Considerations for Lighting in a Manufacturing Environment

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Considerations for Lighting in Manufacturing

Introduction

Thomas Edison first installed his incandescent light bulb in a New York City factory in 1881. Today, Edison's filament technology is still used for industrial applications in the form of incandescent halogen lamps, but there are now other options in the world of industrial lighting. High-intensity discharge (HID) and fluorescent lamps became commercially available in the first half of the 20th century and have improved steadily in the years since. The most important development for industrial lighting to date is the development of light emitting diode (LED) technology.

A form of solid-state lighting, LED technology had very limited applications when it first appeared in 1968. Producing only a dim red light, LEDs were used as indicator lights and in displays. Today, LED luminaires can meet or exceed the performance of other technologies for light output, color quality, efficiency, and lifetime. Moreover, LED design can be extremely varied and flexible, enabling many different applications, form factors, color temperatures, and light distributions. LEDs can also be easily integrated with controls to allow for dimming and color shifting. These features allow LEDs to be used in ways that improve the overall quality of lighting in a space, which can increase the comfort and productivity of the people working in the space.

With so many economically and visually attractive lighting solutions available, choosing among technologies can be difficult. This paper covers four subjects that industrial users must understand to make the best lighting decision:

- Understand the **metrics**: The different ways lighting performance is measured.
- Understand the **costs**: All costs involved, including those related to initial purchase, design and installation, and operating and maintaining the solution over its lifetime
- Understand the **environment**: How the physical dimensions, uses, and conditions of the space impact their lighting needs.
- Understand the **people**: How to maximize the comfort, productivity, and safety of the people in the space.

The following sections explore all four of these issues in depth to give industrial users valuable information for selecting lighting solutions for their spaces.

Understanding the Metrics

When opportunities to upgrade lighting solutions arise, industrial users should be able to compare the performance of different metrics to make a well-informed decision. LED, fluorescent, and HID technologies can all be evaluated using the metrics defined in the table below.

Lighting Metric	Description
Lumens (lm)	The amount of light emitted by a light source. This measurement takes into account light output in all directions from a light source.
Wattage (W)	For electric loads, the measurement of power drawn to operate the device.

Efficacy (lm/W)	The total light output divided by the total electrical power draw of the system, including associated electronics such as the ballast or driver.
Lux (lm/m2)	Measurement for luminance that describes the intensity of light as it hits a surface in lumens per square meter.
Zonal Lumen Distribution	The distribution of lumens emitted by a luminaire in zones in discrete vertical planes and/ or angles from nadir to zenith. Light distribution is used to inform a luminaire's spacing and mounting criteria.
Correlated Color Temperature (CCT)	A description of the color appearance of light. The technical definition of CCT is the temperature, measured in Kelvin (K), of a blackbody radiator at a chromaticity equal to that of the light source. CCT of white light ranges from about 2700K to 6500K. Light with a lower CCT has an orange or yellow hue and is referred to as “warm,” while a light with a higher CCT can be described as white or sometimes blue and is often referred to as “cool.”
Color Rendering Index (CRI)	A measurement of how accurately a light source renders colors compared to an incandescent bulb.
Rated Lifetime	For LED luminaires, manufacturers base the rated lifetime on L70 lumen maintenance. L70 is the projected number of hours at which a luminaire's light output reduces to 70 percent of its initial light output; this is calculated through a test procedure because the lifetimes are longer than 25,000 hours. For traditional technologies, rated lifetime is based on the number of hours at which 50 percent of lamps fail.
Total Harmonic Distortion (THD)	Distortion of the electrical current waveform caused by non-linear loads, including some types of LED drivers.
Power Factor (PF)	The ratio of real to apparent power. A load with a low power factor draws more current than a load with a high power factor for the same amount of useful power transferred. PF is calculated by dividing input power by the product of input voltage and input current.

When considering different technologies for a given application, industrial users should first focus on selecting the proper illumination level. In the past, lighting technology could be compared solely on the basis of wattage, but new technologies can provide the same amount of light while drawing significantly less power than older technologies.

It is also important to recognize that the test methods for certain metrics differ for LED and non-LED products, meaning that comparing products based simply on the metrics can be problematic. For example, LEDs emit light directionally, while non-LED technologies emit light omni-directionally. In practice, two luminaires with similar lumen measurements can appear to have very different levels of brightness. Industrial users should evaluate samples of different lighting options in person before committing to a purchase.

