Module 4

Lighting Calculations

Contents

Determining Average Illuminance

- The standard lumen method formula is also used to calculate average illuminance levels when the Coefficient of Utilization (CU's) are taken from a utilization curve.

$$\text{Footcandles (maintained)} = \frac{\text{lumens/lamp} \times \text{lamps/luminaire} \times \text{\# luminaires} \times CU \times LLF}{\text{area in square feet}}$$

$$\text{\# of luminaires} = \frac{\text{maintained footcandles desired} \times \text{area in sq. ft.}}{\text{lumens/lamp} \times \text{lamps/luminaire} \times CU \times LLF}$$

Average Illuminance Equation

General equation for illuminance in space

$$E_{wp} \quad \frac{\Phi_{(TOTAL)} \times CU \times LLF}{A_{wp}}$$

E_{wp} = average maintained illuminance on the work plane

$\Phi_{(TOTAL)}$ = total system lamp lumen output

CU = coefficient of utilization

LLF = light loss factor

A_{wp} = area of the work plane

The Lumen Method

- Means of determining the average workplane illuminance within a space with a given number of luminaires
- Components
  - Total system lamp lumen output
  - Coefficient of utilization
  - Loss factor determination
  - Calculated illuminance
  - Spacing criteria

Total System Lamp Output

Lamp lumen output is the total initial luminous flux that the lamps emit as specified by the manufacturer.

Example 1:
In an office space 3m x 4.6m with a 2.6m ceiling height, there are 2 recessed fluorescent luminaires. Each luminaire has three (3) 32W 48" T8 fluorescent lamps. Manufacturer's data shows that the initial lumen output of the lamp is 2900 lumens. What is the total lamp lumen output $\Phi_{(TOTAL)}$?

$\Phi_{(TOTAL)}$ = 2 luminaires x 3 lamps/luminaire x 2900 lumens/lamp
= 17,400 lumens

Coefficient of Utilization (CU)

Factors influencing coefficient of utilization:

- The efficiency of the luminaire
- The luminaire distribution
- The geometry of the space
- The reflectances of the room surface

Each luminaire has its own CU table specific to that luminaire's light distribution and efficiency. CU values are listed in tables for different room geometries and room surface reflectances.

Coefficients of Utilization (CU)

- Coefficient of utilization is based on room cavity ratio (RCR)
- RCR is five (5) times the ratio of total vertical surface area to total horizontal surface area within the room cavity, and therefore indicates the relative space proportions.

$$\text{Room-cavity Ratio, RCR} = \frac{5h_{RC}(L+W)}{L\,W}$$

Where, h_{RC} = Room cavity height
L = Length of the room
W = Width of the room

Coefficients of Utilization (CU)

- Cavity ratios :
  - Ceiling cavity ratio – is the space between the ceiling and luminaire plane computed using the equation below in relation to room cavity ratio:

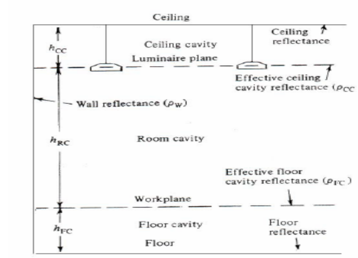
$$\text{Ceiling-cavity Ratio, CCR} = \frac{5h_{CC}(L+W)}{LW} = \text{RCR}\,\frac{h_{CC}}{h_{RC}}$$

  - Floor cavity ratio – is the space between the workplane and the floor computed using the equation below in relation to room cavity ratio:

$$\text{Floor-cavity Ratio, FCR} = \frac{5h_{FC}(L+W)}{LW} = \text{RCR}\,\frac{h_{FC}}{h_{RC}}$$

Coefficients of Utilization (CU)

Cross section of a room showing room cavities.



Coefficients of Utilization (CU)

- For a given room, the cavity ratios are in direct proportion to their respective cavity heights. For the case where the luminaires are mounted on the surface of the ceiling or are recessed into the ceiling, the ceiling cavity ratio is zero.
- Since the coefficient of utilization is based on the room cavity ratio, it is necessary to treat this cavity as if there were a ceiling surface at the luminaire plane and a floor surface at the workplane level.
- It is necessary to convert the actual ceiling reflectance into an effective ceiling cavity reflectance (*p*CC) and the actual floor reflectance must be converted to an effective floor cavity reflectance (*p*FC).

CU Determination

Using Example 1 above, the following steps should be followed in calculating the coefficient of utilization.

