Daylighting performance of sawtooth roofs of industrial buildings

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Natural lighting in industrial, commercial and sports buildings is usually provided by roofs with transparent surfaces. Sawtooth roofs, in which opaque modular elements are combined with transparent surfaces, whether inclined or in various shapes, are especially popular. The exact dimensioning of these roofs is extremely important both in terms of energy savings (less electricity needed for artificial lighting) and as regards vision quality. This paper illustrates a calculation method that accurately assesses daylighting performances of sawtooth roofs. The method allows detailed modelling of the sawtooth roof's shape to be created and the transmittances and reflectances of all the materials making up the roof to be taken into account. The calculation method was applied to 11 different sawtooth roofs supplied by different manufacturers; the results were compared and some technical solutions were suggested for optimizing the performances of the analysed roofs. Experimental verifications were performed on the method in two industrial buildings, with different roofs; the results show that the calculation method being proposed is both accurate and reliable.

List of symbols

\( D_i \) distance between two beams at intrados plane of the roof (m)
\( D_c \) assumed outdoor dimension of one sawtooth roof module (m)
\( E \) illuminance (lux)
\( E_i \) irradiance (W/m²)
\( F_{A-B} \) view factor between two surfaces A and B
\( h \) height (m)
\( K \) luminous efficacy (lm/W)
\( L \) length (m)
\( PW \) work plane
\( R \) radius of bend of the opaque element (m)
\( r \) reflectance
\( t \) transmittance

Greek letters

\( \alpha_1 \) inclination of the transparent surface to the horizontal (°)
\( \alpha_2 \) angle between the transparent and the opaque surfaces of the roof (°)
\( \alpha_3 \) inclination of the opaque surface to the horizontal (°)
\( \beta_1 \) left limit angle (°)
\( \beta_2 \) right limit angle (°)
\( \phi \) radiant energy flux (W)

Subscripts

\( A \) surface A of the roof
\( eb \) external beam

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1. Introduction

The need for good natural lighting in a factory is important and can affect the choice in the design phase between a multi-storey building and a single storey building.

Lighting is also important from a productivity point of view, especially in an industrial environment where visibility needs can be both varied and complex. It is extremely important that lighting enables:1,2

- maximum safety, to reduce injuries;
- good visibility, to promote a good working environment;
- environmental comfort.

Natural lighting includes the two categories of zenithal and lateral lighting. Zenithal lighting allows the use of skylights and sawtooth roofs, characterizing for example, industrial buildings for textile manufacture. These roofs have the advantage of being exposed to lighting from the entire sky; on the other hand, they do have the disadvantages of requiring glass with good mechanical resistance, sealing from rain and maintenance and cleaning of the transparent materials. Sawtooth roofs usually have the transparent parts facing north (seldom north-east and north-west), so as to avoid sunlight penetrating indoors. This gives diffused uniform natural lighting, and avoids glare.3,4

A typical layout of a sawtooth roof is illustrated in Figure 1; the upper angle (α) is in general between 70° and 90°, whereas the inclination of the transparent part to the horizontal (α) can vary between 40° (lowest limit) and 90° (vertical wall). Numerous studies have shown that to maximize daylighting on the horizontal plane it is important that the inclination of the transparent surfaces to the horizontal be approximately equal to the latitude of the location.5 Obviously, configurations other than the one illustrated in Figure 1 are possible, perhaps incorporating curves, domes, horizontal windows, etc.

In buildings with several storeys lateral lighting is used instead. Here, the area of sky illuminating the window is half the area of the sky illuminating the transparent materials in zenithal lighting, and possibly less when there are obstacles or nearby buildings. This disadvantage is compensated by lateral lighting providing larger transparent surfaces than can be provided with zenithal lighting; furthermore, lateral lighting yields high illuminances even on vertical planes.

Finally, in an industrial building, mixed lighting (zenithal/lateral) allows the areas near the perimeter walls to be used more fully.