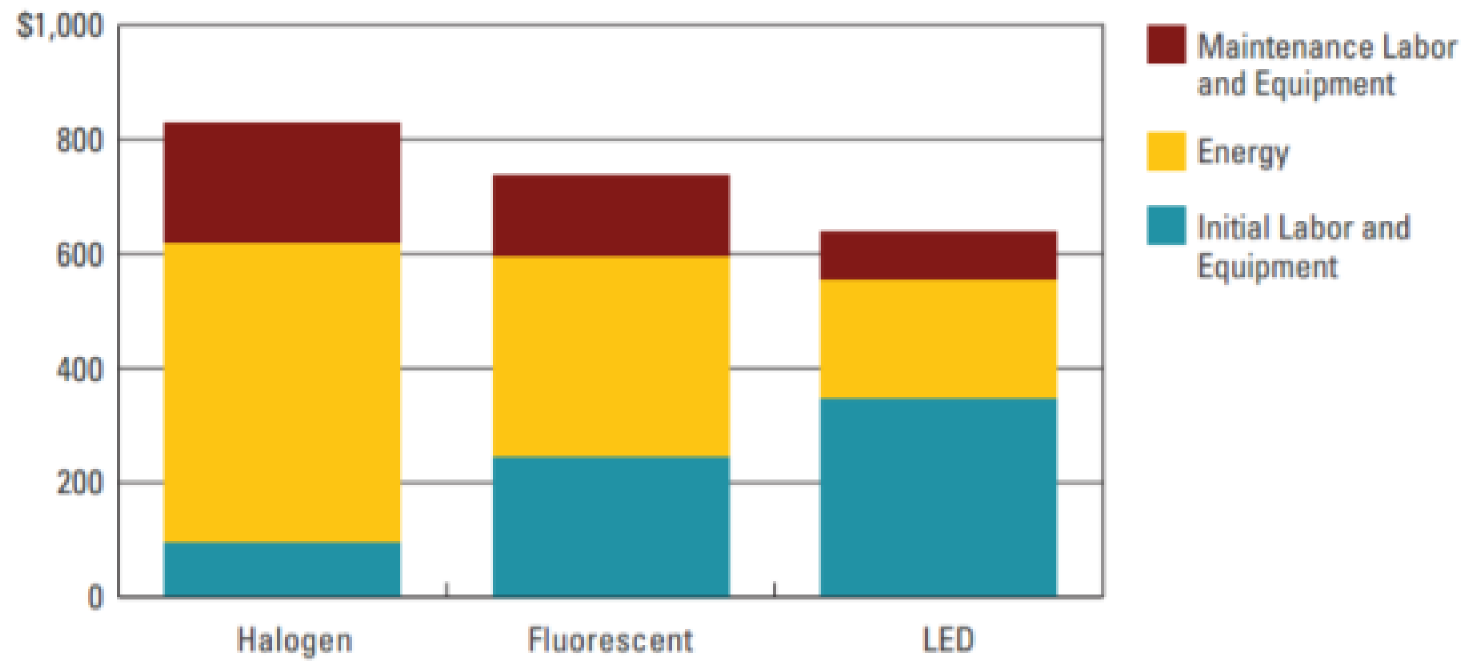
The U.S. Department of Energy (DOE) LED Lighting Facts program provides a database of verified performance measurements for thousands of LED products. There is no similar database for non-LED products, so industrial users should contact manufacturers directly to request product specifications.

Understanding the Costs

Saving money is an important consideration for most industrial users. On average, lighting does not account for a large share of the operating costs of entire facilities or individual machines. In 2010, lighting accounted for 6.8 percent of U.S. manufacturing facilities' net electricity consumption, representing $3.2 billion in total electricity purchases. Nonetheless, every bit of savings can help the bottom line, and upgrading a lighting solution can be an effective way to reduce facility and machine costs while improving the productivity, safety, and design of a space.

