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A HYBRID METHOD FOR ESTIMATING NATURAL LIGHTING POTENTIAL IN BUILDINGS

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ABSTRACT
This paper describes data and algorithms to estimate typical average interior illuminance from daylighting using a hybrid of Hay, Davies, Klucher, Reindl (HDKR) method for calculating total solar radiation on a tilted surface and the Illuminating Engineering Society (IES) Lumen Method for estimating interior illuminance from daylighting. This hybrid algorithm, in conjunction with typical meteorological data, directly accounts for shading and typical local cloud cover effects on an hour-by-hour basis, which is difficult to do using the IES sky-cover or sky-ratio methods. Several experiments show reasonable agreement between measured and calculated results. Case study examples demonstrate of use of the method, when incorporated into software, to quickly analyze daylighting potential in industrial facilities, and the use of this information to develop specific recommendations for cost-effectively reducing lighting energy use in industrial facilities by improving the utilization of natural lighting.

INTRODUCTION
During the first part of the 20th century, most factories were constructed with large areas of glazing, often in clerestory configurations, to provide natural light and ventilation for workers. For example, the Figure 1 shows the factory where the first airplanes were produced by Wilbur and Orville Wright in 1911. Large windows provide all the light necessary for production; the sole electric light in the picture is turned off. Figure 2 shows the floor plan for the Bureau of Engraving and Printing in Washington DC, which was constructed in the early 19th century. The building was designed as a series of wings so each room could be illuminated with natural light. The floor plan is typical of factories and buildings of the era.

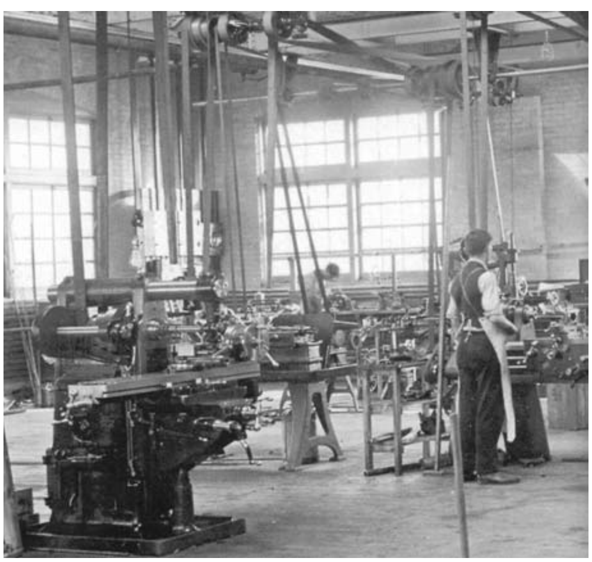

Figure 1. Wright factory in 1911 with abundant natural lighting (Bernstein, 2002).

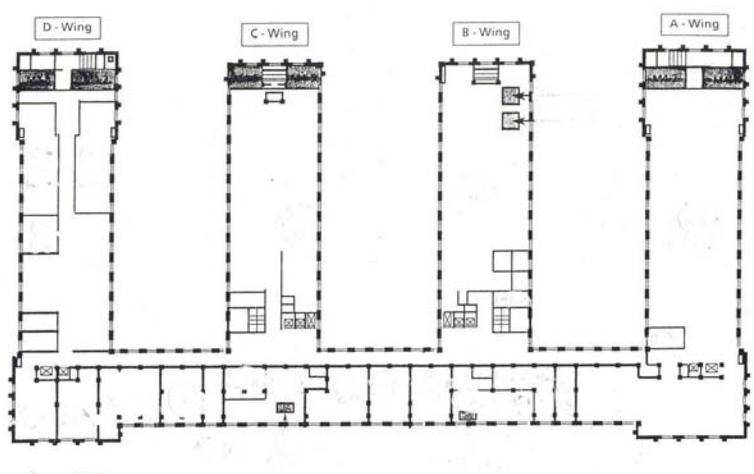

Figure 2. Floor plan of the Bureau of Engraving and Printing in Washington DC.

Over time, the windows in many older factories and buildings have fallen into disrepair; mechanisms for opening and closing the windows have failed and many panes of glass have broken (Figure 3). In many instances, the original glazing has been painted over or replaced with dark or opaque glass. In other cases, the glazing has been covered by fiberglass or corrugated-metal sheets. This process of covering, coating and replacing clear windows accelerated during the 1970s and 1980s as companies sought to reduce heating costs. As awareness of the potential for natural lighting faded, it was replaced by near complete reliance on large banks of electric lights. These electric lights are frequently wired in large blocks that make it difficult to turn off selective lights even when natural lighting is adequate.

Figure 3. Modern factory with missing, broken and opaque window panes.

Today, many industrial facilities that were formerly cathedrals of natural light are now dimly illuminated caverns. The drive to reduce energy costs has led to minimal lighting levels and the widespread adoption of lighting that produces the most lumens per kW, such as high-pressure sodium lighting, regardless of other measures of lighting efficacy. As a result, many factories operate at 25 fc and below using lighting with poor color rendition, harsh glare, and no association with the outside world. In addition the lights are frequently wired so that lights near windows cannot be turned off even when the windows provide more and better light than is necessary.

When performing energy and productivity assessments for industrial facilities, the juxtaposition of poor lighting conditions in buildings that were originally designed for extensive natural lighting is striking. However, to justify the cost of refurbishing the windows, installing skylights, or rewiring lighting panels, it is necessary to quickly and accurately estimate the natural lighting potential of the space throughout the day and year, and organize the output data in a manner which readily supports decisions about how many lights can be turned off for how long.