In the present paper, the daylighting performance of sawtooth roofs for an industrial building is investigated; an original calculation method is described; and an experimental validation of the method is carried out, with satisfactory results.

2. Methods of calculating illuminance

The literature describes different models for assessing daylighting performance of sawtooth roofs, taking into account shape and material.

In particular, CIE 16 ‘Daylight’6 presents a
method in which diagrams for calculating illuminance in the working area of a building in relation to outdoor sunlight are given. The method accounts for the system's shape (dimensions and inclination to the horizontal of the transparent surfaces, height of the building), the glass transmittance, the dirt depreciation factor of the glass itself and finally the reflectances of the internal surfaces. Notwithstanding its complexity, the method is not universal since the tables and figures are valid only for certain shapes of the sawtooth roof and certain values of the characteristic angles. Furthermore, the method does not account for reflection of light from the external surfaces of the roof, but is based only on the direct light passing through the glass. Finally, the illuminances on the interior surfaces are calculated with account being taken of the mean reflectances of these surfaces.

The Building Research Station (BRS) describes a similar method where diagrams are used to calculate the illuminance on the working plane, when the CIE standard sky (5000 lux) is assumed. Unlike the CIE 16 method, the effect of external obstructions can be allowed for.

Other authorities assess the performance of sawtooth roofs by setting up illuminance curves, resulting from the application of the point-to-point method, when effects are assumed as overlapping. Also in this case, only light rays that pass through the window directly are considered.

Theoretical and practical limitations of the different methods available in the literature can be summarized:

- they are often based on standard values of sky illuminance (5000 lux);
- they do not take into account the light reflected from the external surfaces of the roof;
- they assume simple and predefined shapes;
- they do not allow the radiant properties of the materials (reflectance and transmittance) to be defined;
- they can yield significant errors in the graphics and in the interpolation of the tables.

3. Proposed calculation method

To make up for the deficiencies of some of the methods found in the literature, an original method was devised to calculate the lighting performance of buildings with sawtooth roofs.

In contrast to the methods described, the program takes into account the diffuse light reflected from the external and internal surfaces of the opaque elements of the roofs into the interior; the program also allows the inclination both of the transparent and the opaque elements to be varied and to be applied to infinitely wide buildings.

The assumptions made for calculating the illuminance due to the sawtooth roofs, on a horizontal, infinitely extended, work plane, are the following:

- the transparent surface faces north, so that only diffused daylight is received;
- the solar radiation incident on the external surface is constant in every direction;
- the solar radiation reflected from the opaque surfaces is perfectly diffused (cosine law);
- the ratio of solar radiation reflected from a surface of the sawtooth roof which hits another is calculated with the method of view factors. The physical significance of the view factor $F_{A,B}$ between two surfaces A and B is that it represents the fraction of radiative energy leaving surface A that strikes surface B directly;
- the incident solar radiation on the surface of the glass is calculated by considering three consecutive reflections;
- the plane of work is situated 1 m from the ground.

To calculate illuminance in the working area in the case of a real building, the following data have to be introduced:

- dimensions of the building;
- view factors and radiant properties (reflectance and transmittance) of internal surfaces (walls, floor).

The calculation program is made up of six
sheets, according to the block-diagram in Figure 2.

Sheet 1 allows the solar radiation hitting the transparent surface of the roof to be calculated; the required input data are:

- outdoor irradiance on the horizontal plane (W/m²);
- length of the hypothetical surface \( D_e \) delimiting the upper end of the roof, assumed as the surface which emits the visible radiation coming from the sky (see Figure 3a);
- geometrical characteristics and radiant properties (reflectance, transmittance) of the materials which make up the surfaces (both opaque and transparent) of the roof;
- view factors between the various surfaces.

