

# Daylighting Application and Effectiveness in Industrial Facilities

*Brian McCowan, Energy & Resource Solutions, Inc.*

*Daniel Birleanu, Energy & Resource Solutions, Inc.*

*Natalie Hildt, Energy & Resource Solutions, Inc.*

## ABSTRACT

Historically, daylighting has been extensively used for the lighting of industrial spaces. Before the advent of practical mercury vapor and fluorescent lighting, the only available artificial lighting for industrial buildings was incandescent. The illumination of active industrial workspaces with incandescent lighting is difficult, so during the industrial revolution, architects utilized various daylighting strategies such as window walls, skylighting, monitors, etc. However, glazing technologies were also primitive compared with our modern glazing choices, and space conditioning and glare problems plagued day-lit spaces. When more efficient and effective artificial lighting became available, most older day-lit industrial buildings had their daylighting features boarded over. With modern glazing systems and sophisticated designs that minimize glare issues, daylighting for industrial buildings is making a strong comeback. Additionally, new controllable ballasts and automatic lighting controls make possible hybrid lighting systems that are able to provide optimal lighting under all environmental conditions.

This paper will demonstrate discuss how the daylighting systems developed decades ago are being modernized to provide high quality, low-glare, uniform lighting, without the space conditioning penalties of the past. Premium glazing systems that limit heat losses and gain will be discussed. The importance of glare control in day-lit spaces, for worker safety and productivity, will be stressed, and a variety of passive and active strategies will be presented including: redirected beam daylighting; reflective light shelves; and movable baffles and louvers.

In order to take full advantage of daylighting systems, artificial lighting must be able to react to the changing natural illumination conditions, sometimes complimenting daylighting, and oftentimes replacing daylighting. Various continuous dimming and multi-level lighting strategies will be discussed, including the proper placement and commissioning of controls. Matching the quality of natural daylighting with the artificial lighting system is also important for worker comfort and productivity, and the proper selection of lamps for chromaticity and color rendering abilities will be discussed.

## Introduction

Daylight was the primary source of interior lighting in the pre-industrial world. The direct combustion of fuels (wood, coal, peat, oils) were supplementary light sources. Because of the importance of daylighting, early architecture developed with a strong connection between natural lighting and building form and techniques.

Daylight was still an integral part of illumination systems well into the industrial age, as a visit to any historic mill town in the United States will remind us. Early industrial buildings were daylit out of necessity rather than productivity or aesthetic considerations.

Artificial light sources were ineffective, inefficient, and maintenance problems. Additionally, heating fuel was inexpensive, and more importantly, industrial processes were inefficient, producing abundant waste heat for the facility. The fact that windows and skylights were thermally inefficient mattered little, and the ability to open windows provided for ventilation when mechanical ventilation was non-existent or inadequate (Smithsonian Institute 2001).

When fluorescent and high-intensity discharge (HID) lighting were introduced, they quickly replaced incandescent lamps as the technologies of choice for industrial buildings. This was due to their much higher efficacies and their longer lamp lives. The enhanced illumination levels reduced the need for daylighting. Not long after the onset of these technologies, fuel prices started to climb dramatically, thus compelling designers to make industrial process machinery more efficient. Less waste heat was generated, and the need to conserve heating fuel led to boarding over windows and skylights in the 1970s.

The introduction of high performance glazing materials, the advent of controllable industrial lighting, along with an enhanced knowledge of the advantages of daylighting has brought back the popularity of daylighting for industrial buildings. Today we recognize the high performance attributes of daylighting. Architects and lighting designers are borrowing from yesterday's designs, while incorporating modern materials, technologies, and ideas to bring daylight into industrial environments. The benefits of these designs include improved productivity, worker health, energy savings, and enhanced aesthetics (EDC 2001).

### **Condensed History of Pre-Industrial Daylighting**

Around 1500 B.C. the Egyptians developed a style of architecture that featured multiple small openings in thick stone-slab walls that filtered light into interior spaces. The number of openings was varied according to the intended use of the space. Additionally, the use of courtyards to increase exterior wall surfaces was pioneered. In Greece, the use of a single large skylight was developed, and light reflected off of floors was used to illuminate detailed ceiling surfaces and monuments/statues. Romans developed concrete, and the longer spans it allowed gave rise to window walls and domed ceilings. The Romans were the first to use glazings and developed the clerestory. Islamic and Early Christian cultures utilized rows of vertical windows, reducing the dependence on overhead lighting. The development of sophisticated structural arches and vaults in gothic architecture freed-up more wall space for glazing, and the percentage of glazing increased dramatically. The Renaissance brought a level of sophistication to daylighting with an emphasis on illuminating architectural details, and recessed window openings were often hidden from view (Williams 1999, Smithsonian Institute 2001).