The Illuminating Engineering Society of North America (IESNA) describes a method for calculating daylight availability. The method uses standard algorithms to calculate the position of the sun at a specific location and time and the direct clear sky solar illuminance on vertical and horizontal surfaces. The illuminance (lm) is calculated from total solar radiation (W/m^2) using a solar luminous efficiency of 94.2 lm/W. Total solar illuminance, including diffuse solar radiation and cloud cover effects, is then calculated using a sky-ratio or sky-cover method. The methods result in three different relations for clear, partly-cloudy and overcast skies (IESNA, 2000).

A similar method for calculating total solar radiation on a tilted surface, called the Hay, Davies, Klucher, Reindl (HDKR) method, is widely used within the solar energy community (Duffie and Beckman, 1991). A principal difference between the two methods, however, is that the HDKR method estimates total solar radiation on a tilted surface based on location, time and *measured total solar radiation on a horizontal surface*. Thus, the HDKR method can use the widely available typical meteorological data sets (e.g. TMY2, EPW, IWEC data files) as input to account for typical cloud conditions at a given location. This eliminates the need to approximate whether the sky is clear, partly cloudy or overcast, as in the IES method.

The daylighting simulation method described here utilizes the HDKR method to calculate total solar radiation on a tilted surface, then converts the total solar radiation to solar illuminance using the solar luminous efficiency of 94.2 lm/W from the EIS method. To calculate interior illuminance based on exterior solar illuminance, the method described here utilizes the IES Lumen Method for toplighting and sidelighting (IESNA, 2000). The method adapts the IES toplighting method when considering clerestory and vertical windows placed high on a wall.

The advantages of this approach include:

1) The approach can be easily extended to include shading effects from wings and overhangs, and to include multiple fenestrations with different exposures.
2) The use of this method in conjunction with widely available typical meteorological data sets reduces the error from estimating the mix of clear, partly-cloudy and overcast sky conditions at a given location.
3) The use of this method in conjunction with widely available typical meteorological data sets reduces the error from dividing continuously variable cloud cover conditions into three discrete categories.
4) The method can be easily programmed into simulation software, which speeds calculation time and enables the hourly results to be easily manipulated to displayed graphically.

This paper describes the data and algorithms used by a hybrid method to calculate typical interior illuminance levels. Several experiments show reasonable agreement between measured and calculated results The use of the algorithm, when programmed into the computer software LightSim, is demonstrated in case study examples for estimating daylighting potential in industrial facilities. The case study examples also demonstrate the use of this information to develop specific recommendations for cost-effectively reducing lighting electricity use in industrial facilities by improving the utilization of natural lighting.

HDKR METHOD FOR PREDICTING SOLAR RADIATION ON A SURFACE

The procedure described here for calculating total solar radiation on a surface at any orientation is called the Hay, Davies, Klucher, Reindl (HDKR) method (Duffie and Beckman, 1991). The method uses location, time and hourly total solar radiation on a horizontal surface data to predict hourly total solar radiation on a surface at any orientation. The total solar illumination on a surface is then estimated by multiplying the total solar radiation by the solar luminous efficiency.

Hourly total solar radiation on a horizontal surface, Ih, can be measured by a relatively inexpensive solar pyranometer and is included in most data sets of typical meteorological data. For example, Typical Meteorological Year TMY2 (USDOE, 1995), Energy Plus Weather EPW (USDOE, 1999), and International Weather for Energy Calculations IWEC (ASHRAE, 2001a) files all contain 8,760 hourly records of Ih data and are available for hundreds of U.S. and international sites. The following method uses location, time and total solar radiation on a horizontal surface data from these files, in conjunction with the orientation of a window or skylight, to estimate solar illumination on the window or skylight during typical conditions. The method is demonstrated using TMY2 files, but could be easily adapted for other data sources.

Calculate Local Solar Time

The hourly data in TMY2 files are recorded in standard time. To calculate local solar time, adjustments must be made to account for the longitude within the time zone and perturbations of the earth's rate of rotation. To do so, calculate the day of the year in degrees, B, from the day of the year, n, (1-365):

$$B = (n-1)\ 360 / 365$$

Calculate the equation of time, E:

$$E = 229.2\ [0.000075 + 0.001868 \cos(B) - 0.032077 \sin(B) - 0.014615 \cos(B) - 0.04089 \sin(2B)]$$

Calculate the standard longitude, lngstd, from the time zone number, tz, (which is listed in the TMY2 header):

$$lngstd = -15\ tz$$

Calculate the local solar hour, hrsol, from the standard hour, hrstd, (which is the time used in TMY2 files) and the local longitude, lngloc, (which is listed in the TMY2 header):

$$hrsol = hrstd + [4(lngstd - lngloc) + E] / 60$$

Convert from solar hour (1 to 24), hrsol, to solar hour angle (degrees), ωsol, such that ωsol corresponds to the midpoint of the hour over which the solar radiation is measured:

$$\omega sol = [(hrsol - 12) \times 15] - 7.5$$

Calculate the Angle Between Normal to Glazing and Sun

Declination, δ, is the angle between the earth's axis and the perpendicular to the sun-earth axis:

$$\delta = 23.45 \sin[360\ (284 + n) / 365]$$

The angle between the perpendicular of the glazing and south, γ, is defined such that $\gamma = -90$ for east facing glazing, $\gamma = 0$ for south facing glazing, $\gamma = 90$ for west facing glazing and $\gamma = 180$ for north facing glazing. The angle between the glazing and the horizontal, β, is defined such $\beta = 0$ for a horizontal glazing and $\beta = 90$ for a vertical glazing.