When considering lighting costs, industrial users should recognize that the initial cost of a luminaire is only part of the life-cycle cost of the lighting solution. Maintenance and lamp replacement costs depend on the lifetime of the equipment, and the energy costs depend on the equipment's efficiency. For this reason, longer-lasting and more-efficient technologies can produce significant savings, even if they are initially more expensive. Figure 1 illustrates the costs of a lighting solution over a 15-year cycle, assuming typical costs, wattage, and lifetimes, for different technologies. Industrial users should calculate the life-cycle costs of the specific equipment options they are considering before making a decision.

Figure 1. Demonstration of Luminaire Costs over 15-Year Cycle



Sources: D&R analysis of lighting replacement costs from IES, The Lighting Handbook, 10th ed., pp. 18.2-18.11 and R.S. Means, Repair and Remodeling Cost Data 2010 and luminaire and lamp costs from proprietary data.

LEDs often have higher initial costs for a given application than other technologies; however, they often are the most efficient option available and have the longest lifetime. Some industrial users may find fluorescent or HID technology better suited to their needs, but that may not be the case for much longer given the rapid pace of advancements in LED technology. It has been observed, in what is known as Haitz's Law, that the cost of LED chips falls by a factor of 10 every decade, while their light output increases by a factor of 20.5 DOE predicts that this trend will continue for individual LED chips, but significant decreases in costs for complete luminaires will be somewhat limited by the static costs of housings and other components.

Initial Costs

The initial equipment costs for a lighting solution include the housing, electrical equipment (e.g., the ballast or driver), and the light engine (e.g., the lamp or LED panel). LED equipment is often more expensive than competing technology options, and the difference can be significant for certain applications. The difference is most apparent in the cost of lamps. For example, T8 fluorescent lamps can sell for less than $2 each, while LED T8 replacement lamps can cost more than $60.[7] Some utilities and state and regional energy efficiency programs offer rebates or other incentives to offset some of the initial costs. Industrial users may also find that the initial cost of the lighting housing depends on the environment. As discussed below, some lighting can withstand the extreme conditions that are often present in industrial environments. These safeguards may increase the cost of the equipment, but the risk of damage or injury to people or other materials in the space is reduced.

Different types of lighting upgrades require different investments in equipment. Lighting upgrades can be classified as retrofits or redesigns. Retrofits involve replacing the existing luminaires with more-efficient technologies, while making use of the existing housing, lighting pattern, and electrical equipment. On the other hand, redesigns require new fixtures, modification of the existing lighting pattern, and partial or complete rewiring of the electrical system. Both retrofits and redesigns can involve upgrading to more-efficient technologies, increasing or decreasing the total amount of illumination, and/or adding lighting controls.

Industrial users should consider a redesign of the lighting system if any of the following situations apply:

- The existing lighting solution is in poor condition
- The light distribution of the existing solution is uneven
- The light distribution of the existing solution does not suit the uses of the space (e.g., if there have been changes in the design, components, furnishings, or conditions in the space)
- The desired illumination or distribution cannot be achieved with the available retrofit options

Operating Costs

Small improvements in efficacy can result in significant operating cost savings over the lifetime of a lighting solution. Reducing the total level of illumination by downsizing area lighting and using lower-power, focused task lighting can also save on operating costs. Lighting controls that dim or turn off lights when they are not needed is another way to reduce operating costs. Efficacy ratings vary significantly among different technologies and applications, from less than 15 lumens per watt (lm/W) for standard 60W incandescent lamps, to nearly 150 lm/W for the latest LED area luminaires.

Generally, luminaires with higher lumen outputs have higher efficacy ratings. LED luminaires often have better efficacy than other technologies, but highly efficient fluorescent and HID options can provide better or similar efficacies for some applications. Reducing the lighting system's power will also save on demand charges. When commercial or industrial customers significantly reduce their power draw, they should review their utility rates schedules to determine which schedule is most economically attractive. Large customers that face "ratchet" charges may benefit by shifting to a different schedule if demand reductions are significant. Taking ratchet charges into account may significantly improve the cost-effectiveness of more-efficient technologies.

Maintenance Costs

Industrial users should understand the maintenance costs associated with a lighting solution. Having a plan in place for routinely replacing lamps and cleaning surfaces can reduce the total amount of labor needed for maintenance. Maintaining the appearance and uniformity of the lighting can also help with workplace safety and productivity.