Sheet 2 allows the illuminance on a hypothetical surface \( D_i \) at the intrados plane of the sawtooth roof (see Figure 3b) to be calculated. By using solar radiation data for light transmitted through the transparent surface (from Sheet 1) and by inserting the geometrical characteristics as well as the radiant properties of the internal materials and the view factors among the various surfaces, illuminance on \( D_i \) can be calculated, under the assumption that two consecutive reflections on the surfaces of the roof intrados give sufficient accuracy.

Sheet 3 allows the determination of the illuminance on the work plane due to the single surfaces which make up the sawtooth (Figure 4). By use of the superposition principle, the illuminance due to the contribution of several sawtooths (by adopting the convention that an infinitely extended roof could be approximated by a number of sawtooths 100 m in length) is calculated. Calculations were carried out starting from the values of radiant power emitted from each internal surface of the roof, assuming they were concentrated at the centre of gravity (data from Sheet 2).

With reference to Figure 5, let us consider the contribution to illuminance in the generic point \( P \) due to the emitting surface \( A \) of the roof; the procedure may be repeated for all the other surfaces of the roof.

The following parameters have to be defined:

- \( L_A \) = length of surface \( A \) (m);
- \( \beta_1 \) = left limit angle (°);
- \( \beta_2 \) = right limit angle (°);
- \( h \) = distance between the centre of gravity of surface \( A \) and the work plane of the building (m).

Sheet 3 allows the illuminance on the work plane to be calculated only for those points which fall within the angle \( \beta = \beta_1 + \beta_2 \); these points are in fact in the area of influence of surface \( A \) since the radiation emitted by surface \( A \) is not intercepted by other surfaces of the roof.

The sheet uses the logic operator 'function 0.1', which multiplies by 0 or 1 the equation for
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![Diagram](image)

(a)

Figure 3 Luminous flux transfer from extrados plane \((D_1)\) to intrados plane \((D_2)\) of the sawtooth roof, as modelled by the calculation code

![Graph](image)

Figure 4 Illuminance on the work plane under one sawtooth roof module (total amount and contribution due to the various surfaces)

the calculation of illuminance depending whether point \(P\) is within or outside angle \(\beta\).

The illuminance on surface \(A\), with regard to a 1 m wide roof, due to direct and reflected daylight on the other surfaces, is given by:

\[
E_A = \frac{\Phi \cdot K}{L_A \cdot 1}
\]

where \(\Phi\) is the radiant energy flux hitting surface \(A\) (obtained from Sheet 2) and \(\Phi \cdot K\) is therefore
the corresponding luminous flux; \( L_A \cdot 1 \) is the area of a 1 m wide roof strip.

The illuminance at point \( P \) due to the emitting surface \( A \) is therefore given by:

\[
E_p = \frac{\Phi \cdot K \cdot L_A \cdot (1 \cdot \cos(\alpha_1 + \alpha_2) \cdot \cos^2 \alpha_2)}{\pi \cdot h^2} \\
= r \cdot \Phi \cdot K \frac{\cos(\alpha_1 + \alpha_2) \cdot \cos^2 \alpha_2}{\pi \cdot h^2} \text{ [lux]}
\]

with \( r \) = reflectance of surface \( A \).

The total illuminance at point \( P \) is obtained by the superposition principle, applied to the contributions to illuminance at \( P \) from the various emitting surfaces of the roof.

Sheet 4 gives the plot showing the variation of illuminance on the work plane under one sawtooth roof module, from each of the various contributions and their total.

Sheet 5 is a plot showing the variation of illuminance due to the sawtooths contained in a 100 m length of the building (Figure 6).

Finally, Sheet 6 allows the determination of the mean illuminance on the work plane when the sawtooth roof is installed in a real building. As an example, a building with a base of 60 m \( \times \) 40 m and a height of 8 m was chosen. Once the building dimensions, the view factors of the surfaces and the luminous flux emitted by the various surfaces of the roof (supplied by Sheet 2) are inserted, the average illuminance on the plane of work is calculated.