The local latitude, φ, is listed in the TMY2 header. From solar geometry, the cosine of the angle between the normal to the glazing and the sun, cos(θ), is:

$$\begin{aligned}\cos(\theta) = \ & \sin(\delta) \sin(\varphi) \cos(\beta) \\ & - \sin(\delta) \cos(\varphi) \sin(\beta) \cos(\gamma) \\ & + \cos(\delta) \cos(\varphi) \cos(\beta) \cos(\omega sol) \\ & + \cos(\delta) \sin(\varphi) \sin(\beta) \cos(\gamma) \cos(\omega sol) \\ & + \cos(\delta) \sin(\beta) \sin(\gamma) \sin(\omega sol)\end{aligned}$$

The cosine of the angle between the normal to the horizontal and the sun, cos(θz), is:

$$\cos(\theta z) = \cos(\varphi) \cos(\delta) \cos(\omega sol) + \sin(theta) \sin(\delta)$$

Calculate Beam and Diffuse Radiation on Horizontal Surface

The mean radiation normal to the earth-sun radius at the edge of the atmosphere is called the solar constant, gsc. The value for the solar constant, gsc, used by IES is of 1,350 W/m2 (IESNA, 2000). The mean radiation parallel to the earth's surface at the edge of the atmosphere, Io, is:

$$Io = gsc\ [1 + 0.033 \cos(360\ n / 365)] \cos(\theta z)$$

The hourly clearness index, kt, is defined as the ratio of the radiation on a horizontal surface, Ih, from the TMY2 file, and Io:

$$kt = Ih / Io$$

The total solar radiation on any surface is the sum of the diffuse and beam components. Using empirical data, Erb et al. (1982) developed a relationship between diffuse, Id, and total, Ih, radiation on a horizontal surface:

$$Id / Ih = 1 - 0.09\ kt \quad (\text{when } kt \leq 0.22)$$

$$Id / Ih = 0.9511 - 0.1604\ kt + 4.388\ kt^2 - 16.638\ kt^3 + 12.336\ kt^4 \quad (\text{when } 0.22 < kt \leq 0.80)$$

$$Id / Ih = 0.165 \quad (\text{when } kt > 0.80)$$

Thus, the diffuse, Id, and beam, Ib, components of total solar radiation on a horizontal surface are:

$Id = (Id / Ih) Ih$
$Ib = Ih - Id$

Calculate Beam Radiation on Glazing

The ratio of the cosine of the angle between the normal to the glazing and the sun, $\cos(\theta)$, and cosine of the angle between the normal to the horizontal and the sun, $\cos(\theta z)$, is:

$$Rb = \cos(\theta) / \cos(\theta z)$$

Rb represents the fraction of direct radiation incident on the glazing. From solar geometry, the beam radiation on a glazing at any orientation is:

$$Itb = Ib\ Rb$$

Calculate Diffuse Radiation on Glazing

As solar radiation passes through the atmosphere, both its directional and spectral properties change due to absorption and scattering. The diffuse component of solar radiation has four sources: circumsolar, isotropic, horizontal and reflected.

The diffuse component of solar radiation from the area surrounding the solar disk depends on sky clarity, as characterized by the ansiotropic index, Ai:

$$Ai = Ib / Io$$

The diffuse component of solar radiation from the area surrounding the solar disk, It,cs, is then:

$$It,cs = Id\ Rb\ Ai$$

From solar geometry, the diffuse component of solar radiation spread evenly over the sky, It,iso, is:

$$It,iso = Id\ [(1 + \cos(\beta)) / 2]\ (1 - Ai)$$

From solar geometry, the diffuse component of solar radiation from the horizon, It,hz, is:

$$It,hz = Id\ [(1 + \cos(\beta)) / 2]\ (1 - Ai)\ (Ib/Ih)^{1/2} \sin^3(\beta/2)$$

The reflectivity of the ground in front of the collector, ρg, ranges from about 0.1 for dark surfaces to 0.8 for snow. From solar geometry, the component of solar radiation reflected from the ground, It,ref, is:

$$It,ref = Ih\ \rho g\ [(1 + \cos(\beta)) / 2]$$

The total diffuse solar radiation incident on a glazing at any orientation is:

$$Itd = It,cs + It,iso + It,hz + It,ref$$

Total Solar Radiation on Glazing

The total solar radiation incident on a glazing at any orientation, It, is the sum of the beam and diffuse components:

$$It = Itb + Itd$$

The total solar illuminance on a glazing at any orientation, Eg, is the product of the total solar radiation and the solar luminous efficiency of 94.2 lm/W.

$$Eg\ (lx) = It\ (W/m^2) \times 94.2\ (lm/W)$$

Method For Predicting Shading from Wings and Overhangs

Shading from Horizontal Overhangs

The solar altitude angle between the glazing and the height of the sun is θz . To predict shading on vertical glazings from overhangs, the relevant dimensions are the protrusion of the overhang, po, the gap between the overhang and top of the glazing, gapo, and the height of the glazing, hc (Figure 4).