Step 1. Determine the room cavity ratio using the equation below

$$\text{Room-cavity Ratio, RCR} = \frac{5h_{RC}(L+W)}{L\,W}$$

Room cavity height (h_{RC}) = Luminaire height – Workplane height

Assuming a workplane height of 0.76m (typical desk height)

h_{RC} = 2. 59 m – 0.76m
= 1.83m

CU Determination

In this example, the luminaires are recessed in the ceiling so the luminaire height is the as the ceiling height. Computing the room cavity ratio, we have:

$$RCR = 5 \times \frac{\text{Room cavity height (Length + Width)}}{\text{Length x Width}}$$

$$RCR = 5 \times \frac{1.83m\ (3.05m + 4.57m)}{3.05m \times 4.57m}$$

RCR = 5

CU Determination

Step 2. Since the Lumen Method considers what occurs only within the room cavity, the ceiling and floor cavities are replaced with their effective reflectances.

To find the effective reflectance of a floor or ceiling cavity, find the floor cavity ratio and ceiling cavity ratio using the equations below

$$\text{Ceiling-cavity Ratio, CCR} = \frac{5h_{CC}(L+W)}{LW} = \text{RCR}\ \frac{h_{CC}}{h_{RC}}$$

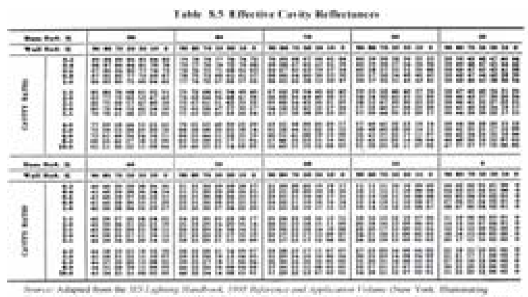
$$\text{Floor-cavity Ratio, FCR} = \frac{5h_{FC}(L+W)}{LW} = \text{RCR}\ \frac{h_{FC}}{h_{RC}}$$

CU Determination

Step 3. Find the effective cavity reflectances using cavity surface reflectances. The surface that is opposite the opening to the cavity is called the base cavity. The base reflectance, the wall reflectances, and the cavity ratio determine the effective cavity reflectance. Using the IESNA Lighting Handbook, look for the cavity reflectances and cavity ratios.

For the ceiling cavity, the base reflectance is the actual ceiling surface reflectance while the floor cavity, the base reflectance is the actual floor surface reflectance.

CU Determination



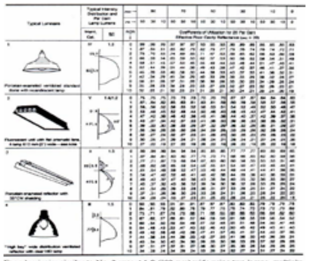
CU Determination

- **Step 4**. Once all room cavity reflectances and the room cavity ratio are known, the CU value can be determined by selecting the appropriate value from the luminaire's CU table.
- Continuing with Example 1, the following assumptions are made after consulting the IES Lighting Handbook Table on Effective Reflectances:
  - Effective Ceiling Cavity Reflectance, ρCC = 0.70
  - Wall Reflectance, ρW = 0.50
  - Effective Floor Cavity Reflectance, ρFC = 0.20
  - RCR = 5 (calculated in Step 1)

CU Determination

CU = 0.50, which means that 50% of the lumens given off by the lamps reach the workplane and the other 50% are absorbed by the luminaire or the room surfaces and never reach the workplane.

Coefficients of Utilization for Some Luminaire



For a luminaire similar to No. 2 except 1 ft (300 mm) wide using two lamps, multiply CU values by 0.9.

Source: Adapted from the IES Lighting Handbook, 1993 Reference & Application Volume (New York: Illuminating Engineering Society of North America, 1993). Refer to this Handbook for a more complete listing of luminaires.

Light Loss Factor

- Two types of Light Loss Factor (LLF)
  - Recoverable
  - Non-recoverable
- Total Light Loss Factor (LLF) is the product of the individual light loss factors, recoverable and non recoverable

Light Loss Factor

- Recoverable LLF
  - Lamp Lumen Depreciation (LLD)
  - Lamp Burnout Factor (LBO)
  - Luminaire Dirt Depreciation Factor (LDD)
  - Room Surface Dirt Depreciation Factor (RSDD)
  - Area of workplane (A_{WP})

Lamp Lumen Depreciation

- The lamp lumen depreciation factor is the fraction of initial lumens at a specific time during the life of the lamp
- Lamp lumen depreciation comes from aging and dirt accumulation on lamps, reflectors, lenses and room surfaces.
- Most lighting designs base calculations on "maintained" as opposed to "initial" lamp lumens

Lamp Burnout Factor

- If lamps are not replaced immediately after burnout, a lamp burnout factor should be applied to any analysis of the system.
- Unreplaced burned out lamps will vary in quantity, depending on the kind of lamps and the relamping program used.
- This factor is simply the ratio of the number of lamps that would be burning o the total number of lamps in the system.

