THE AVERAGE TOTAL DAYLIGHT FACTOR

Luisa Brotas
LEARN - Low Energy Architecture Research Unit
London Metropolitan University
INETI Department of Renewable Energy
National Institute Engineering, Technology and Innovation I.P.
l.brotas@londonmet.ac.uk
the sun is invisible although its position above the clouds affects the brightness of the sky depending on the turbidity of atmosphere
the luminance of the CIE overcast sky depends on the altitude of the point of the sky in relation to the zenith, independent of the sun position and for the same altitude is equal in all azimuth

the luminance distribution varies with location time density and uniformity of the clouds
the luminance at the zenith is 3 times brighter than the horizon
Clear sky

- the brightness of the sky varies in terms of altitude and azimuth of the point
- the sky luminance varies with the position of the sun and the amount of atmospheric dust or haze
- the brightest point is the sun. It tends to progressive darken to the opposite point around 90 degree in azimuth. The luminance at the horizon is a value between these two extremes
Sky distribution

- when the sun is behind the building a vertical window can face a less bright part of the sky on a clear day than on an overcast day
- the illumination on a vertical surface receiving light from half of the sky of uniform luminance is greater than from an overcast with the same zenith luminance, the ratio being approximately 1.6

- except the circumsolar area around the sun position the clear sky is brighter at the horizon than overhead
Daylight calculations are usually based on uniform or overcast skies, but in areas where clear skies are predominant it may underestimate the illuminance levels and might lead to inappropriate urban and window design.
Global horizontal illuminance

Frequency exceed 40,000 lux

The amount of light reflected by a ground reflecting 25% of light is equivalent to the one provides by an overcast sky delivering 10,000 lx horizontally. Maps show a strong potential to use outdoor reflected sunlight to light interiors:
- above 60% of the time for most Europe from April to August
- for the rest of the year, the section of Europe located above 45° in latitude cannot benefit from reflected sunlight.
Daylight

The sun is the main source of light

The light that reaches a surface has:
- a direct component – from the sun
- a diffuse component – light from the sky

Both may be reflected by external surfaces, namely buildings and obstructions and internal surface of a room

On an overcast sky the sun component is excluded
Daylight factor

- $D$ most used method for daylight calculations
- $D$ at a point is the ratio of the indoor illuminance to the outdoor unobstructed horizontal illuminance, expressed as a percentage

$$D = \frac{E_{\text{in}}}{E_{\text{out}}} \cdot 100\%$$

By definition the sun component is excluded
Daylight factor may be calculated as

$$D = D_c + D_e + D_i$$

where

- $D_c$ is the sky component
- $D_e$ externally reflected component
- $D_i$ internally reflected component
Daylight analysis in the UK has been traditionally associated with the CIE overcast sky for the following reasons:

- If the natural lighting is sufficient on an overcast day it is likely to be more than adequate during a clear day;
- The overcast sky luminance is independent of the azimuth therefore the effect of orientation is not considered in the calculation;
- The indoor illuminance is directly proportional to the simultaneous outdoor horizontal unobstructed illuminance independent of the overcast sky brightness.
Average Daylight Factor

**BRE formula**

$$ADF = \frac{M \tau A_w \theta}{A(1 - \rho_{av}^2)}$$

**Lynes’s formula**

$$ADF = \frac{\tau A_w \theta}{2A(1 - \rho_{av})}$$

where
- $\tau$: diffuse transmittance
- $A_w$: net glazed area
- $\theta$: vertical angle
- $A$: total area of interior surfaces
- $\rho_{av}$: area weighted average reflectance of interior surfaces
- $M$: Maintenance factor
Daylight calculations under a clear sky distribution should consider:

- **Sun component** – direct light from the sun and reflected from obstructions and ground
- **Sky component** – diffuse light from the sky and reflected from obstructions and ground
- **Interreflections** inside the space
Reflected sunlight can play an important role in the illumination of buildings, particularly in orientations and during times of the day where sunlight is not incident on the windows. Obstructions and ground can redirect the light to other interior surfaces rather than the horizontal plane and promote a better uniformity of light inside the space.