From trigonometry, the distance from the overhang to the center of the window, y, is:

$$y = po / \tan(\theta z)$$

Assuming that the overhang extends lengthwise beyond both sides of the glazing such that these relations hold at all solar azimuth angles, the fraction of the glazing not shaded by the overhang, Co, is:

$$Co = (gapo + hc - y) / hc$$

Shading from Vertical Wings

A similar development is used to estimate shading from vertical wings. The solar azimuth angle between the glazing and the sun as it moves from east to west across the southern sky is γz. The algorithm for calculating γz (Duffie and Beckman, 1991) uses four coefficients, c1, c2, c3 and c4:

IF $|\tan(\delta)/\tan(\varphi)| > 1$ THEN
c1 = 1
ELSE
IF $|\omega| < \cos^{-1}(\tan(\delta) / \tan(\varphi))$ THEN c1 = 1 ELSE c1 = -1 END IF
END IF

IF $\varphi (\varphi-\delta) \geq 0$ THEN c2 = 1 ELSE c2 = -1

IF $w \geq 0$ THEN c3 = 1 ELSE c3 = -1

$$C4 = \sin^{-1} [\sin(\omega) \cos(\delta) / \sin(\theta z)]$$

$$\gamma z = c1\ c2\ c4 + c3\ (1 - c1\ c2)\ 90$$

To predict shading on glazings from vertical wings, the relevant dimensions are the protrusion of the wing, pw, the gap between the wing and side of the glazing, gapw, and the width of the glazing, wc (Figure 5).

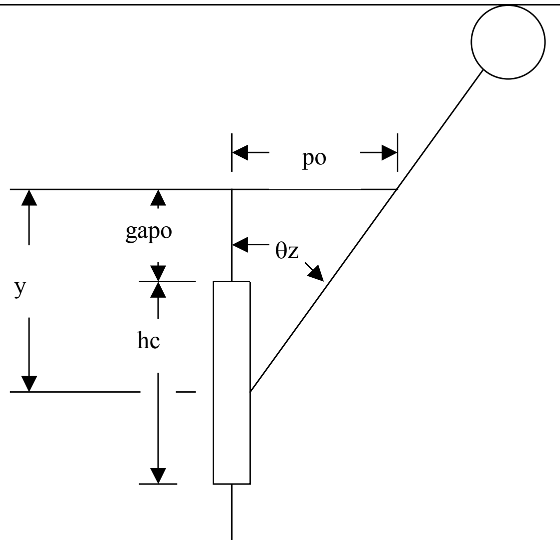

Figure 4. Relevant dimensions for predicting shading on a vertical glazing from an overhang.

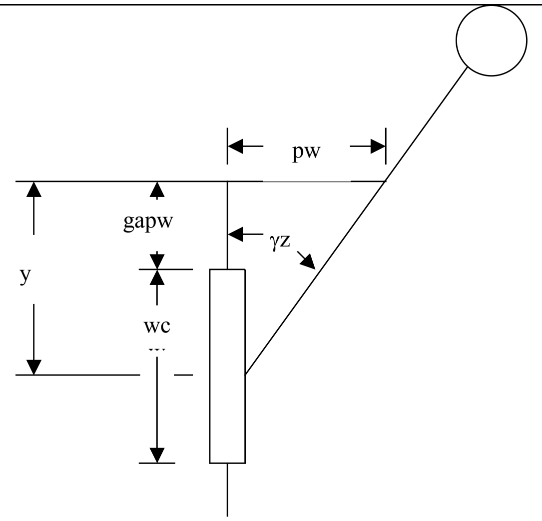

Figure 5. Relevant dimensions for predicting shading on a glazing from a vertical wing.

From trigonometry, the distance from the wing to the center of the window, y, is:

$y = pw / \tan(\gamma z)$

Assuming that the wings extend vertically above both sides of the glazing such that these relations hold at all solar altitude angles, the fraction of the glazing not shaded by the wing, Cw, is:

$Cw = (gapw + wc - y) / wc$

The product of the fractions of glazing not shaded by overhangs or wings should be applied to the directional components of the total solar radiation on the glazing to estimate total solar radiation on a glazing including shading effects:

$It = Itb\ Co\ Cw + It,cs\ Co\ Cw + It,iso + It,hz + It,ref$

When overhangs and/or wings do not extend sufficiently beyond the glazing, this algorithm slightly overestimates the shading effect. As before, the total solar illuminance is the product of the total solar radiation and the solar luminous efficiency of 94.2 lm/W.

IES LUMEN METHOD FOR PREDICTING INTERIOR ILLUMINANCE FROM TOPLIGHTING

The general equation to calculate the illuminance on a work plane, Ew, from the illuminance on a horizontal skylight, Eg, is (IESNA, 2000):

$Ew = Eg \times Cu \times \tau g \times \tau lw \times Asl / Aw$

where

Cu = coefficient of utilization
τg =average transmittance of glazing in skylight
τlw = transmittance of the light well
Asl = area of the skylight
Aw = area of the work plane.