4. Roofs typology

Eleven sawtooth roofs from different manufacturers were examined, to simulate and compare their daylighting performance. The roofs were divided into four groups, each comprising similar geometrical shapes, but having different dimensions and inclinations, together with different reflectances of the materials.

- **Group A** includes sawtooth roofs 01, 02, 03 composed of plane elements in opaque material and another plane element in transparent material.
- **Group B** includes sawtooth roofs 04, 05, 06, characterized by a curved opaque element and by a plane transparent element.
- **Group C** includes sawtooth roofs 07, 08, 09 characterized by an opaque plane element and by a transparent plane element; this group also includes a pre-stressed concrete beam with a square cross-section of variable height.
- **Group D** includes sawtooth roofs 10 and 11, characterized by a curved opaque element having a radius of curvature greater than that used...
in the group B sawtooth roofs and by a plane transparent element.

The geometrical parameters characterizing the different sawtooth roofs are indicated in Figure 1a and 1b; the values that these parameters have in the 11 roofs examined are given in Table 1; the materials' characteristics are given in Table 2.

5. Calculation results

The results of the calculations carried out on the 11 different sawtooth roofs are summarized in Table 3. The table gives the illuminances on the intrados plane of the roofs and on the work plane both for an infinite roof and a roof for a real, finite building. To compare the results, a stan-

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Table 1 Geometrical features of the sawtooth roofs

<table>
<thead>
<tr>
<th>Group</th>
<th>Number</th>
<th>$L_e$ (m)</th>
<th>$\alpha_1$ (°)</th>
<th>$\alpha_2$ (°)</th>
<th>$L_a$ (m)</th>
<th>$\alpha_3$ (°)</th>
<th>$R$ (m)</th>
<th>$D$ (m)</th>
</tr>
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<td>64</td>
<td>90</td>
<td>3.8</td>
<td>26.6</td>
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<td>5</td>
</tr>
<tr>
<td></td>
<td>02</td>
<td>1.1</td>
<td>63</td>
<td>90</td>
<td>2.4</td>
<td>26.6</td>
<td></td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>03</td>
<td>1.0</td>
<td>63</td>
<td>93</td>
<td>2.3</td>
<td>23.4</td>
<td></td>
<td>5</td>
</tr>
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<td>160</td>
<td>4</td>
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<td>66</td>
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<td></td>
<td>135</td>
<td>1.4</td>
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<td></td>
<td></td>
<td>290</td>
<td>2.6</td>
</tr>
<tr>
<td>C</td>
<td>07</td>
<td>3.6</td>
<td>90</td>
<td>65</td>
<td>2.6</td>
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<td>27</td>
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<td>25.2</td>
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<td>3.1</td>
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<tr>
<td>D</td>
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<td>1.7</td>
<td>79</td>
<td>88</td>
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<td>1064</td>
<td>7.5</td>
</tr>
<tr>
<td></td>
<td>11</td>
<td>1.7</td>
<td>79</td>
<td>88</td>
<td></td>
<td></td>
<td>1065</td>
<td>7.5</td>
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</tbody>
</table>
Table 2 Characteristics of the materials of the sawtooth roofs: mean reflectance coefficient \( r \) and mean transmittance coefficient \( t \) for visible radiation