### **Early Electric Lighting Supplemented Daylight**

Historically, daylighting has been extensively used for the lighting of industrial spaces. Prior to the 1940s, incandescent lighting was the only practical choice for factories and warehouses. Even with very high wattage (500W, 1,000W, & 1,500W) lamps, lighting levels were quite limited. If facility owners were willing to install numerous high wattage incandescent fixtures in a high-density installation pattern, the maximum amperage of the circuits and/or the facility was still a limiting factor. With the limited performance of electrical lighting, industrial spaces were typically illuminated with a combination of

daylight and artificial light. Buildings were kept narrow to take advantage of natural lighting, and courtyards were often incorporated into designs. Most work was performed during day shifts, with second and third shifts typically restricted to critical tasks that were illuminated with local illumination. The development of steel frame architecture allowed building widths and heights to be increased. It also allowed glazing areas to be increased dramatically, bringing more natural light into the interiors of these wider structures (Smithsonian Institute 2001).

Increases in the amount of glazing introduced and/or aggravated many problems. Glare as well as building heat loss/gain were significantly increased. Glazings were still primitive, with most building relying on single layers of translucent glass. The resulting discomfort from direct and indirect daylight glare was a major problem, and sometimes totally debilitating for workers. Cold glass surfaces in the winter caused workers to radiate their heat toward the glazing, but more significant was the discomfort from summer heat gain contributing to an environment already made uncomfortable from waste process heat.

### **Fluorescent and HID Technologies**

As mercury vapor and fluorescent technologies became practical and prevalent, designers were able to provide greatly increased illumination levels for the same electrical demand. It is important to remember that the emphasis was not on energy conservation, but on providing enough light for productive work to be accomplished.

The acceptance of mercury vapor and fluorescent lighting had many effects. One was that companies began operating second and third shifts, because they could now provide effective lighting. Additionally, workers began to adjust to and expect reasonable amounts of lighting in the workplace. In fact, the Illuminating Engineering Society (IES) began increasing the recommended levels for industrial lighting dramatically during the 1940s and 1950s (IES '49, '52, '59).

### **Industrial Daylighting Enters a Dark Age**

In the 1970s and 1980s, three coinciding events led to the boarding up of windows and skylights, and a virtual temporary end to designing industrial buildings with daylighting. These factors were rising fuel prices, improved process efficiencies, and the advance of fluorescent and high intensity discharge lighting technologies.

- **Fossil Fuel Prices.** Readers of this paper do not need an education on what happened to the cost of fossil fuels during the 1970s and 1980s. The increased fuel prices forced plant managers to focus on heating and cooling loads as well as process efficiency. Process efficiency was seen as the hardest “nut to crack,” so heating and cooling loads were approached first. Unfortunately, even in many facilities where process waste heat was the main heat supply and windows provided the only ventilation, glazing was seen as a major culprit. Window walls, skylights and monitors were boarded over and (sometimes) insulated. By the 1970s, fluorescent, mercury, or metal halide lighting was used widely and was for the most part supplying adequate light for second and third shift operations. During this period, architects began to shift

from daylit industrial building design to designs with little or no glazing in the process areas, reserving glazing for office areas.

- **Improved Process Efficiencies.** In recent decades, industrial processes have seen steady gains in efficiency. By the 1970s, most steam-driven processes had been replaced with electric motor drives, and compressed air had begun to be reserved for its most appropriate uses. The slow but steady process efficiency gains were given a significant boost by the fuel crisis of the 1970s. Suddenly, machine designers were asked to develop machines that used energy more efficiently, not just worked faster. The result of course was less waste heat to the work environment, reducing the need for thermal exchange through operable glazing.
- **Continuing Advancement of Fluorescent and HID Lighting Sources.** During the 1960s and 1970s most industrial facilities replaced their high wattage incandescent lighting with fluorescent and/or HID lighting. The efficacy, color rendering, and lamp life of fluorescent lighting benefited from steady improvement, and the development of high output T12 fluorescent systems offered not only greater illumination, but also operation at low temperatures. Mercury vapor lighting had also been improving, but metal halide lighting was rapidly becoming the HID system of choice for white lighting. High pressure sodium also was making inroads because of its high efficacy, but its poor color rendering abilities created another set of problems. All of these advancements allowed building designers and facility managers to provide sufficient artificial lighting at reasonable installed and operational costs, eliminating the core needs for daylighting.