Cu is a function of ceiling reflectivity, floor reflectivity and the room cavity ratio, RCR where:

$RCR = 5h\ (w + l) / wl$

where h is the height of the skylight over the work plane, w is the width of the room and l is the length of the room. Values of Cu for skylights are tabulated in the IESNA Lighting Handbook (IESNA, 2000, Figure 8-20, pg. 8-12) as a function of ceiling reflectance, ρc, and wall reflectance, ρw. A $R^2 = 0.99$ least-squares regression of the data in this table yields the following relation for Cu:

$Cu = 1.0169 + 0.074074\ \rho c - 0.14778\ RCR + 0.11111\ \rho w + 0.037037\ \rho c^2 + 0.0081333\ RCR^2 + 0.125\ \rho w^2$

Similarly, the transmittance of the light well, τlw, is a function of well reflectivity, ρlw, and well cavity ratio, WCR, where:

$WCR = 5h\ (w + l) / wl$

where h is the height of the well, w is the width of the well and l is the length of the well. Values of the transmittance of the light well, τlw, are shown in the IESNA Lighting Handbook (IESNA, 2000, Figure 8-18, pg. 8-12) as a function of light well wall reflectance, ρlw. A $R^2 = 0.98$ least-squares regression of the data in this figure yields the following relation for τlw:

$\tau lw = 0.82 - 0.04067\ WCR + 0.3\ \rho lw$

The transmittance of the glazing in the skylight, τg, is different for direct and diffuse light. Transmittance of direct light is greatest when the sun is normal to the surface of the glazing and decreases rapidly as the angle of incidence between the sun and glazing increases. For single glazing, the transmittance of direct light at an incidence angle of 80 degrees is about ½ of the transmittance of direct light normal to the glazing; for double glazing, the transmittance of direct light at an incidence angle of 80 degrees is about 1/3 of the transmittance of direct light normal to the glazing. The transmittance of diffuse light is not dependent upon angle of incident, but is generally about 90% of the transmittance of direct normal light (ASHRAE, 2001b).

Although it is possible to disaggregate total illumination into direct and diffuse components and calculate the direct and diffuse transmittances separately, the accuracy gained by this effort is highly dependent on the specific relationship of direct transmittance with angle of incidence, and on the diffuse transmittance for a particular glazing. In practice, this information is rarely available. Most glazing manufacturers simply specify a single value for transmittance, which in most cases is the transmittance of direct visible light normal to the surface. Thus, the method described here simply estimates that the average transmittance, τg, is 70% of the transmittance of direct normal visible light normal normally specified by the glazing manufacturer:

$\tau g = 0.7\ \tau g,\text{specified}$

The method described here also uses the toplighting method to estimate interior illuminance from clerestory windows or windows located very high on a wall. The only modifications required are that transmittance of the light well, τlw, is set to 1.0 and the illuminance on the skylight is replaced by the illuminance on the window.

IES LUMEN METHOD FOR PREDICTING INTERIOR ILLUMINANCE FROM SIDELIGHTING

The general equation to calculate the illuminance on a work plane, Ew, from the illuminance on a vertical window Eg is:

$Ew = Eg \times Cu \times \tau g$

where

Cu = coefficient of utilization

τg = average transmittance of glazing in window

Cu is a function of the window length and height, room depth and the distance between the window and the work plane (expressed as a fraction of the room depth). Values of Cu for windows are tabulated in the IESNA Lighting Handbook (IESNA, 2000, pgs. 8-15 to 8-17). Cu is expressed as a function of three ratios:

wh = ww / wh (If wh > 8 Then wh = 9 'curves flatten out)
dh = dr / hw (If dh > 10 Then dh = 12 'curves flatten out)
pd = dw / dp

where

ww = window width
wh = window height
dr = depth of room from window
hw = height of window
dw = depth of workplane from window

A $R^2 = 0.90$ least-squares regression of the data in the Table 8-22 (IESNA, 2000, pg 8-15) yields the following relation for Cu:

$Cu = 0.98441 - 0.15029\ dh - 1.4311\ pd + 0.074284\ wh + 0.0088150\ dh^2 + 0.89427\ pd^2 - 0.0065955\ wh^2$

If Cu < 0.003 Then Cu = 0.003 'min value in table
If Cu > 1 Then Cu = 1

As before, the average transmittance of the glazing, τg, is assumed to be 70% of the transmittance of direct visible light normal to the surface specified by the glazing manufacturer.

COMPARISONS OF HYBRID METHOD WITH MEASURED RESULTS

In order to test the method, several experiments were conducted to compare measured and calculated results. The following tests summarize some of these comparisons. The precision of the multimeter used to measure the pyranometer output is $\pm$ 0.1 mV; thus, the precision of solar radiation measurements is $\pm$ 11 W/m^2 or $\pm$ 109 fc. Considering this base level of precision, and subsequent measurement errors, the tests show reasonable agreement between measured and calculated values.

Test 1: Conversion of Solar Radiation to Illuminance

Total solar radiation on a horizontal surface was measured with a solar pyranometer on a cloudy day to be 35 W/m^2. The method described here estimated the solar illuminance to be about:

$Eg = 35\ W/m^2 \times 94.2\ lm/W / 10.76\ ft^2/m^2 = 306\ fc$

A light meter positioned directly upward next to the solar pyranometer read 351 fc. The absolute deviation was 13%.

Test 2: Calculation of Average Transmittance

Total solar radiation on a north-facing double-glazed window was measured with a solar pyranometer to be 98 W/m2. The method described here estimated the solar illuminance on the glazing to be:

$Eg = 98\ W/m^2 \times 94.2\ lm/W / 10.76\ ft^2/m^2 = 858\ fc$

According to ASHRAE (2001b), the transmittance of direct visible light normal to the surface for clear double glazing is 0.81. The method described here estimates the average transmittance to be 70% of the specified transmittance:

$\tau g = 0.7\ (0.81) = 0.57$

Using the method described here, the illuminance just inside the glazing was calculated to be:

856 (fc) x 0.57 = 487 fc.