<table>
<thead>
<tr>
<th>Group</th>
<th>Number</th>
<th>( r_{\text{ex}} )</th>
<th>( r_{\text{eb}} )</th>
<th>( r_i )</th>
<th>( R_i )</th>
<th>( t_i )</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>01</td>
<td>0.6</td>
<td>0.3</td>
<td>0.8</td>
<td>0.1</td>
<td>0.8</td>
</tr>
<tr>
<td></td>
<td>02</td>
<td>0.8</td>
<td>0.1</td>
<td>0.8</td>
<td>0.1</td>
<td>0.8</td>
</tr>
<tr>
<td></td>
<td>03</td>
<td>0.8</td>
<td>0.4</td>
<td>0.8</td>
<td>0.1</td>
<td>0.8</td>
</tr>
<tr>
<td>B</td>
<td>04</td>
<td>0.8</td>
<td>0.4</td>
<td>0.8</td>
<td>0.1</td>
<td>0.8</td>
</tr>
<tr>
<td></td>
<td>05</td>
<td>0.1</td>
<td>0.1</td>
<td>0.8</td>
<td>0.1</td>
<td>0.8</td>
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<tr>
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<td>06</td>
<td>0.8</td>
<td>0.1</td>
<td>0.8</td>
<td>0.1</td>
<td>0.8</td>
</tr>
<tr>
<td>C</td>
<td>07</td>
<td>0.8</td>
<td>0.1</td>
<td>0.8</td>
<td>0.1</td>
<td>0.8</td>
</tr>
<tr>
<td></td>
<td>08</td>
<td>0.8</td>
<td>0.1</td>
<td>0.8</td>
<td>0.1</td>
<td>0.8</td>
</tr>
<tr>
<td></td>
<td>09</td>
<td>0.8</td>
<td>0.1</td>
<td>0.8</td>
<td>0.1</td>
<td>0.8</td>
</tr>
<tr>
<td>D</td>
<td>10</td>
<td>0.8</td>
<td>0.1</td>
<td>0.8</td>
<td>0.1</td>
<td>0.8</td>
</tr>
<tr>
<td></td>
<td>11</td>
<td>0.8</td>
<td>0.1</td>
<td>0.8</td>
<td>0.1</td>
<td>0.8</td>
</tr>
</tbody>
</table>

\( r_e = \text{external roof}; \quad r_{\text{eb}} = \text{external beam}; \quad r_i = \text{indoor parts}; \quad t_i = \text{transparent surface}.\)

The standard sky (5000 lux) was assumed in all the simulations.

The verification of lighting uniformity was carried out on the assumption that the working area was infinitely extended. For all the sawtooth roofs examined, the ratio of the minimum illuminance to the mean illuminance were in the range of 0.93 to 0.98, which is considerably higher than the 0.80 minimum value recommended by CIE.\(^{11}\)

Figures 7, 8, 9 and 10 plot the illuminance variation evaluated on an infinite work plane for the sawtooth roofs.

5.1 Group A

Group A sawtooth roofs, especially 01 and 02, produce the highest mean illuminance: 700–900 lux at the intrados plane of the beams and 500–650 lux on the work plane.

These sawtooth roofs have the same roof layers and glass inclination, but different beam heights. As the latter increases, more obstruction to the luminous flux entering is created. Sawtooth roof 03 has the same \( D_i \) as sawtooth roof 01 and 02, but the length of the transparent surface \( L_i \) is less than for the other two sawtooth roofs (1.0 m instead of 1.1 m), so that it has a smaller useful area for the entry of daylight. Moreover, it also has a less favourable inclination to the horizontal (23.4° compared to 26.6°) of the transparent surface.

5.2 Group B

Group B sawtooth roofs produce illuminances of 500 lux at the beam intrados and 250–400 lux on the work plane.

Table 3 Simulated illuminance on the intrados plane and on the work plane, for the different sawtooth roofs (infinite and real building)