The performance of any lighting solution will deteriorate over time through the complete failure of lamps, ballasts, or drivers; gradual lumen depreciation and color shift; or the accumulation of dust and dirt on lenses and reflector surfaces. The deterioration rate can be determined by the system's operating profile, the system's technical characteristics, and the conditions of the operating environment. To plan effectively, it is important to attempt to predict the lifetime of a given technology and understand how and when the lighting system will likely deteriorate.

LED technology is treated differently from non-LED technology in this regard. LED chips degrade slowly over time, producing less light and shifting their color characteristics. The metric used to define the lifetime of LEDs is L70 lumen maintenance, which is the number of hours the LED package will operate before deteriorating to 70 percent of its initial lumen output. Non-LED technologies have electrical components or filaments that fail completely at some point; the rated lifetime for those products is defined as the number of hours of operation at which 50 percent of the units in a sample fail. Non-LED technologies also experience depreciation in lumen values over time, with some technologies depreciating more quickly than others.

The following presents a range of rated lifetimes and lamp lumen depreciation (LLD) values at the end of the rated life for selected technologies.

Lighting Technology	**Rated Lifetime (Hours)**	**Lamp Lumen Depreciation (LLD) at end of rated life**
Halogen Incandescent	3,000 – 5,000	5 percent
Linear Fluorescent	15,000 – 45,000	10 percent
High Pressure Sodium	15,000 – 40,000	30 percent
LED	20,000 – 50,000+	N/A

Source: Rated lifetimes from David L. DiLaura et al., eds., The Lighting Handbook, 10th ed., 13.7; LLD from Illuminating Engineering Society and InterNational Association of Lighting Management Companies, Recommended Practice for Planned Indoor Lighting Maintenance: IESNA/NALMCO RP-36-03, 2.

The projected L70 value for LEDs can exceed 50,000 hours, but manufacturers are encouraged not to claim a longer rated lifetime because of uncertainties of the projection methodology. In addition, the LED chips often last longer than the drivers that power them, which means that industrial users may need to replace drivers before the light engine needs to be replaced.

The maintenance schedule for a lighting solution should also account for the amount of dirt and dust in the operating environment. Dirt accumulating on a lamp lowers the light output and can skew the light distribution; dirt accumulating on reflective surfaces, such as walls and ceilings, can also lower total illumination. Regular cleaning, painting, and general upkeep can help ensure that the lighting solution operates at its highest level.

Understanding the Environment

Industrial users should also assess the physical characteristics of the space and the work that will take place there to determine how solutions should be designed. Industrial and manufacturing facilities have a wide variety of tasks, machines and purposes, but the following key features are common:

- Most industrial facilities have high ceilings and large open spaces, and they often host detail-oriented or risky work that can require very specific (and bright) lighting solutions.
- Lighting systems may need to withstand rough environmental conditions, such as extreme temperatures, dust, or moisture.
- Lighting systems may be exposed to non-stationary equipment and heavy machinery that can easily damage their housing and power supply.
- Industrial facilities often have sensitive equipment that can be damaged by electrical noise from poor quality lighting. Conversely, equipment in the space may create electrical noise that can damage a lighting system.

- Industrial facilities are subject to more stringent worker safety standards for hazardous locations that require brighter lighting solutions. Sanitary standards require the protection of consumable goods or other manufactured products against contamination from the failure of the luminaire.

The following sections discuss what lighting applications are appropriate for industrial spaces, the standards that industrial users should keep in mind, and other important technical considerations.

Industrial Lighting Applications

Industrial lighting can be categorized as area lighting or task lighting. Area lighting includes high-bay and lowbay applications, such as warehouses and other wide open spaces that often require high-power luminaires to achieve adequate illumination over a large area. Troffers and downlights are also used for area lighting and are common in office environments; these applications usually require a large number of evenly-spaced fixtures to provide a consistent level of illumination on the workplane.