## **Renewed Interest in Daylighting for Industrial Facilities**

Ironically, the concerns over fuel prices that helped shelve daylighting were also a major factor in its return. During the 1970s and early 1980s, Europe, Asia, Australia and the United States experienced an amazing effort to develop practical solar energy systems. Passive solar buildings were at the forefront of this movement, and in an effort to heat space with solar energy, architects began to design commercial and industrial buildings with glazing oriented toward the winter sun. Many existing buildings that had previously had the glazings on all orientations covered over were now having selected areas opened back up to the winter sun. The desire to bring solar energy into the buildings as a source of heat was inadvertently reintroducing daylighting (EDC 2001).

Of course, this reintroduction of large glazed surfaces also brought back the same problems that had plagued earlier daylit buildings: glare, uncontrolled heat gain, heat loss, etc. Materials engineers and building designers moved quickly to resolve these problems (Miller 1998).

## **Modern Industrial Daylight Design: Breaking New Ground with Ideas from Past**

In the early days of industrial daylighting, daylight was relied upon because it was far superior to any other available source of light. Today, daylighting is experiencing a resurgence for the same reasons. Light from the sun is the highest-quality form of light for the performance of visual tasks. The performance of all artificial lighting is measured against

daylight, as daylight offers the ultimate ability to render colors and provide contrast. Daylight “brings the outdoors, indoors” providing an attractive and interesting environment. The lively changes in brightness and color give building interiors visual interest that cannot be obtained with artificial lighting. In addition, daylighting can offer significantly reduced electrical consumption for lighting, even if the connected lighting load (lighting power density) remains essentially unchanged (IES 1999).

As pleasing as natural daylight can be, if it is not properly incorporated into the design, it can create problems to rival the poorest designed artificial lighting system. Sunlight is not always reliable or constant, and without careful daylighting design, direct and indirect glare can be severe. Careful control of daylight, as well as its integration with electrical lighting and lighting controls is the key to lighting that is appropriate, comfortable, and energy efficient (Levy and Wegman 1994).

It has long been theorized that controlled, comfortable, natural daylight enhances worker comfort, productivity, and accuracy. Recent studies, including those performed by the Heschong Mahone Group on both worker and student performance in various environments, support this theory. In addition to the advantages of bringing abundant, high color rendering light into the workplace, many types of daylighting designs connect the workers with the outside world, reducing or eliminating the feeling of being trapped in an artificial environment while at work. As previously mentioned, introducing daylight into buildings presented many difficulties and challenges. Advancements in many materials and techniques are meeting these challenges (Heschong Mahone 1999).

- **Improved Glazing Materials.** As one segment of the solar energy industry developed insulating window treatments, the glass manufacturers began developing higher performance glazing. Multiple layers of glass became common, while other developments included Low-E (emissivity) coatings and Low-E membranes installed between glass layers, such as Heat Mirror™. Today, there is an amazing selection of high-performance glazing materials available for daylight design. These include materials with a low “U” value, tinted glass for reduced heat gain, materials that offer reflectance of UV and IR rays, and glazing assemblies that include auto-adjusting shading features. Performance of these materials is presented in Table 1. Modern skylights feature improved gasketing and flashings to eliminate the leakage problems that previously plagued these products (New Buildings Institute 2001).
- **Advanced Gasketing for Operable Windows.** Widely recognized as one of the biggest mistakes of modern architecture was the loss of operable windows. Total reliance on mechanical ventilation is not only energy intensive, but also further removes workers from the natural environment.
- **Improved Adjustable Blinds.** Controlling glare is one of the most significant challenges in daylight design. Adjustable blinds have seen many improvements over the last two decades, including new materials and automatic controls that respond to incoming sunlight. For practical reasons however, blinds are typically restricted to “clean” manufacturing areas, as well as office areas, within industrial facilities.