<table>
<thead>
<tr>
<th>Group</th>
<th>Number</th>
<th>Intrados (lux)</th>
<th>Work plane ( P_{W_\infty} ) min-mean-max</th>
<th>Plane of work ( P_{W_i} ) (real)</th>
<th>Uniformity on ( PW_{\infty} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>01</td>
<td>698</td>
<td>624–639–649</td>
<td>692</td>
<td>0.98</td>
</tr>
<tr>
<td></td>
<td>02</td>
<td>709</td>
<td>621–519–640</td>
<td>546</td>
<td>0.98</td>
</tr>
<tr>
<td></td>
<td>03</td>
<td>587</td>
<td>405–413–420</td>
<td>453</td>
<td>0.96</td>
</tr>
<tr>
<td></td>
<td>04</td>
<td>532</td>
<td>364–379–381</td>
<td>410</td>
<td>0.96</td>
</tr>
<tr>
<td>B</td>
<td>05</td>
<td>502</td>
<td>371–401–429</td>
<td>387</td>
<td>0.93</td>
</tr>
<tr>
<td></td>
<td>06</td>
<td>358</td>
<td>254–269–276</td>
<td>287</td>
<td>0.95</td>
</tr>
<tr>
<td></td>
<td>07</td>
<td>474</td>
<td>337–359–376</td>
<td>366</td>
<td>0.94</td>
</tr>
<tr>
<td></td>
<td>08</td>
<td>592</td>
<td>350–367–375</td>
<td>456</td>
<td>0.95</td>
</tr>
<tr>
<td></td>
<td>09</td>
<td>512</td>
<td>374–387–400</td>
<td>395</td>
<td>0.97</td>
</tr>
<tr>
<td>D</td>
<td>10</td>
<td>540</td>
<td>381–397–407</td>
<td>416</td>
<td>0.96</td>
</tr>
<tr>
<td></td>
<td>11</td>
<td>539</td>
<td>365–393–403</td>
<td>415</td>
<td>0.93</td>
</tr>
</tbody>
</table>
5.3 Group C

These sawtooth roofs all have the same inclination and length of the roof; they use the same materials and have the same beam shape, but they have different dimensions thus yielding different performances.

Sawtooth roof 08 is better than sawtooth roof 07 notwithstanding the lower length of the glass.
surface (1.0 m instead of 1.10 m); this disadvantage is in fact more than compensated for by the lower inclination compared to the horizontal (63° instead of 90°).

Sawtooth roof 09 is better than sawtooth roof 07 since the height of the beam is lower, thus favouring the entry of daylight.

5.4 Group D
Sawtooth roofs 10 and 11 have the same illuminance at the beam intrados and on the work plane; there is a slight difference (397 and 393 lux) due to the different height of the beam.

6. Performances optimization
As mentioned, the calculation method can be used, owing to its flexibility, not only to verify the daylighting performance of actual sawtooth roofs with fixed geometrical and material characteristics, but also to evaluate the influence of
these characteristics on the performance themselves.

It is possible to improve the performance by varying the geometrical parameters of the system, or by varying the mean reflectance and transmittance for visible radiation of the different materials.

As an example, the reflectances given by the manufacturer of some of the roof materials were changed. In particular, for the best and the worst roof, 01 (group A) and 06 (group B), the following results were found:

Sawtooth roof 01: \( r_e \) was increased from 0.6 to 0.8 and \( r_{cb} \) from 0.3 to 0.4 attaining the following illuminances on the infinitely long work plane: 637 lux – 652 lux – 662 lux (minimum–mean–maximum), with the mean value increased by 2%.

Sawtooth roof 06: \( r_{cb} \) was increased from 0.1 to 0.4, attaining the following illuminances on the infinitely long work plane: 278 lux – 293 lux – 302 lux (minimum–mean–maximum), with the mean value increased by 9.5%.

As can be seen, sawtooth roof 01 shows less improvement. On the contrary, sawtooth roof 06 has the worst performance not only due to its shape, but also to the characteristics of the materials chosen by the manufacturer; in fact, its improvement increases illuminance by about 10%.

7. Measurements

To evaluate the reliability of the calculation program, measurements in two different buildings with sawtooth roofs were carried out.

7.1 Description of the buildings

The industrial buildings chosen, called A and B for the sake of simplicity, are situated in Faenza (Forlì) and Foligno (Perugia). Both relatively new buildings were basically free from equipment, plant and furniture at the time of measurement. This made it easier to take measurements indoors.

In particular, building A has a covered area of about 11 000 m² with a rectangular base (350 m × 31.2 m). The roof has V-shaped beams of 1.2 m height and 30 m span, placed at regular distances of 5 m; the transparent surfaces have a 63° inclination to the horizontal and a width of 1.2 m (sawtooth 02); a dome in pre-stressed concrete is placed beside the sawtooth module. The roof intrados plane is 8 m from the finished floor (Figure 11a).