Room Surface Dirt Depreciation

- Room Surface Dirt Depreciation Factor (RSDD) is influenced by:
  - The amount of dirt in the environment
  - The room cavity ratio (proportions of the room)
  - Type of lighting equipment used

Room Surface Dirt Depreciation

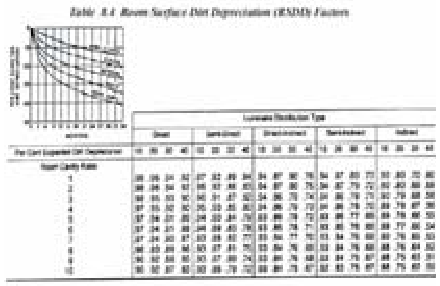
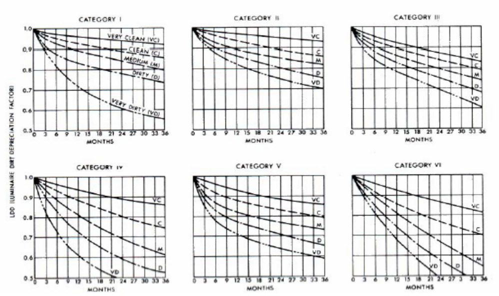


Table 8.4 Room Surface Dirt Depreciation (RSDD) Factors

Luminaire Dirt Depreciation

- Luminaire Dirt Depreciation Factor (LDD) depends on three (3) aspects of the situation:
  - The amount and type of dirt in the environment (a clean office environment compared to a dirty manufacturing facility)
  - The type of luminaire used
  - The expected cleaning cycle for the equipment

Luminaire Dirt Depreciation



Area of Workplane

- Is the area of the entire workplane, which is typically the same as the floor area
- Illuminance will be greatest near the center of the room and slightly less toward the walls for a given uniform layout of luminaires

Light Loss Factor

- Non-Recoverable LLF
  - Luminaire Ambient Temperature Factor
  - Heat Extraction Thermal Factor
  - Voltage to Luminaire Factor
  - Ballast Factor
  - Ballast Lamp Photometer Factor
  - Equioment operating Factor
  - Lamp Position *(Tilt)* Factor
  - Luminaire Surface Depreciation Factor

Luminaire Ambient Temperature

- Variations in temperature, above those normally encountered in interiors, have little effect on the output of incandescent and high intensity discharge (HID) lamps, but can have a significant effect on light output of fluorescent lamps

Heat Extraction Thermal Factor

- Heat extraction factor is the fractional lumen loss or gain due to airflow
- Airflow has an effect on lamp temperature and lamp lumens especially those air handling fluorescent luminaires which are integrated with the HVAC system as a means of introducing or removing air from the room

Voltage to Luminaire Factor

- High or low voltage at the luminaire will affect the lumen output of lamps
- High voltage condition will increase the lumen output of lamps over their rated output
- Low voltage condition will reduce the lumen output
- The rate of change of lumen output with a voltage change varies with each light source, but has the greatest effect on incandescent lamps

Ballast Factor

- Ballast used for a specific application is usually different from the ballast used to determine the rated lumen output for a lamp
- Ballast factor corrects this difference to maintain the arc within the lamp
- Ballast factor is the ratio of the lamp lumens generated on commercial ballasts to those generated on the test quality ballasts . The ballast factor for good quality fluorescent ballast is nominally is 0.95while electronic ballasts can have ballast factors ranging from 0.70 to 1.28

Ballast Lamp Photometer Factor

- Ballast Lamp Photometer Factor adjusts the lumen output when a different lamp ballast combination is used other than the manufacturer's set up
- Temperature effects within the luminaire may cause the lamp to operate at less than the rated output and should be considered in the determination of the luminaire's coefficient of utilization

Equipment Operating Factor

- Effects on the lumen output of lamps caused by the ballast, the lamp operating position and the effect of power reflected from the luminaire back onto the lamp are collectively incorporated into the equipment operating factor