A light meter on the inside of the glazing read 500 fc, for a deviation of 3%, showing good agreement with the assumption that average transmittance is 70% of direct normal transmittance.

Test 3: HDKR Calculation of Solar Radiation on Vertical Surfaces

Wynn and Joseph (1997) compared measured values of solar radiation on vertical surfaces with values calculated using the HDKR method. Their results, shown in Table 1, show an average absolute deviation of 9% between measured and calculated values.

Table 1. Measured and calculated values of solar radiation on vertical surfaces (Wynn and Joseph, 1997).

	Measured W/m2	HDKR W/m2	Deviation W/m2	Abs Deviation %
Asphalt				
Horizontal	788			
S	615	631	-16	3%
W	536	536	0	0%
N	95	95	0	0%
E	88	95	-6	7%
Red Court				
Horizontal	914			
S	568	599	-32	6%
W	394	473	-79	20%
N	142	142	0	0%
E	142	142	0	0%
Gray Concrete				
Horizontal	788			
S	410	504	-95	23%
W	236	315	-79	33%
N	221	189	32	14%
E	158	158	0	0%
Average				9%

In another experiment, total solar radiation on a horizontal and four vertical surfaces was measured with a solar pyranometer at about 10 am on 3/15/2004 in Dayton, Ohio. The HDKR method described here overestimated measured values when the time of day was set to 10 am; however, the method came closer to measured values when the time of day was set to 11 am. Measured and calculated values, when the time was set to 11 am, are shown in Table 2. This demonstrates the sensitivity of the method to time-of-day.

Table 2. Measured and calculated values of solar radiation on vertical surfaces.

	Measured W/m2	HDKR W/m2	Deviation W/m2	Abs Deviation %
Horizontal	607			
East	676	618	58	9%
South	596	629	-33	6%
West	149	90	59	40%
North	115	90	25	21%
Average				19%

Test 4: Hybrid HDKR/EIS Sidelighting Method

This experiment compared interior illuminance in a classroom with north facing windows to the illuminance calculated using the hybrid HDKR/EIS sidelighting method. Total solar radiation on a horizontal surface was measured with a solar pyranometer to be 504 W/m^2 at about 3:00 pm on 3/15/2004 in Dayton, OH. The illuminance outside a north- facing wall was measured to be 870 fc with a light meter. The average illuminance on the inside surface of the north facing windows in the classroom was measured to be 390 fc. Interior illuminance on the work plane at increasing depths from the windows, d, was then measured and compared to the illuminance calculated using the hybrid HDKR/side lighting method described here. The results, shown in Table 3, show good agreement between the illuminance on north facing surfaces, the illuminance on the interior surface of the glazing, and the average illuminance on the workplane, but show significant deviations for illuminance at specific locations within the room.

Table 3. Measured and calculated values of illuminance using hybrid HDKR/EIS sidelighting method.

	Measured fc	Calculated fc	Deviation fc	Abs Deviation %
III, north surf	870	845	25	3%
III, inside glazing	390	355	35	9%
III, d=25%	60	78	-18	30%
III, d=50%	17	11	6	35%
III, d=75%	7	1	6	86%
III (avg of d=25,50,100%)	28	30	-2	7%

Test 4: Hybrid HDKR/EIS Toplighting Method

This experiment compared illuminance in a manufacturing facility with north and south-facing windows to the average illuminance calculated using the hybrid HDKR/EIS toplighting method. The 1920-era building in Dayton, Ohio has large expanses of wall and clearstory windows on both the north and south exposures (Figure 6). The 11,250 ft^2 workspace depends almost exclusively on natural light; only nine 200-W incandescent bulbs are installed. In addition, workers report that the building stays warm throughout the winter due to the passive solar heating through the south windows.

Figure 6. Exterior and interior views of building.

Interior lighting levels, as measured in a traverse between the south to north walls of the building, are shown in Table 4. The illuminance near the south windows ranged from 300 fc, when measured in the shade of a pillar, to over 2,000 fc when measured in direct sunlight.

Table 4. Interior lighting levels at a traverse of the midpoint of factory.

Distance from south wall (ft)	Illuminance (fc)
12	300-2000
25	100
38	215
50	90
63	60

Total solar radiation on horizontal, north and south surfaces was measured with a solar pyranometer. The illuminance on the south and north windows and average interior illuminance was then calculated using the hybrid HDKR/EIS toplighting method. Comparison of measured and calculated values (Table 5) shows good agreement when the average measured interior illuminance is taken to be the illuminance at the midpoint of the building.

Table 5. Measured and calculated values of illuminance using hybrid HDKR/EIS toplighting method.

	Measured W/m2	Measured fc	Calculated Fc	Deviation Fc	Abs Dev %
Horizontal	756				
South	653	6,206	6,806	-600	10%
North	126	1,198	897	301	25%
Workplane		215	240	-25	12%

Summary of Testing

These experiments indicate relatively good agreement between the hybrid HDKR/EIS method described here and measured values of illuminance over a wide range of circumstances. The measured and estimated illuminances in several other industrial facilities have also been compared. In each case, it was possible to calibrate the estimated illuminance to the measured illuminance by adjusting estimates of wall and ceiling reflectivity and overall transmittance of the glazing. Thus, as in the case of building simulation models, these comparisons serve to suggest reasonable agreement between the method and measured results, but can't precisely quantify the accuracy of the method.