Building B has a covered area of 24 000 m², with a squared plan of 154 m × 150 m. The sawtooth roof is made up of secondary V-shaped beams in prestressed concrete of 0.71 m height and 19.8 m span; the transparent surface is inclined at 65° to the horizontal and is 1.2 m (sawtooth n. 01); also in this case, the roof intrados plane is placed at 8 m from the finished floor (Figure 11b).

In both buildings the transparent surfaces were made of polycarbonate 0.01 m thick.

7.2 Equipment

The measurements were carried out with the following equipment:

- BABUC MBA020 acquisition card for outdoor measurement of solar radiation power, equipped with BSR030 global radiometric probe (survey range 300–1100 nm; power range 0–1500 W/m²), placed on the transparent surface of the examined roofs. Because of its positioning, the probe also accounts for reflection from the roof;
- Mavolux Gossen digital luxmeter, cosine and \( V(\lambda) \) corrected, to measure illuminance (E) inside the buildings.

7.3 Measurement methodology

The measurements on the work plane inside the buildings were carried out on 2 m × 2 m grids as specified in UNI 10 380/94. The minimum number of points specified by UNI, selected according to building dimensions, is 25 for both buildings. However, for building A, a 16 × 15 = 240 measurement grid was set up, and for building B instead a 16 × 20 = 320 measurement grid was set up. The measurements were carried out in the period March to August 2001.
To carry out the measurements quickly, some reference points were pre-laid on the ground; the luxmeter was equipped with a level and mounted 0.85 m above ground level. The measurement of external solar radiation power was carried out throughout the entire internal measurement period. Since the model calculates the illuminance at the intrados plane of the roof, some measurements were also carried out at this height.

7.4 Results

It is not possible to report here all the results of the measurements carried out since they were repeated at different hours of the day and in different days for each building. Moreover, the aim of the measurements was not only to assess the lighting performance of the roofs but to validate the proposed calculation method.

The typical trend of the illuminance measurements in the working area along a longitudinal line in the centre part of building A is shown in Figure 12, along with the corresponding irradiances measured outdoors. It can be seen that in the time needed to measure illuminance along a line inside the building the outdoor solar radiation remains constant. To apply the calculation model, all the points along a line can therefore be correlated to a single value of outdoor solar radiation.

Figure 12 also shows how the illuminances fall within the range 570 lux to 700 lux with the incident irradiance on the transparent surface of about 1150 W/m².

Similarly for building B, the typical trend along a central row of the building is shown in Figure 13; the illuminances vary within the range 1050 lux and 1120 lux, when the incident
irradiance is about 900 W/m². Building B definitely has better performances than building A since its beam is shorter and the transparent surfaces are spaced at 5 m instead of 10 m.

8. Comparison with the model

Figure 14 shows the comparison between the illuminances obtained from calculations for
building A and the corresponding values measured in a central row of the building; the maximum difference is 2%. As for building A, Figure 15 shows the comparison between the measurements taken at the intrados of the roof and the values from simulation.

Figure 16 compares the measured and calculated values for a central row of points in building B. Since the maximum difference between the two sets of values was 1% the modelling was accurate.

The comparisons were carried out for the cen-
tral rows of the buildings, since the assumption of an infinitely long roof on which the calculation model is based seems to be better estimated.

The dimensions and the reflectances of the walls and floors were then introduced into the calculation model and the mean illuminance was calculated in the working area of the two buildings. This value, obtained from a mean value of solar radiance in a particular time span, was compared with the mean illuminance measured on the work plane in the same time. The following values were obtained:

- **Building A**: mean measured illuminance 642 lux; mean calculated illuminance 697 lux; difference 8%.
- **Building B**: mean measured illuminance 1023 lux; mean calculated illuminance 1097 lux; difference 7%.