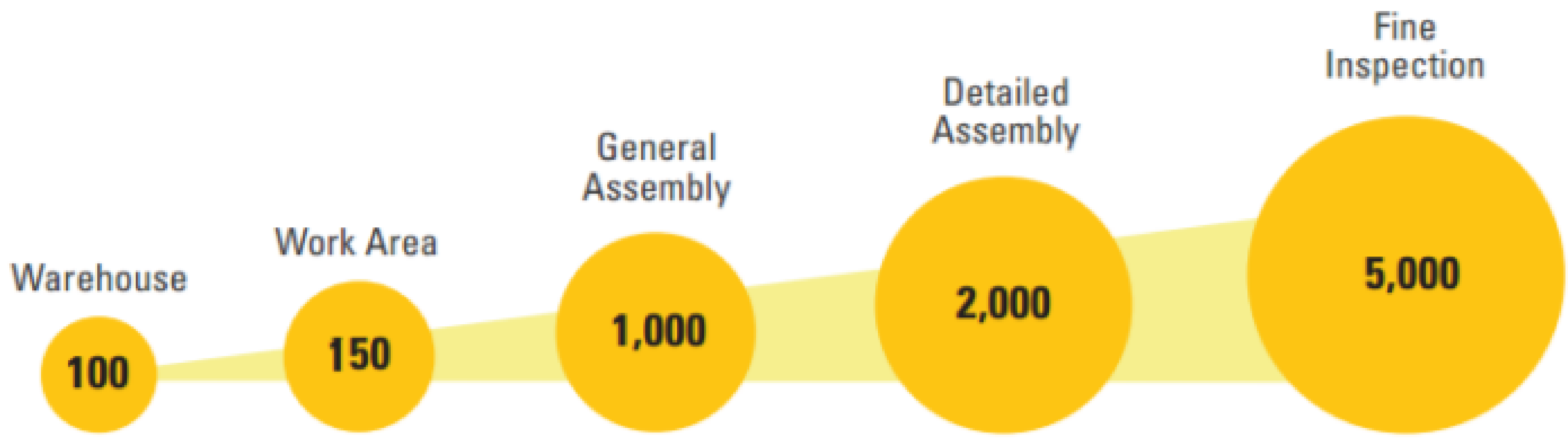
Task lighting, on the other hand, can be used to augment the area lighting in a space by focusing illumination where the work actually occurs. By bringing the light source closer to the workplane, industrial users may be able to achieve recommended illumination with lower-powered luminaires. Task lighting is also easier to maintain and replace than high-bay lighting. Industrial users should consider using task lighting for the following:

- Worker assembly cells
- Machine/robotic assembly cells
- Electrical panels and other enclosures
- Mobile applications

Performance Standards for Industrial Lighting

Determining the appropriate level of light for a given application can be challenging. Too little light can potentially be dangerous, while too much light can create unpleasant glare and add unnecessary costs. Because of the variety in architecture and uses of industrial space, there is no one-size-fits-all recommendation for light output. The Illuminating Engineering Society (IES) publishes appropriate light levels and distributions for more than 100 industrial and manufacturing tasks in its exhaustive Lighting Handbook. For this reason, lighting designers often begin an initial assessment by taking an inventory of spaces in a facility, including the occupants and their functions.

The following image shows recommended lux levels for different industrial applications.



There are standards for the energy performance of commercial lighting systems. The ANSI/ASHRAE/IES Standard 90.1 and the International Energy Conservation Code (IECC) require the use of lighting controls (e.g., timers, occupancy sensors, photosensors, on/off-switches, or dimmers) and sets a limit on lighting power density (LPD). These standards apply to interior and exterior lighting for commercial building new construction and renovation projects. Commercial buildings must include at least one lighting control per room, individual controls of task lighting, and for buildings larger than 5,000 square feet, timers or occupancy sensors to shut off all lighting automatically. The LPD requirements, which were calculated based on light level recommendations from IES and the energy efficiency characteristics of typical lighting options, vary by space type. If a retrofit project replaces fewer than half of the luminaires in a space and does not increase the LPD, the LPD requirement does not apply.

Lighting upgrades generally must exceed building code requirements to be eligible for incentives from utilities and energy efficiency programs. Eligibility requirements vary by program, but many offer rebates for LED products that meet or exceed minimum performance levels. The DesignLights Consortium® (DLC) is a collaboration of more than 50 utility companies and regional energy efficiency organizations that have joined together to establish a common set of technical requirements for different commercial lighting applications.16 More than 50,000 LED products are listed on the DLC's Qualified Products List, with more being added every day.