LIGHTSIM DAYLIGHTING ANALYSIS SOFTWARE

The algorithms described here have been incorporated into the computer program LightSim (Kissock, 2000) to simulate typical hour-by-hour illuminance on a work plane using TMY2 meteorological data. LightSim is designed to quickly assess the feasibility of daylighting in buildings. The principle output of LightSim is an estimate of the fraction of time that daylighting can meet or exceed a target illumination on a work plane.

For many facility owners, this information is critical for deciding whether to proceed with daylighting opportunities. The following case studies demonstrate the use of LightSim to quickly quantity opportunities to reduce energy use by improving the utilization of natural lighting.

Case Study 1: Use Of LightSim To Justify Replacement of Damaged Windows

An industrial facility in Cincinnati, Ohio was built with large expanses of clear windows along the east and west walls. Over time, many of these windows were damaged and replaced with dark glass that allows little or no sunlight to enter the building. As a consequence, the building, which was originally designed to function using only natural lighting, was now illuminated primarily by high-bay high-pressure sodium (HPS) lights.

Lighting levels throughout the plant varied considerably depending on proximity to the windows and the type of window covering, but averaged about 18 fc. The IESNA recommends lighting levels between 30 and 50 fc for most manufacturing applications (IESNA, 2000). The combination of poor color rendition from the HPS lights and low lighting levels resulted in poor overall lighting. In addition, broken windows increased heating costs and contributed to unpleasantly cold working conditions during winter.

Near the south end of the plant, a few windows had been repaired by removing the panes of glass and covering the window area with 4 ft x 8 ft sheets of semi-transparent corrugated fiberglass. The transmittance of light through the corrugated fiberglass was measured to be about 10 times higher than through the dark replacement glass. Figure 7 shows windows along the south wall of the plant, including dark replacement panes and corrugated fiberglass. The window to right of the door is covered with corrugated fiberglass, and allows much more light to pass into the plant than the windows to the left of the doors.

Figure 7. South windows with a mix of semi-transparent glass, dark glass and corrugated fiberglass. The bright window to the right of the open doors is covered with corrugated fiberglass.

The effort to remove panes of glass and cover the windows with corrugated fiberglass resulted in lower maintenance, increased security, reduced heating costs and improved plant lighting. However, over time, the effort lost momentum and was discontinued, in large part because the benefits of replacing the windows could not be quantified.

To quantify the benefits of replacing the windows, current plant lighting levels were simulated with the LightSim software. Assumptions used in the simulation include setting wall and ceiling reflectance to 0.1 and the average transmittance of the current windows to 0.1. The LightSim output screen shows average hourly lighting levels over a 24-hour period calculated using the hybrid HKDR/toplighting method (Figure 8). The trace shows no natural lighting before 5 am or after 7 pm. The double hump is caused by increasing lighting through the east windows in the morning and through the west windows in the afternoon. The results indicate that the current windows provide an average lighting level between 8 am and 5 pm of about 8 fc.

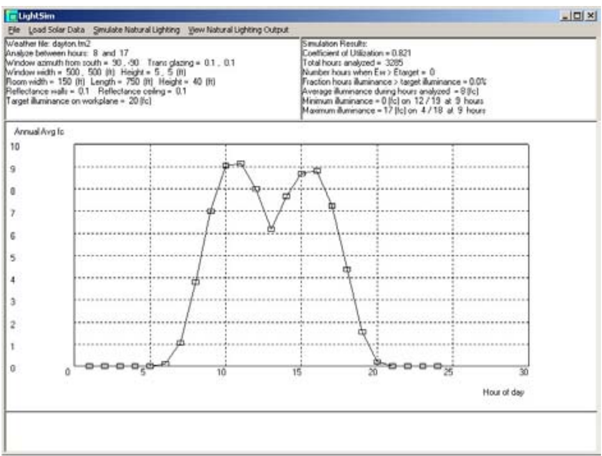

Figure 8. Simulated average hourly lighting levels from natural light, with current windows.

The average measured lighting level in the plant was about 18 fc. Thus, the HPS lighting is assumed to contribute about 10 fc to the total lighting. The results also indicate that the current windows never produce an average lighting level of 20 fc. Thus, as confirmed by multiple measurements, the plant never achieves the recommended average lighting level of 30 fc.

Next, plant lighting levels were simulated assuming that the current windows were replaced with corrugated polycarbonate. Corrugated polycarbonate was selected over corrugated fiberglass because the light transmittance of corrugated fiberglass degrades significantly over time due to UV degradation of the glass fibers. In comparison, the initial light transmittance of corrugated polycarbonate is about 96%; and, because polycarbonate does not contain fibers, the transmittance stays high for much longer. Corrugated polycarbonate is installed just like corrugated fiberglass, and costs about \$0.90 per ft^2 compared to about \$0.70 per ft^2 for corrugated fiberglass.

In the second simulation, the transmittance of the corrugated polycarbonate was assumed to be 0.4 rather than the rated transmittance of 0.96 to account for losses from framing, dirt, aging, and internal reflectivity due to the corrugations. The LightSim output screen in Figure 9 indicates that the average lighting level between 8 am and 5 pm would increase to about 32 fc, and that natural lighting would result in an average lighting level of greater than 30 fc for about 73% of the time. Thus, assuming that the HPS lights produce 10 fc, plant lighting would virtually never dip below the recommended 30 fc and would maintain an average level of about 42 fc. In addition, the ability to discern color would be significantly improved due the natural light. Based on this analysis, and a supporting analysis showing heating energy savings, the facility owner decided to replace the current windows with corrugated polycarbonate sheeting as recommended.