**Table 1.****Selectivity Performance of Glazing Options**

	U - value	T <sub>vis</sub>	Shading coefficient	SHGC	K <sub>e</sub>
Single clear	1.11	0.90	1.01	0.87	0.89
Double clear	0.49	0.82	0.90	0.78	0.91
Double low-e e = 0.20	0.35	0.75	0.81	0.70	0.93
Double low-e e = 0.10	0.32	0.77	0.69	0.60	1.12
Double low-e e = 0.03	0.30	0.71	0.51	0.44	1.39
Single PPG Azurlite	1.11	0.77	0.67	0.57	1.15
Single LOF Evergreen	1.11	0.77	0.72	0.62	1.07

Source: Florida Power and Light – www.fpl.com

(T<sub>vis</sub>) - Visible transmittance (SHGC) - Solar heat gain coefficient (K<sub>e</sub>) - Luminous efficacy constant (U-value) – Heat transfer coefficient

- **Revitalized and New Architectural Design Ideas.** History shows that indirect daylighting was developed over 3,000 years ago. Early daylit industrial building took advantage of indirect sunlight through the use of standard monitors, saw tooth monitors, and clerestories. Although rarely sophisticated designs, these systems typically included the reflecting of at least some of the light off of solid architectural surfaces before it was delivered to the workplace, thus softening the effect and reducing debilitating glare. Better technology has allowed for a resurgence in these old techniques.

Today, daylight control techniques also include monitors, clerestories, and skylights. Added to this mix of design approaches are: dedicated vertical visual glass (windows) and dedicated daylight glass (above line of sight), reflective light shelves, redirected “beam” daylighting, and movable baffles and louvers (New Buildings Institute 2001, Weidhaas 1981).

- **Longitudinal Monitors.** This design feature is essentially a penthouse that runs the length of the building, straddling the main roofs ridgeline. Typically, vertical glazing covers both sides of the monitor, with some monitors also incorporating skylights. The daylight is introduced above the workers normal line of sight. Morning and afternoon sunlight is usually reflected off of architectural surfaces, further reducing glare.
- **Saw Tooth Monitors.** These rooftop architectural features are shaped like saw teeth, with the vertical planes being glazed to allow daylight to reflect off of the angled opposite surface bringing indirect light into the space.
- **Clerestories.** These are essentially sections of vertical glazing that are incorporated into the design, high on the wall, above the main story that they are illuminating.
- **Skylights.** We are all familiar with skylights, but new designs offer advanced glazings, integral diffusers, reflective wells/shafts, and movable baffles.
- **Dedicated Visual and Daylight Glass.** Window walls are a nice architectural feature in that they introduce both daylight and a visual connection to the outdoor environment. Glare and heat gain/loss are of course problems. Increasingly, architects

are distinguishing between visual and daylighting glass. Asking one window to provide both elements is a difficult, sometimes impossible, task.

- **Reflective Light Shelves.** These architectural features redirect daylight to provide a diffuse indirect source. Interior or exterior light shelves are typically associated with vertical glazing. Often the most effective light shelves direct light upward to be reflected again off of a light-colored ceiling surface.
- **Redirected Beam Daylighting.** In reality, all indirect forms of daylighting take advantage of redirected beams. However, the term has come to be used to describe systems that do not include visual sight lines to the outdoors. For this reason they are usually used in conjunction with visual glass. Redirected beam systems can be integral architectural site-built features, or can be manufactured products to be site installed. These systems often include a series of reflective surfaces and also may include refractive diffusing lenses in their illumination delivery systems.
- **Movable Baffles and Louvers.** Although sometimes hard to distinguish from shade and blind systems, louvers and baffles are used to control and direct incoming daylight. Some louver/baffle systems are automatically controlled by astronomical time clocks or photo-sensors that track the sun's path.

## **Modern Artificial Lighting Systems and Daylight Design**

Most industrial facilities are designed for 24-hour operation. Lighting systems are designed to provide adequate light for all shifts, regardless of the inclusion of daylighting. Although daylighting has many other documented advantages, without energy savings, it is a marginal proposition for most facilities. Proper integration of electric and daylighting systems, as well as commissioning of sensors and controls, are key to lamp performance, human comfort and energy savings. Recently developed technologies have produced a series of products that harvest the energy savings possible from effective daylighting (NBI 2001; DLC 2000).

