunction with daylighting, offer considerable opportunities to reduce peak lighting demand. However, this isn't a certainty, since in any given year a utility peak load might occur during a day or time period that was not optimum for daylighting. If the building owner can't be guaranteed that demand savings are absolutely predictable, he or she may not be willing to include demand savings in a comparison between systems. (See discussion of demand management in section 8.1.5.)

Fixed Charges. Energy pricing structures seem to be headed in the same direction as telephone bills: numerous types of fees and charges, such as breaking energy charges down into connection charges, fixed monthly charges, variable time-of-day rates, and peak use surcharges. Telephone companies have learned to compete based on minimizing the advertised cost of a call per minute, while making their profit on other fees and charges. Similarly, when utility companies shift more of the cost of providing electricity to fixed charges per customer, the incremental value of energy savings to the customer is generally diminished.

Escalation Rates. If energy prices are expected to rise in the future, the value of current energy savings also increases. Of course, no one really knows what's going to happen in the future, so any guess might be as good as another, unless one is trying to compare cost-benefit analyses of projects generated under different assumptions. To simplify and standardize life-cycle cost analysis, the Energy Information Administration[32] studies energy availability and cost escalation rates and publishes an official prediction for energy escalation rates by fuels type and region. With deregulation, these predictions have become less certain.

Discounts and Other Benefits. Deregulation promises building owners even more options in fee structures. One utility might offer free phone service based on your energy bills. Another utility might offer an initial discount on energy rates for the first year if you sign on with them for multiple facility locations or across state lines. How will building owners compare lighting alternatives with this proliferation of pricing structures? If deregulation also allows the price of energy to float with the open market, much as variable rate home mortgages do, the time value of energy savings will become even more unpredictable.

Given this growing complexity, building managers will need to carefully analyze their billing structure in order to understand the relationship between energy use and energy cost. Complexity and unpredictability work against easy analysis of energy costs.

Maintenance Costs

The cost of maintaining a lighting system include:

[32] See http://www.eia.doe.gov.

- Routine maintenance, such as cleaning luminaires, troubleshooting systems, and spot replacement of early failures, including both labor and equipment costs
- Scheduled group replacement, including both labor and equipment costs
- Stocking costs to warehouse parts, or order as needed
- Disposal costs for lamps and ballasts

Labor costs of lighting systems are not trivial and should be included in any comparison between system options. Because maintenance costs are periodic, and both labor and equipment costs are likely to escalate over time, a life-cycle cost analysis is the most sensitive approach to evaluating the impacts of maintenance costs. Generally, lighting maintenance costs will be reduced by: reducing the number of luminaires and variety of components per facility; extending the system's life; improving the system's reliability; increasing the accessibility and simplicity of the system; improving the cleanliness or airtightness of a system so that there's less dirt accumulation; and making the system more environmentally benign so that disposal and liability costs are reduced. Chapter 7 provides information about lighting system maintenance issues.

Productivity Benefits

The ideal economic analysis would include human factors in the costs and benefits of different lighting systems. This is, of course, very difficult to do as it usually involves comparing apples to oranges. For example, a recent study showed that increased daylighting in elementary schools improved student learning rates by 20% on standardized math tests and 26% on reading (Heschong Mahone Group 1999). While this is clearly important to the central mission of a school district, how much is it worth in terms of an investment in a daylighting system?

It's clear that the cost of providing and operating lighting systems is minuscule compared to the cost of employees. A careful study looking only at the federal government's office workforce concluded that the yearly cost of labor, in 1995 dollars, is about $164/ft² of building area (Harris et al. 1998). This is a function of both the cost of labor and the density of the workers in the building. Many higher paid and higher density corporate offices have been estimated at $300 to $400/ft². Compare this to the cost of a new efficient lighting system, at a one-time installation cost of perhaps $2.50/ft², and the value of energy to operate it, at perhaps $.20/ft² per year.

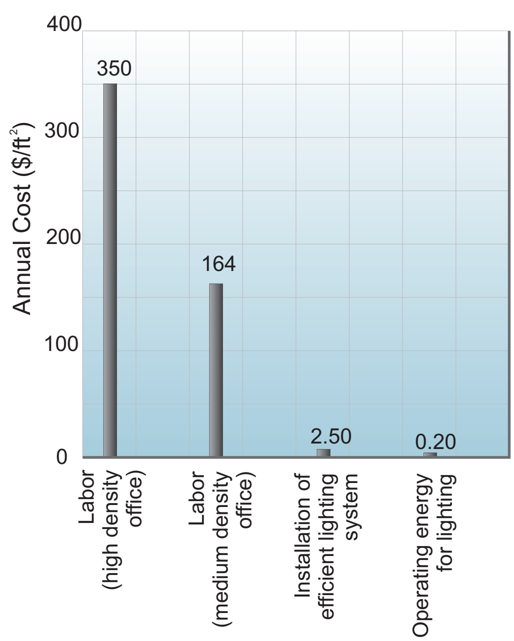


Figure 4-3 – Building Costs Relative to Business Operating Costs

In the case of the federal office workers, consider a higher quality lighting system, which resulted in a 50% increase in lighting installation cost, from $2.50/ft² to $3.75/ft². If this system also resulted in a mere a 1% increase in productivity, the additional cost would be paid for in nine months, without accounting for any other savings from energy or maintenance. For the corporate case, this payback is reduced to four or five months.