Considerations for Extreme Conditions

Lighting products can be designed to withstand rough or even hazardous conditions inside typical industrial facilities. The National Electrical Code (NEC) classifies three types of hazardous locations:

- Class I – flammable gasses or vapors
- Class II – combustible dust
- Class III – easily ignitable fibers or flyings

Electrical equipment used in these locations needs to be designed and installed to certain safety standards. Federal regulations require that "equipment shall be marked to show the class, group and operating temperature or temperature range, based on operating in a 40 °C ambient temperature for which it is approved."

Along with other kinds of electrical equipment, luminaires can be rated based on Ingress Protection (IP) Code designations. IP ratings have two numerals, the first describing the resistance of the equipment to solid foreign objects, such as dust, and the second describing the degree of protection against water. Manufacturers may also add additional letters to the two numerals to describe the protection level needed for accessing the hazardous components of the device. A rating of IP00 means that the equipment is not protected against ingress.

Lights rated IP67 and above are dust and water resistant, making them ideal choices for many industrial lighting applications, including machine lighting and machine tool environments. Enclosures rated IP67 are able to withstand temporary immersion in water. Lights rated IP68g are resistant to oil and water penetration. The American National Standards Institute (ANSI), the U.S. ratings organization includes ratings up to IP68; the German Institute for Standardization includes IP69K. IP69K rated enclosures are able to withstand high-pressure wash-down environments necessary for sanitation procedures common to food, beverage, and pharmaceutical manufacturers.

Dust and water resistance is important, but luminaires in industrial environments may also need to withstand vibration or impact from heavy equipment. Incandescent and fluorescent technologies use glass enclosures that can shatter upon impact, exposing workers and other equipment to risk. Constant vibration can also reduce the lifetime of some lighting solutions, especially those with fine filaments and other delicate components. On the other hand, LED luminaires do not use glass enclosures or filaments, and are therefore extremely resistant to vibration and impact.

Industrial facilities may also be subject to extreme ambient temperatures that make certain technology options ideal. LEDs perform better in cold conditions compared with traditional technologies. LED luminaires are an ideal lamp for refrigerated warehouses with temperatures as low as -40 °C.20 LED manufacturers continue to make improvements in designing for higher temperatures, using high-grade housing materials that dissipate heat and temperature sensors that automatically dim lights as heat increases. High ambient temperatures reduce the efficacy and lifetime of LEDs.

Equipment and Power Quality

Power quality is a characteristic of a system, not just its components. Poor power quality can waste energy and the capacity of an electrical system; it can harm the electrical distribution system as well as the devices operating on the system. Heat generation within equipment, when little or none is anticipated, is generally an indicator of power quality deficiencies. The utility's feed into your facility has direct effects on the durability and life of equipment. Lighting systems and equipment can affect the electrical system's voltage and current by distorting the voltage waveform and/or the shifting the phase relationship of voltage and current in multi-phase electrical systems.

The power factor of an AC electrical power system is defined as the ratio of the real power flowing to the load to the apparent power in the circuit; it is a dimensionless number between 0 and 1. In an electric power system, a load with a low power factor draws more current than a load with a high power factor for the same amount of useful power transferred. Because of the additional electricity demand, electric utilities usually charge higher rates to industrial or commercial customers who have low power factors.

A power factor below 0.9 is considered low. The power factor can be assessed on each meter in a building or facility, so it is important to know what equipment is powered on each circuit. Adding or replacing lighting equipment requires that the lighting designer understand whether existing equipment uses ballasts or transformers. Correcting and modifying power factor is fairly straightforward with installation of capacitors and the power factor should be reevaluated when a lighting system is upgraded.

For lighting equipment, the two electric performance metrics are power factor and total harmonic distortion (THD). A product's power factor must be at least 0.90 for the manufacturer to claim that it has high power factor. Utilities prefer new luminaires to have a maximum THD of 20%, whether the luminaire has a ballast for fluorescent or HID lamps or drivers for LED-based ones.

Understanding the People

Lighting upgrades can save industrial users money through efficiency improvements, but higher-quality lighting can produce even more substantial benefits by increasing the productivity of the people working in the space. In fact, the average commercial facility spends more than 400 times as much on salaries and benefits for employees as it does on lighting. For this reason, it is extremely important to select lighting options that reduce eye strain, boost mood, and protect safety.