### 9. Comparison with other models

Finally a comparison was made between the results given by the model and those obtained by applying CIE 16 methodology. As for building B, when the outdoor illuminance is equal to 10 500 lux (80% of working hours), CIE 16 gives a mean illuminance on the work plane equal to 890 lux, as compared to 883 lux given by the calculation program.

### 10. Conclusions

A calculation model was developed for calculating the illuminance from sawtooth roofs in industrial buildings.

The program was tested for 11 different roofs made by various manufacturers; the results were sufficiently encouraging for an experimental verification to be carried out. Two relatively new buildings were chosen with different sawtooth roofs. Extensive and systematic measurements were carried out.

The results show that the model allows the illuminance due to daylighting on the work plane to be accurately calculated. The model is therefore a valid tool to:

- estimate in the design phase the daylighting performance of roof;
- optimize the performance by varying materials or shape of the roof or both;
- evaluate energy savings due to daylighting maximization;\(^1\)
- estimate depreciation with time of the per-
formance of a roof due to the deterioration of the materials.

Future research development foresees the integration of artificial lighting systems into the model, to attain an integrated lighting design which takes into account both lighting comfort and energy savings.

11. References

12. UNI 10380 Illuminotecnica — Illuminazione di interni con luce artificiale, 1999 (in Italian).

Discussion

Comment on ‘Daylighting performance of sawtooth roofs of industrial buildings’ by F Asdrubali
M Paroncini and B Calcagni (Dipartimento di Energetica, Università Politecnica delle Marche, Ancona, Italy)

Providing a design tool to support the design of well daylight and energy efficient buildings is a topical subject in the outline of the recent integrated architectural design. Daylighting is important in creating a pleasant visual environment and is the light source that most closely matches human visual response. Recently, there has been an increasing interest in incorporating daylight for an energy-efficient building design. Artificial lighting is one of the major electrical energy consuming items in many non-domestic buildings. Many studies have indicated that proper lighting controls, integrated with daylighting, have a strong potential for reducing energy demand in non-domestic building by exploiting daylight more effectively. In many industrial buildings there is a widespread use of sawtooth roofs which permit zenithal entry of daylight so providing diffuse light and high light levels without contrast with the space below and avoiding glare.

Considering the limitation of the methods mentioned in the paper for calculating the illumination on a working area under a sawtooth roof, the development of a specific methodology that can be applied to several shapes at the same time allowing the radiant properties of the materials to be defined is valuable. Another interesting aspect is the possibility of evaluating the indoor lighting condition due to the specific outdoor solar radiation. The examination of several sawtooth roofs from different manufacturers can give an indication of the flexibility of the method. The importance of a validation study
with real buildings of the accuracy and limitation of the computer simulation tools is widely shared in the scientific sphere and, in particular, in the professional field. In fact the designers, as final users of these different types of software, need an unfailling and reliable design tool to support their work. Thus, a comparison of the numerical results with the experimental measurements carried out on real buildings and with a well-known method in the literature (such as that given in CIE 16) would validate the method for future application. It will be worthwhile in future developments to introduce the method for the purpose of evaluating energy savings in an integrated lighting design.

References


Author’s response to M Paroncini and B Calcagni

F Asdrubali

The discussion comments correctly point out that lighting is one of the major electrical consuming items in industrial buildings. Though the use of sawtooth roofs in these buildings is really widespread, their potential contribution to daylighting—and therefore to both visual comfort and electrical energy savings—is not fully appreciated.

The paper presents a specific methodology to assess daylighting performances of sawtooth roofs, since methods found in the literature are not exhaustive and flexible; the proposed simulation code—validated with experimental measurements carried out in real buildings—has proven its reliability and flexibility.

As suggested in the discussion comments, the development of the study is already focused on integrated lighting design, by introducing a module for electrical lighting design and energy savings evaluation in the code. Also in this case, the methodology will be validated through experimental campaigns in real buildings.