Clearly, productivity impacts are vastly more important than energy savings. A 1% increase in office worker productivity is equivalent to an additional 5 minutes of productive work per day, clearly within the range of plausibility. Actual studies have shown significantly higher productivity impacts than 1%. Researchers at Natural Resources Canada (Veitch and Newsham 1998) found that lighting conditions could be shown to affect clerical workers' performance on various tasks. Overall, these effects ranged from 1% to 25% for various task types.

This argument, however, has two sides. If a lighting system causes any loss in productivity, the impacts are just a great, but in the opposite direction. This is an excellent argument for investing in professional design services to ensure that lighting installations truly optimize conditions for workers.

Environmental Impacts

Environmental impacts that are not charged directly to a building owner are also very difficult to include in an economic analysis. While most business owners may have good intentions to help the environment, these intentions are likely to be dropped unless they can be included in the bottom-line equation. Environmental labeling programs attempt to make environmental benefits more tangible by providing a business owner with a third-party evaluation that they have achieved a real reduction in environmental impacts. Labeling programs also offer an opportunity for marketing and advertising benefits that may improve the bottom line. The U.S. EPA's Energy Star Buildings program, the U.S. Green Building Council's LEED labeling system, and various other "green" or "sustainable" building rating programs are all efforts to increase the value of environmentally sensitive buildings. An alternative approach adopted by some government agencies is a policy allowing a blanket "environmental multiplier," on the order of 10%, to the annual value of any energy savings to account for various externalities like a reduction in acid rain or smog generation due to power plants. (See section 3.2 for more information about the environmental impacts of lighting.)

Retrofit Assessment and Lighting Audits

Retrofit projects typically involve a different type of analysis than new construction projects because they compare existing conditions and costs with proposed retrofit design options. This analysis usually includes a lighting audit, an assessment of what is already in place and what the current ownership costs are. The following discusses economic analysis of retrofit opportunities; see section 7.9 for information about design criteria for lighting retrofits.

Lighting audits can be expensive, so to reduce initial costs it's wise to take a stepped approach to assessing the economic viability of any retrofit project. The first step, screening, offers the lowest cost and quickest assessment of a range of potential projects and allows a facility manager to prioritize which projects should be addressed first. Those that are most likely to be economically attractive, or pressing for other reasons, would then be investigated a little more deeply in a scoping study. A scoping study permits the project to obtain financial commitments from the owner or lenders before incurring the larger cost of an investment grade audit. These three assessment types are described below.

Screening

The first step in identifying a retrofit project is to screen all potential projects for their potential value. Questions to ask include: Are the energy savings likely to be substantial? Will lighting quality improvements make a difference to worker performance? Are there other benefits, in terms of maintenance costs, environmental benefits or aesthetics that may justify the cost of a retrofit?

Screening multiple projects is typically done with very rough default assumptions about the equipment and operation of lighting systems in a building. Quick "guess-timates" based on the age of the lighting system and type of building are often sufficient at this stage to rank potential projects. There are a few simple criteria to consider at this stage:

- Older lighting systems are likely to have more energy and maintenance savings potential from efficiency improvements
- Longer hours of operation will increase the value of any energy savings
- Higher energy costs will increase the value of any energy savings
- Vision-critical tasks will increase the value of lighting quality improvements. Highly paid workforces and high value products both increase the monetary significance of performance benefits from improved lighting.
- Simultaneous remodeling projects will offer opportunities for shared costs and integrated design solutions that will expand retrofit options. Historic renovations or interior remodeling both present important opportunities for lighting improvements.
- Missed lighting control opportunities often present very cost-effective retrofits, as substantial cost savings can be achieved without major alterations. Adding photocontrols to a building that already has significant daylight, or adding time or motion controls to lights that are left burning all night are easy retrofits with enormous savings potential. (Controls are discussed in chapter 8.)

Scoping Studies

A scoping study or “walkthrough” involves a rapid survey by an experienced auditor, followed by an economic analysis of the approximate energy conservation measures. To save time and money, an auditor performing a scoping study will usually only observe a sample of typical spaces within a building, to get a sense of the general type and condition of the lighting equipment and the major opportunities for a retrofit project.

A scoping study reduces financial risks by estimating the financial viability of a project before an owner makes a commitment to the more significant cost of a full audit. If the proposed project doesn’t occur, only the smaller costs are lost. A scoping study can also sometimes be sufficient to define the scope of an energy services performance contracting (ESPC) project, or can be appropriate to identify the simplest component retrofits in highly uniform buildings. A scoping study might cost on the order of $.01/ft² or less.

Investment Grade Audits

An investment grade audit is a thorough survey and engineering study supported by complete documentation. A detailed audit and evaluation might cost two or three times as much as a scoping study. The intent of the investment grade audit is threefold:

- Provide sufficient information about existing lighting equipment, energy use, and lighting quality to document the "before" condition.
- Analyze the economic potential and other benefits of proposed retrofits to optimize retrofit choices and to justify financial investment.
- Provide sufficient information to define the scope of work for the retrofit contract. An investment grade audit that analyzes more than one alternative can provide the owner with a choice of project levels to pursue.

Information collected in an investment grade audit should include:

- Detailed utility rate data and history, including time of use charges, demand, etc.
- Room-by-room, luminaire-by-luminaire equipment counts for the entire building including light level readings.
- Use of lighting loggers to determine actual operating hours and control system function.

Analysis provided in an audit report should:

- List all energy conservation opportunities, and propose one or more appropriate retrofit measures for each.
- Evaluate the energy and cost savings of each retrofit measure, using detailed cost information and taking all nuances of utility rate structure into account.
- Discuss the lighting quality, human performance, aesthetic and maintenance improvements that may be realized.
- Estimate construction budgets and life-cycle costs for alternative approaches.