Depends on:
- reflectance of surfaces
- geometry of the canyon
- position on the facade
Reflected light from ground and obstruction

Reflected sunlight is an important contribution to the illuminance of buildings when the sun is behind the building.
In a 1:1 canyon reflected sunlight from vertical surfaces contributes significantly to the illuminance of the building in comparison to reflected sunlight from the ground. The contribution from the obstructions is around ten times higher than the contribution from the ground at the equinox in a canyon in Lisbon. For higher latitudes this difference may increase as the sun reaches lower altitude angles, therefore predominantly being incident on vertical surfaces. During the summer however, the ground contribution can be high, but for the remaining period of the year it is reduced or is even non-existent as the lower winter sun angles may never reach the ground in a canyon.
Higher reflectance will significantly increase the illuminance of the building. However, the effects of reduced facade maintenance, dark colours, window reveals, setbacks and balconies casting shadows may significantly reduce the effective reflectance of the facades. A conservative figure of 0.2 reflectance may not be far distant from the reality.
Real measurements

urban canyon

- facing buildings provide considerable obstruction to daylight by reducing the skylight contribution and sometimes blocking the access to sunlight.
- however, reflected sunlight is an important contribution in the time of the day when the sun is behind the building.

There is a linear relationship between the global horizontal illuminance and the total vertical illuminance.
Several methods are available to predict daylight conditions under sunny conditions, but either require a well advanced state of the project or tend to be difficult to use by architects.

Although absolute values of illuminance are strongly dependent on sun altitude and therefore are variable for different times of day and latitudes, the linear relationship between the global and the total vertical illuminance on a north facade remains relatively constant at the equinox and solstice days.
The linear relationship is fairly stable at different times of the year.

A few exceptions occur in the summer months when the sun's azimuth is around 90 or 270 particularly affecting the lower floors.
The linear relationship is fairly stable for different orientations when the sun is not incident in the façade.
Analytical approach

- The linear relationship doesn't change a lot for latitudes between 35 and 50°
\[ E_{tv} = k \cdot E_{gh} + C \]

where

- \( E_{tv} \) is the illuminance on a vertical plane due to direct sunlight, skylight and the inter-reflections.
- \( E_{gh} \) is the illuminance on a horizontal unobstructed plane due to direct light from sun and diffuse light from the sky.

\( k \) and \( C \) are constants.

<table>
<thead>
<tr>
<th>Floor</th>
<th>( k )</th>
<th>( 1:0.5 )</th>
<th>( R^2 )</th>
<th>( K )</th>
<th>( 1:1 )</th>
<th>( R^2 )</th>
<th>( k )</th>
<th>( 1:1.5 )</th>
<th>( R^2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>( C )</td>
<td></td>
<td></td>
<td>( C )</td>
<td></td>
<td></td>
<td>( C )</td>
<td></td>
</tr>
<tr>
<td>Ground</td>
<td>0.052</td>
<td>-</td>
<td>0.845</td>
<td>0.069</td>
<td>8.45</td>
<td>0.915</td>
<td>0.068</td>
<td>14.04</td>
<td>0.878</td>
</tr>
<tr>
<td>1\text{st}</td>
<td>0.067</td>
<td>-</td>
<td>0.938</td>
<td>0.089</td>
<td>6.74</td>
<td>0.979</td>
<td>0.091</td>
<td>10.85</td>
<td>0.939</td>
</tr>
<tr>
<td>2\text{nd}</td>
<td>0.072</td>
<td>1.45</td>
<td>0.970</td>
<td>0.090</td>
<td>9.58</td>
<td>0.993</td>
<td>0.095</td>
<td>12.94</td>
<td>0.967</td>
</tr>
<tr>
<td>3\text{rd}</td>
<td>0.070</td>
<td>7.21</td>
<td>0.896</td>
<td>0.085</td>
<td>1.412</td>
<td>0.985</td>
<td>0.093</td>
<td>16.54</td>
<td>0.980</td>
</tr>
<tr>
<td>4\text{th}</td>
<td>0.066</td>
<td>14.73</td>
<td>0.816</td>
<td>0.080</td>
<td>1.975</td>
<td>0.961</td>
<td>0.089</td>
<td>19.21</td>
<td>0.981</td>
</tr>
<tr>
<td>5\text{th}</td>
<td>0.062</td>
<td>23.95</td>
<td>0.794</td>
<td>0.076</td>
<td>2.438</td>
<td>0.939</td>
<td>0.086</td>
<td>23.00</td>
<td>0.974</td>
</tr>
</tbody>
</table>

The slope of the equation is fairly constant for different floors.
The constant $C$ weighs significantly in the illuminance on the facade when global illuminance is low. However, on a clear day the illuminance obtained on the horizontal plane can be high, therefore $C$ may be ignored. The Figure shows that the constant $C$ contributes significantly to the overall illuminance on the facade when the global horizontal illuminance is below 10 000lx. On a clear day these values will correspond to a solar altitude below 10°, therefore can be ignored without significant influence on the overall illuminance.
Total daylight factor

The ‘Total Daylight Factor’, TD, at a point is the ratio of the total internal illuminance, i.e. direct and indirect for both sky and sun, to the external unobstructed global illuminance.