### **Controllable HID Systems**

Dimming systems for HID and for fluorescent lamps have been limited or non-existent until recent times. The advancement of HID lighting has not been conducive to the reintroduction of daylighting for industrial facilities, as the long strike and re-strike times of these fixtures make them unsuitable for on/off control over short periods of time.

Both mercury vapor and the technology that has replaced it, metal halide, suffer from long strike and re-strike times. Although it is possible to simply turn-off these systems for several hours during a day with sufficient daylight, it is usually necessary to react to changing daylight conditions. Pulse-start metal halide lamps have reduced these striking times, but not enough to warrant frequent control.

High-Low dimmable metal halide systems have been available for about ten years, and their acceptance and reliability have been steadily improving. Typically these systems utilize a different capacitor, or two capacitors, in the ballast system to allow the lamp to be powered at two levels. Most systems will operate at 100 and 50 percent of full power, based on the receipt of a low-voltage signal. When operating on 50 percent power, the lamp delivers approximately 30-40 percent of its full output, as some additional energy is lost to

ballast heat. The transition from one power setting to the next occurs over a few seconds, and could be described as a “gradual ramping.”

The low-voltage signal that controls these high/low fixtures can be provided any number of ways: manual low-voltage switches, automatic time clock, energy management system (EMS) control point, occupancy sensors, and daylight harvesting sensors. Although timer function is sometimes used for the control of high-low fixtures, daylight-harvesting sensors certainly offer the most accurate and flexible approach. Some fixture manufacturers now offer built-in sensors on high-low fixtures, however, placement of daylight sensors is critical, is often found to be in inappropriate.

Continuous-dimming metal halide fixtures have been offered for years by such manufacturers as Widelite. These fixtures usually offer continuous dimming to about 25 percent effective output. Unfortunately, reliability has been a problem, and cost has remained high. Problems with harmonic distortion, electromagnetic interference, lamp flicker, and shortened lamp life have limited the adoption of this technology. Electronic ballast technology for high-wattage HID lighting is a long-standing promise that would likely allow higher performing continuous dimming HID systems.

### **Controllable Fluorescent Systems**

Much has been said at ACEEE conferences concerning the advantages of T8 and T5 fluorescent lighting for industrial facilities. This paper will not cover the range of those advantages, however, there are some features and advantages that directly relate to daylighting systems.

The first advantage is that fluorescent lighting can more easily match the characteristics of daylighting. Selected properly, the chromaticity and the color rendering are closer to daylight than that obtainable from HID sources. This is important for transitioning from daylight to artificial light, as well as when both systems are contributing light to the same area. This factor is less critical in industrial areas than it is in office or educational environments.

Probably the single biggest advantage of fluorescent lamps is that they can be turned on and off without long warm-up (striking/re-striking) times. The starting performance lends itself to being controlled for changing daylight conditions. Proper adjustment of lighting controls, including lighting threshold and dead-band, allow the fixtures limited cycling while still harvesting impressive savings.

Electronic ballasts are now available for virtually all fluorescent lamps, and many ballasts are available 1, 2, 3 or 4 lamp configurations. This allows an impressive amount of flexibility in the design of fixtures with multiple outputs levels. A typical industrial fluorescent high bay fixture might contain six T5 lamps powered by three electronic ballasts. A daylight-harvesting sensor can be connected to two of the ballasts, allowing two lamps to remain lit. Alternatively, the control can be staged, allowing lamps to be turned-off two at a time as daylight increases. As with daylight sensors for HID systems, placement and adjustment of sensors is critical (NBI 2001; IES 2000).



## Fluorescent Continuous Dimming

Again, numerous ACEEE papers have investigated continuous fluorescent dimming, so this paper will not go into the details of these systems. Continuous fluorescent dimming, however, is ideal for daylit applications, as the artificial lighting can react instantly and seamlessly to natural lighting conditions.