Lamp Position Factor

- Lumen output is sensitive to the lamp orientation especially for high intensity discharge (HID) lamps when they are tilted from their rated horizontal or vertical position
- Lamp position factor adjusts the lumen output and is defined as the ratio of luminous flux in the given operating position to that in the test position

Luminaire Surface Depreciation

- Luminaire surface depreciation results from adverse changes in metal, paint and plastic components that result in permanently reduced light output
- Luminaire surface depreciation factor adjusts light output to original reflectance

Loss Factor Determination

Example 2. LLF Determination

Detailed description of the determination of the light loss factors can be found in the *IESNA Lighting Handbook*. The product of the recoverable factors and the non-recoverable factors will give us the total light loss factor.

Recoverable Factors

Lamp Lumen Depreciation (LDD)	0.90
Lamp Burnout Factor (LBO)	1.00
Luminaire Dirt Depreciation Factor (LDD)	0.94
Room Surface Dirt Depreciation Factor (RSDD)	0.96

Loss Factor Determination

Nonrecoverable Factors

Ballast Factor	0.93
Other Non Recoverable Factors	1.00

LLF_{TOTAL} = Recoverable Factors x Nonrecoverable Factors

$LLF_{TOTAL} = 0.90 \times 1.00 \times 0.94 \times 0.96 \times 0.93 \times 1.00$

$LLF_{TOTAL} = 0.75$

Total Light Loss Factor (LLF) is 0.75, which means that 25% (100%-75%) of the luminous flux that might otherwise reach the workplane is lost due to ballast factor, dirty luminaires, room surfaces, and aged lamps.

Calculated Illuminance

At this point it is possible to calculate the illuminance on the workplane:

$$\mathbf{E}_{wp} \quad \frac{\Phi_{(TOTAL)} \times CU \times LLF}{A_{wp}}$$

E_{wp} = average maintained illuminance on the work plane

$\Phi_{(TOTAL)}$ = total system lamp lumen output

CU = coefficient of utilization

LLF = light loss factor

A_{wp} = area of the work plane

Calculated Illuminance

Substituting all the computed values in Example 1and using the equation for average illuminance on the workplane, we have:

$$E_{WP} = \frac{17{,}400 \text{ lm} \times 0.50 \times 0.75}{3.05\text{m} \times 4.57\text{m}}$$

$= 468 \text{ lm/m}^2$ or 486 lux (Maintained)

The average initial illuminance on the workplane can be determined by substituting only the non-recoverable light loss factors for the total light loss factor.

$$E_{WP} = \frac{17{,}400 \text{ lm} \times 0.50 \times 0.0.93}{3.05\text{m} \times 4.57\text{m}}$$

$= 581 \text{ lm/m}^2$ or 581 lux (Initial)

Calculated Illuminance

- An average maintained illuminance of 468 lumens per square meter will strike the area covered by the workplane in a completely empty space
- Some points on the workplane will have an illuminance higher than 468 while others will have an illuminance lower than this value
- During first time that this system will be turned on, wherein the lamps are new and the surfaces are clean, the average initial illuminance will be greater than the maintained value, which is computed as 582 lumens per square meter (lux)

Calculated Illuminance

- By rearranging the Lumen Method equation, it is possible to find the number of luminaires required to meet a specific average illuminance level:

$$E_{WP} = \frac{(\text{lumens/lamp}) \times (\text{lamps/luminaire}) \times (\text{no. of luminaires}) \times CU \times LLF_{TOTAL}}{A_{WP}}$$

$$\text{No. of luminaires} = \frac{A_{WP} \times E_{WP}}{(\text{lumens/lamp}) \times (\text{lamps/luminaires}) \times CU \times LLF_{TOTAL}}$$

Calculated Illuminance

Example 2. Find the number of luminaires needed in a room given the following:

Room dimensions: 9.15m by 9.15m by 3.5m

Target Illuminance: 300 lux average maintained

Working Plane Height: 0.76m

Luminaire: Recessed round

Lamp: 70 watt metal halide, 5600 lumen initial output

Reflectances (ρ):	Ceiling cavity	0.70
	Walls	0.30
	Floor Cavity	0.20

Assume LLF_{TOTAL} = 0.75

Calculated Illuminance

Step 1. Calculate RCR

Using the equation for RCR, we get 3 as the answer.