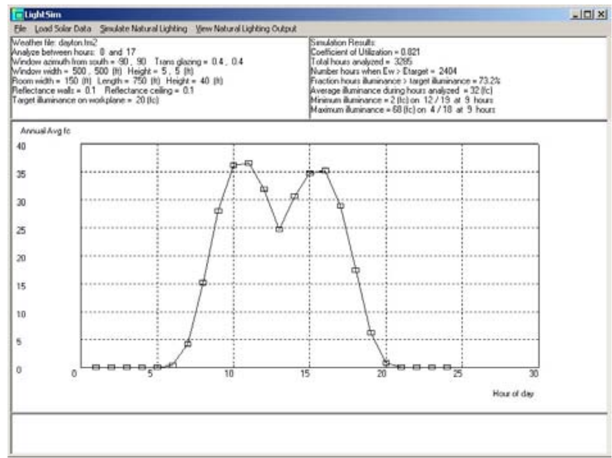

Figure 9. Simulated average lighting levels from natural light if the current windows were replaced with corrugated polycarbonate.

Case Study 2: Use Of LightSim To Evaluate Cost-Effectiveness Of Natural Lighting

A 13,000 ft^2 foundry in northern Ohio had 840 ft^2 of windows located high on an east-facing wall. Natural lighting was measured to provide about 45 fc of light for 40% of the foundry. This enabled two rows of lights to be completely turned off during first shift (Figure 10). The foundry owner was considering whether to cover the existing windows to reduce heating costs or leave the windows in place to reduce lighting costs.

Figure 10. Foundry with east-facing windows that provide enough light to turn-off two of the five rows of lights.

To answer this question, typical illumination from the windows was simulated using the LightSim software and a TMY2 weather data file. To support the simulation, the visible transmittance of the glazing was measured to be about 0.60. The results of the simulation indicated that the east-facing windows could provide 40 fc of lighting at 40% of the room's depth for over 95% of the time between 8 am and 5 pm (Figure 11). Thus, the electrical lighting over about 5,200 ft^2 of floor area could be turned-off year round during these hours.

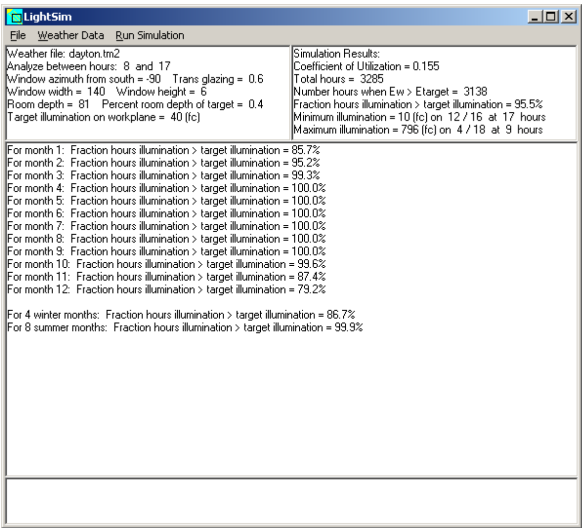

Figure 11. LightSim simulation results for foundry.

The heating energy savings from replacing the windows with a concrete block wall were then calculated. The results indicated that the current practice of turning off the lights over about 5,200 ft^2 of floor space saves about $1,980 per year in energy costs compared to replacing the windows with R5 concrete-blocks. Based on this analysis, the owner decided to keep the windows in place.

Summary of Case Studies

Many older industrial facilities were designed to maximize natural lighting. Unfortunately, the natural lighting potential of many of these facilities has been lost over time due to neglect and due to the lack of specific information about how maximize the use of natural lighting to reduce energy costs and improve the safety and productivity of the workplace. These case studies demonstrate the usefulness of the hybrid HDKR/Lumen method, as incorporated into the LightSim software, for analyzing natural lighting potential in industrial buildings. No other software is known to provide this type of information to practitioners seeking to improve utilization of natural lighting.

SUMMARY AND CONCLUSIONS

This paper described data and algorithms to estimate typical average interior illuminance from daylighting using a hybrid of HDKR method for calculating total solar radiation on a tilted surface and the IES Lumen Method for estimating interior illuminance from daylighting. This hybrid algorithm, in conjunction with typical meteorological data, directly accounts for shading and typical local cloud cover effects on an hour-by-hour basis, which is difficult to do using the IES sky-cover or sky-ratio methods.

Several experiments compared measured and calculated values of illumination. The experiments showed reasonable agreement between measured and calculated results, with typical deviations of less than 25%.

Case study examples demonstrated the use of the method, when incorporated into the LightSim software, to quickly analyze daylighting potential in industrial facilities, and the use of this information to develop specific recommendations for cost-effectively reducing lighting energy use by improving the utilization of natural lighting. The principle output of the software is an estimate of the fraction of time that daylighting can meet or exceed a target illumination on a work plane. In addition, graphical displays of average hourly illuminance over different periods are helpful for communicating results.

For many facility owners, this information is critical for deciding whether to proceed with daylighting opportunities. No other software is known to provide this type of information for practitioners seeking to improve utilization of natural lighting. Hence, it is critical that the software be tested under a wide range of circumstances in order to better understand its applications and limitations. In addition, internal algorithms for calculating coefficients of utilization can be expanded and improved, and graphical and numerical displays of the results can be improved.

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