The first commercially available lighting dimmers consisted of tanks of salt water with submerged electrodes (Williams 1999). We've come a long way from that technology, and numerous ballast manufacturers have developed continuous-dimming fluorescent ballasts that operate from 100 percent to less than 10 percent of full output. Strategies for controlling input signals range from manual dimmers and time clocks to low voltage daylight sensors and fiber optic cable sensors. For the immediate foreseeable future, fluorescent continuous dimming systems hold the most promise for daylight supplemental lighting.

## Developing Daylighting Technologies

There are several cutting-edge daylighting technologies presently in the works, some of which will no doubt have dramatic effects on the way we light buildings. A few of the most interesting concepts are discussed below.

- **Fiber Optic Delivery of Daylight.** Fiber optic cable can deliver light from any source. Typically, projection boxes of 250 watts and up are used to generate the light delivered through the optic cables. A few companies are presently working on fiber optic daylight delivery systems that they hope can efficiently deliver daylight exactly where it is needed. Some type of collector/concentrator device would act as the projection box, and the delivery would be similar to other fiber optic systems. Current fiber optic systems do not deliver the light efficiently, and cannot deliver full spectrum light over great distances.
- **Hybrid Daylight and Electric Lighting Fixtures.** At least one manufacturer is developing hybrid lighting fixtures that combine daylight and artificial light in the same delivery vehicle. A roof penetration (skylight) delivers natural light to multiple light fixtures containing fluorescent lamps. An internal sensor controls dimmable ballasts within each fixture, reacting to the amount of available light.
- **Light-Bending Glazings.** Several glass manufacturers are working on glazing materials that incorporate elements that actually bend the rays of light. Different versions would be available that could, as an example, direct high angle sunlight back upwards to be bounced off the ceiling, while low angle sun would be reflected back out to reduce heat gain and glare (EDC 2001).

## Electric Lamps and Daylight Design

As discussed, daylight offers color rendering abilities against which all artificial light sources are measured. Although lighting studies disagree on the visual performance effects of color rendering, when designing lighting systems that incorporate both daylighting and artificial lighting, it can be argued that providing the highest color rendering, while still maintaining high lamp efficacy, is desirable. Additionally, although the color temperature of

daylight varies with climatic conditions, daylight is a “cool” source of light. Lamps delivering color temperatures of 4,000-5,000K tend to blend better with daylighting. There is no scientifically supportable evidence that demonstrates that so called “full spectrum” lamps provide any advantage (NBI 2001). Table 2 illustrates the characteristics of several lamps types.

**Table 2.**

Lamp Group	Lamp Type	CRI	Color Temp*	Lamp Efficacy**	Notes
HID	High Pressure Sodium	21-25	1900-2100	85-95	
	Color Corrected High Pressure Sodium	60-85	2000-2200	65-75	Decreased life and light output
	Mercury Vapor	15-50	3900-5700	26-32	
	Metal Halide	65-70	3000-4000	45-50	
	Color Enhanced Metal Halide	75-80	5000-6000	40-45	Decreased life and light output
	Pulse Start Metal Halide	65-70	3700-4000	65-70	
Fluorescent	4' T-12 34 watt Lamp	50-62	3000-4100	65-70	
	4' T-12 34 watt Lamp "Color Enhanced" Lamp	70-80	3000-4100	65-77	
	4' T-8 700 Series Lamp	72-75	3000-4100	82-84	
	4' T-8 800 Series Lamp	82-85	3000-4100	86-88	
	40" T-5 H.O. Lamp	80-85	3000-6500	80-85	
	32-42 watt compact fluorescent lamp	82-85	2700-4100	56-62	

\* Range typically available without lamp efficacy penalty  
 \*\* Based on mean lumens and with normal ballast factor

## Daylighting Design Tools and Resources

### Software Tools

- **Skycalc™** is a software tool designed by the Heschong Mahone Group that assists designers in developing a daylighting strategy using skylights. The program takes into account building type and use, region of the country, seasonal weather, etc. to calculate light patterns and building energy savings in terms of reduced lighting and HVAC costs. SkyCalc and accompanying guidelines are available for free on the web at <http://www.designlights.org>.
- **Radiance** is a suite of programs for the analysis and visualization of lighting in design. The system was developed with primary support from the U.S. Department Of Energy and additional support from the Swiss Federal Government. It is copyrighted by the Regents of the University of California. Versions for UNIX and Windows based computers (*Desktop Radiance*) are available. Radiance is useful for the prediction of illumination, visual quality and appearance of spaces, and to evaluate artificial and daylighting designs.
- **Lightscape**, published by Autodesk®, is useful for the rendering of daylighting designs. VIZ 4 software incorporates Lightscape and offers advanced modeling, rendering, and animation.
- **AGI-32** is a popular lighting designer’s tool published by Lighting Analysts Inc. Version 1.6 was recently announced and includes daylight modeling. This paper’s authors are now testing a pre-release version of this software.