Step 2. Determine Cavity ratios for ceiling and floor

Step 3. Obtain Effective Ceiling Cavity Reflectance (ρCC) using Tables in CU determination for metal halide lamps

Step 4. Obtain Effective Floor Cavity Reflectance (ρFC) using Tables in CU determination for metal halide lamps

Step 5. Obtain Coefficient of Utilization (CU) from Manufacturer's Data

The CU based on calculated value of RCR and the given reflectances, we get 0.55 as the answer.

Calculated Illuminance

Using the equation below, and substituting all the known values:

$$\text{Number of luminaires} = \frac{A_{WP} \times E_{WP}}{\text{lumens/lamp} \times \text{lamps/luminaires} \times CU \times LLF_{TOTAL}}$$

$$\text{Number of luminaires} = \frac{9.15\text{m by } 9.15\text{m by } 3.5\text{m} \times 300 \text{ lux}}{5600 \text{ lumen} \times 1 \times 0.55 \times 0.75}$$

Number of luminaires = 10.9

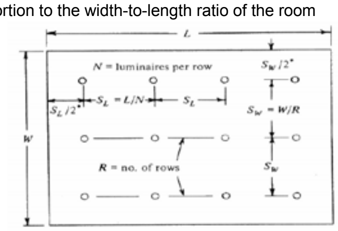
In this example, 12 fixtures can be spaced uniformly in a 3 by 4 pattern. Although 12 is more than the calculated value of 10.9 fixtures, results within a 10% margin is generally acceptable for meeting this target criterion

Spacing Criteria

- Spacing Criteria is the maximum ratio of spacing to mounting height of the luminaire above the workplane that provides reasonable uniformity of illumination within the space
- Spacing ratios for specific luminaires are given in the data sheets published by each manufacturer. This number, usually between 0.5 to 1.5, when multiplied with the mounting height, gives the maximum distance that the luminaires maybe separated and provide uniform illuminance on the workplane

Spacing Criteria

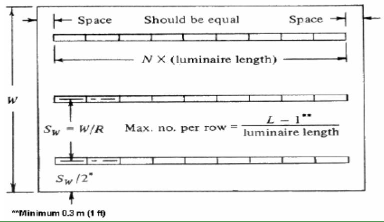
- For luminaires using essentially point sources of light, such as incandescent or HID lamps, the number of luminaires per row should be in proportion to the width-to-length ratio of the room



S_L and S_W should be approximately equal.
*Can be reduced to one-third luminaire spacing.

Spacing Criteria

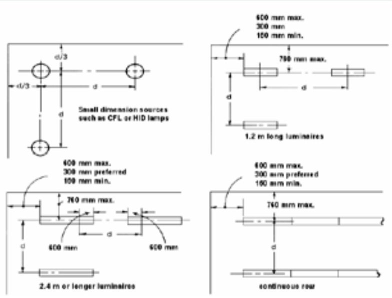
- For fluorescent luminaires, it is necessary to first establish the maximum number that can be installed in one row. the maximum number is calculated by subtracting at least 0.3 meter from the room length and then dividing by the length of the luminaire.



Spacing Criteria

- The exact spacing between rows is calculated by dividing the room width by the number of rows
- Spacing between luminaires in each row is calculated by dividing the room length by the number of luminaires per row.
- spacing between the outer luminaires and the adjacent wall is one-half of the luminaire spacing
- If desks or other work areas are to be located alongside the walls, then the wall-to-luminaires spacing should be reduced to one-third of the luminaire spacing

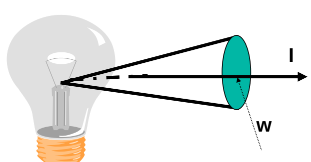
Spacing Criteria



Illuminance at a Point-Direct Component

- Examples:
  - What is the illuminance on a wall display from a spotlight aimed at the display?
  - How much light is striking a point on the façade of a building or in a parking lot from a floodlight?
- Factors to consider
  - Luminous intensity
  - Distance
  - Orientation of the surface