Effect of Lighting on Mood and Productivity

The type of light in an environment can affect the human brain and nervous system, influencing alertness and mood. The daily cycle of light and darkness affects a body's circadian rhythm, which governs physiological and behavioral processes like blood pressure, hormone production, and sleep. Studies have also shown that the color of light can have a similar effect, with blue light being associated with calm.

While the physiological and psychological impacts of light are important, the occupants of industrial spaces will be concerned mainly with whether the brightness, color, and quality of the light help them do their jobs. One study conducted by Cornell University found that under poorly lit conditions, 24 percent of workers reported an average of 15 minutes a day of lost productive work time, which adds up to a full week each year.

Visual acuity suffers when the light level is too low, but too much light can lead to discomfort from glare. Both scenarios can result in eye strain and loss of productivity. Color and contrast recognition are important for detailed-oriented tasks, and light with a poor color rendering index (CRI) rating can increase the risk of errors. As the human eye ages, the pupil becomes less responsive, adapts to changing light levels more slowly, and becomes more sensitive to glare. The IES recommends approximately double the level of illumination for all applications when the occupants are over age 65.

Design Recommendations

The challenge for industrial users is to provide enough light to illuminate the large, open spaces of industrial facilities while avoiding glare. Solutions include selecting luminaires with diffused lenses and shielding so there is no direct view of the light source. It is also important to have appropriate levels of reflectance on the ceiling, walls, and floors. In general, the ceiling should be the most reflective surface and the floors should be the least reflective.

Using dedicated task lighting in place of additional area lighting can reduce the possibility of glare, while ensuring that specific tasks have adequate illumination. Proper distribution of light that maintains uniformity and vertical brightness and ensures that light levels are consistent throughout the space can protect the eye from needing to constantly adjust.

This is especially important for spaces with vertical surfaces that need to be illuminated, such as warehouses. Dark vertical surfaces can create the impression that the entire space is under-lit. Luminaires are generally rated to specific spacing and mounting criteria that dictate how they should be installed based on spatial dimensions, including luminaire height. Because LED technology is directional, luminaires need to make use of specialized lenses to achieve different distributions. The flexibility of LED design means that there are a wide variety of products in the market to meet to meet any design challenge.

Some areas of a facility often have multiple tasks. It is necessary to rank the tasks by importance, prevalence, or frequency to determine the commonly occurring task with the highest recommended illuminance. It is wasteful to provide the highest illuminance level with the area lighting system. Task lighting can be employed for more visually challenging tasks, with the benefits of lower energy use and increased user satisfaction. If possible, industrial users should also consider ways to adjust light levels for the time of day. This can be achieved through automated lighting controls or daylighting (i.e., allowing the natural light of the sun in through the windows). When using task lighting, occupants can be given control over the light levels in their space and can adjust to their own comfort.

Because people perceive light and color differently, the occupants in a facility can have a range of color preferences within the white light spectrum. LEDs have the widest range of CCT and CRI performance levels of all lighting technologies. It is possible to produce LEDs with CCT ranging from 1000K to 9000K, easily covering the preferred range for most lighting applications. The CRI range for LEDs has a low of 20, which is comparable to low-performance high-pressure sodium lamps, and a high of 95.35 Most high-quality LEDs for indoor use have a CRI of 80, which is comparable to metal halide and fluorescent technologies, and is considered satisfactory for nearly all tasks. Newer LED technologies and controls may also allow for color shifting, which can help occupants to adjust the light to fit their preferences.

Conclusion

Industrial users must balance many different considerations when selecting a lighting solution. Lighting industrial workspaces requires consideration of the application and tasks in the space and the space's physical conditions. The lighting solution must provide appropriate illumination for the space and task; this often includes area and task lighting. Lighting upgrades must also make economic sense. Industrial users should focus on the full life-cycle costs of a lighting solution when choosing among technologies, recognizing that solutions with high initial costs may actually be the least expensive after taking efficiency and lifespan into account. Industrial customers must also understand their own needs so that they choose luminaires that meet their needs for ingress protection, power quality, occupational safety, and sanitation. Though balancing all these considerations can make the selection process complicated, the right lighting system can help you ensure that your facility is appropriately lit and safe for everyone who works there.

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