Total daylight factor on a working plane on a 2nd floor room facing north in a 1:1 canyon in Lisbon in spring equinox.
Total average illuminance

The average illuminance within the room can be based on the principle of the interreflection.
Let the flux entering the room be

$$\phi_0 = E_{tv} A_w \tau$$

Where

- $E_{tv}$ is the total vertical illuminance
- $\tau$ is the net glazed area of window
- $A_w$ is the diffuse light transmittance of glazing

The average illuminance on the surfaces due to the flux entering the room is

$$\overline{E_0} = \frac{\phi_0}{A} = \frac{E_{tv} A_w \tau}{A A}$$

The average illuminance due to the first reflected flux. The first interreflection

$$\overline{E_1} = \frac{\phi_1}{A} = \frac{\phi_0 \rho_{av}}{A} = \frac{E_{tv} A_w \tau \rho_{av}}{A A}$$
Total average illuminance

The average illuminance due to the second reflection

$$\overline{E_2} = \frac{\phi_1 \cdot \rho_{av}}{A} = \frac{E_{tv} \cdot A_w \cdot \tau \cdot \rho_{av} \cdot \rho_{av}}{A}$$

and the following ones

$$\overline{E_{in}} = \frac{\phi_0}{A} + \frac{\phi_0 \cdot \rho_{av}}{A} + \frac{\phi_0 \cdot \rho_{av} \cdot \rho_{av}}{A} + ...$$

$$= \frac{\phi_0 \left(1 + \rho_{av} + \rho_{av}^2 + ...ight)}{A}$$

$$= \frac{\phi_0}{A \left(1 - \rho_{av}\right)}$$

$$= \frac{E_{tv} \cdot A_w \cdot \tau}{A \cdot \left(1 - \rho_{av}\right)}$$

Then

$$\frac{\overline{E_{in}}}{E_{tv}} = \frac{A_w \cdot \tau}{A \left(1 - \rho_{av}\right)}$$
Average Total Daylight Factor

\[
TD = \frac{k.A_w.\tau}{A.(1 - \rho_{av})}
\]

Where

- \( k \) is the slope of equation previously defined
- \( \tau \) is the diffuse light transmittance of glazing
- \( A_w \) is the net glazed area of window
- \( A \) is the total area of interior surfaces
- \( \rho_{av} \) is the area weighed average reflectance of interior surfaces

\[
k = \frac{E_{tv}}{E_{gh}}
\]
Average Total Daylight Factor

with obstruction

without obstruction
Conclusions

- The definition of a simplified calculation for daylight analysis under clear sky distributions is important in order to avoid the use of calculations designed for overcast conditions and their consequent inadequacy;
- There is a relationship between the global horizontal illuminance and the vertical illuminance when sunlight is not incident on the facade;
- This relationship is relatively stable throughout the year;
- The slope of the linear relationship is similar for different canyon aspect ratios, but the constant of the equation tends to increase with floor height and for wider canyons due to larger angles of visible sky;
- The slope of the relationship is relatively constant at all floors for lower obstruction’s reflectance, but varies with higher reflectance;
- The reflectance of the surfaces of the canyon, in particular that of the obstruction have the most effect on the illuminance of the buildings, for European latitudes;
- The orientation of the buildings does not affect the linear relationship when the sun is behind the building in an urban canyon;
- A variation of the latitude does not affect the linear relationship for the urban canyon;
The average total daylight factor calculation is a simple calculation similar to the average daylight factor but taking into consideration reflected sunlight in an urban canyon;

The average total daylight factor may provide a similar characterisation of how well a space is lit;

The average total daylight factor is proportional to the window size, therefore may be an useful method for estimating window sizes in early stages of design. Particularly as it does not require the definition of the window shape or position to be known in advance.

An initial estimation of average total daylight factor as a quarter of the recommended values of the average daylight factor has been put forward. In should be stressed that estimations proposed to characterise a daylit space are based on quantitative data obtained in this study with RADIANCE simulations. The definition of visual comfort indices similar to those assumed for the average daylight factor should mainly be based on experimental surveys in real situations.
Acknowledgements

This work was carried out with financial support from:
- Fundação da Ciência e Tecnologia though their PhD scholarship
- Low Energy Architecture Research Unit
- National Institute Engineering, Technology and Innovation I.P.

Thank you!
Luisa