Luminous Intensity



Luminous Flux in a certain direction, radiated per unit of solid angle

Unit : Candela

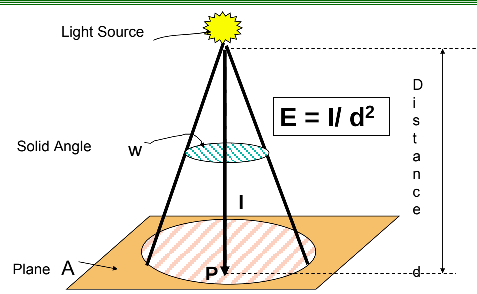
Symbol : I

$$I = \frac{\text{Luminous flux}}{\text{Solid Angle}} = \frac{\phi}{w}$$

Distance

- Distance between a surface and the source affects the illuminance (luminous flux per unit of area) striking that surface
- Surface of a given area that is closer to the source captures a larger portion of the flux in the cone than a surface of the same given area that is further away
- Considering the luminous intensity as the luminous flux (lumens) leaving a source in a cone traveling in a specific direction, as the area increases the illuminance decreases while the luminous flux remains the same
- Inverse Square Law states that the cross-sectional area of the cone increases with the square of the distance from the source. Therefore, the illuminance on this surface varies inversely with the square of the distance from the source

Distance



Distance

Inverse Square Law

$$E = I/ d^2$$

Where:

E = Illuminance on the surface

I = Luminous intensity of the source in the direction of the surface

d = Distance from the source to the surface

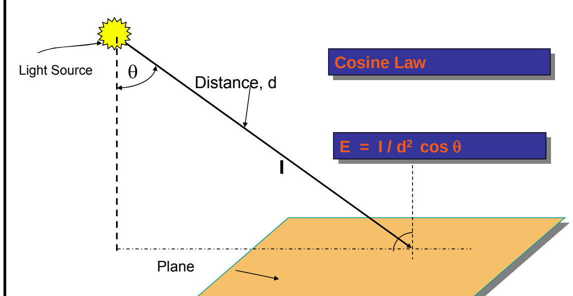
Orientation of the Surface

- Surface orientation is included in the Inverse Square Law by adding a cos θ term:

$$E = I/ d^2 \cos \theta$$

- θ is the angle between the light ray coming from the source to the point, and a line that is perpendicular (normal) to the plane or surface on which the illuminance is being measured or calculated

Orientation of the Surface



Illuminance at a Point-Direct Component

Example 1. This example will consider the illuminance at a single point on a horizontal surface from a single luminaire straight down. An assumed LLF of 0.85 will be used.

D = 2.13 m

θ = 15°

LLF = 0.85

I = 2200 candelas

The luminous intensity (I) is determined using the photometric data for the specific luminaire used and the angular relationship between the luminaire aiming direction and the direction from the luminaire to the calculation point.

Illuminance at a Point-Direct Component

Using the equation;

$$E = I/ d^2 \times \cos \theta \times LLF_{TOTAL}$$

$$E = \frac{2200 \text{ cd}}{2.13 \text{ m}^2} \times \cos 15° \times 0.85$$

E = 398 lux *(maintained)*

This tells us that 398 lux will strike the point in question directly from the luminaire and no reflected light is calculated. The answer is a maintained illuminance level since a light loss factor of 0.85 was included to account for the loss of light over time due to reduced lumen output of the lamp and dirt on the luminaire surfaces.

Illuminance at a Point-Direct Component

Example 2. This example will consider the illuminance at a single point on a horizontal surface from two luminaires aimed straight down. An assumed LLF of 0.85 will be used and Luminaire #1 is the same in Example 1.

D_1 = 2.13m θ_1 = 15°

D_2 = 2.29m θ_2 = 25°

β_1 = 15° I_1 = 2200 cd

β_2 = 25° I_2 = 2000 cd

E_1 = 398 lux (from previous calculation)

E_2 = 291 lux (from calculations)

$E_{TOTAL} = E_1 + E_2 = 689$ lux

Illuminance at a Point-Direct Component

Example 3. This example will consider the illuminance at multiple points on a vertical surface from a luminaire aimed at the surface. An assumed LLF of 0.85 will be used.

Table 1. Components of Example 3

Point	Distance, m	θ°C	β°C	I	LLF	$E_{maintained}$
1	1.74	45	0	2300	0.85	463 lux
2	1.37	27	18	2225	0.85	893 lux
3	2.29	56	11	2100	0.85	194 lux

The luminaire is now aimed at the vertical surface so β is no longer measured from straight down, and β and θ are no longer equal. Illuminance is calculated using the same equation as the prior examples.

Illuminance at a Point-Direct Component

- In Table 1, illuminance at point 2 is greater than at point 1 and illuminance at point 3 is the least. This is because the distance at point 2 is less than point 1 and the angle theta (θ) at point 2 is less than at point 1, despite the fact that the intensity in that direction is less.

- Similar reasoning can be used with regard to point 3. These two factors cause the illuminance at point 2 to be greater than the illuminance at point 3.