**Non-computer based tools.** Architects have always been fond of building scale models of their projects. Some architects, rather than relying on software to model daylight performance, prefer to use physical modeling. Bruce Coldham, a Massachusetts architect well know for his daylit designs, has developed a daylight modeling stand that is adjustable

to model daylight conditions for any time or day of the year. Light sensors can be inserted into the various spaces to record foot-candles delivered to various spaces.

## Other Resources and Initiatives

The U.S. Department of Energy sponsors many daylighting initiatives that provide assistance for the design and implementation of daylight design in a variety of building types. Additionally, there are regional efforts that support the use of daylight design. The authors of this paper have worked extensively with a regional lighting efficiency organization in the Northeast, the DesignLights Consortium, which is an initiative of the Northeast Energy Efficiency Partnership (NEEP).

The DesignLights™ Consortium (DLC) is a public-private partnership involved in the promotion of lighting designs that offer premium-quality, efficiency, and comfort. One of the major goals of the DLC is to support the integration of daylighting into the design of all types of commercial and industrial buildings. The DLC publishes guides (Knowhow Series) and case studies pertaining to high performance lighting projects, including daylighting projects. Several case studies are available from the DLC including the following two examples that have particular relevance for industrial buildings:

- **University of Rhode Island's Dining Services Warehouse** – This project features ten 22'x18' ridge-shaped skylights that are centered above each aisle. Supplemental light is metal halide. The warehouse and the three other university buildings that incorporate daylighting are considered showpieces of campus architecture.
- **U.S. Postal Service Facility, Nashua, New Hampshire** – This innovative project features large steeply-pitched skylights with deep wells and diffuse glazing. Daylight harvesting sensors keep the electrical lighting off when natural light is sufficient. On average the electrical light remain off from 10:30 A.M. through 5:00 P.M.

## Conclusion

Early daylighting systems for industrial buildings were developed because natural daylight was the best available lighting system of the time. Various circumstances pushed daylight design to the background for a period of approximately 50 years. Renewed awareness of the advantages of daylighting, combined with the development of new design techniques and products, has fueled a renaissance in the design of daylit industrial buildings. The authors believe that for the foreseeable future, daylight and daylight/electric integrated systems will remain the preferred strategies for industrial facilities, offering premium efficiency, reliable, high-quality illumination. As these technologies continue to be refined and improved upon, we will see more seamless integration of daylight with electric lamps. Better color rendering, visual acuity and greater control of light will contribute to worker comfort and safety, productivity and retention. Modern daylighting has proven to be the best light source. It is also the most promising strategy for conserving energy and reducing building operation costs.

## References

DesignLights Consortium (DLC), *KnowHow Series and Case Studies* –2000.

Environmental Design & Construction (EDC), *Daylighting Today and Tomorrow*, 2001.

Ernest Weidhaas, *Architectural Drafting and Design*, 1981.

Florida Power and Light (FPL), E-Source *Energy Advisor* www.fpl.com.

Heschong Mahone Group. *Daylighting in Schools – An Investigation into the Relationship between Daylighting and Human Performance*, 1999.

Illuminating Engineering Society (IES), *IES Lighting Handbook* 1949, '52, '59, '93, '00.

Levy and Wegman, *Occupational Health; Recognizing and Preventing Work Related Disease*, 1994.

Miller, David M, “Daylighting Innovation Creates Smarter Solutions for Energy Savings, Aesthetic Appeal, Interior Comfort,” *New York Real Estate Journal*, September 1998.

New Buildings Institute (NBI), *Advanced Lighting Guidelines*; 2001.

Smithsonian Institute, *Lighting the Way: History of Industrial Lighting*, 2001.

Williams, Bill, “A History of Light and Lighting,” <http://www.mts.net/~williams5/history/hol.htm> Edition 2:2, 1999.