A SIMPLE CHART TO DESIGN SHADING DEVICES
CONSIDERING THE WINDOW SOLAR ANGLE DEPENDENT PROPERTIES

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Abstract – A simple chart useful to design shading devices is presented. The chart, which is complementary to existing solar path diagrams, provides additional information about the window’s solar angle dependent properties and its geometrical relationship to the sunbeam. This information allows to make meaningful hypotheses about the optimum geometry of the shading device. Two examples are provided where the chart is used to define the geometry of an awning on a south- and west-oriented office room in Stockholm. The examples show that the chart is useful to restrict the early design hypotheses and identify the optimum awning geometry at an early design stage.

1. INTRODUCTION

Solar shading devices can substantially reduce the cooling load of buildings. According to a recent literature review (Dubois, 1997), this reduction is between 23-89% depending on the type of shading device used, the building orientation, the climate, etc.

In order to save energy, shading devices should be integrated to a building’s facade at an early design stage. This can be achieved using “traditional” design tools like solar path diagrams and shading masks or special computer programs that automatically “generate” the optimum shading device geometry as a function of a set of input parameters (e.g. orientation, latitude).

1.1 Traditional tools

Although there exist numerous design methods based on solar path diagrams (Dourgnon, 1965; Van den Eijk, 1965; Markus & Morris, 1980; Etzion, 1992), the Olgyays’ (1957) and Mazria’s (1979) methods are probably the most popular ones. In both the Olgyays and Mazria’s design methods the building’s overheating period is plotted onto the solar path diagram and a shading “mask” that avoids direct sun during the overheating period is defined.

The main difference between the two methods is the kind of solar projection used. The Olgyays used a projection of the sun onto a horizontal plane parallel to the ground (Fig. 1) while Mazria used a projection onto a vertical cylinder (with the long axis perpendicular to the ground). By “unfolding” the cylinder, a two-dimensional diagram is obtained, where the abscissa and ordinate represent the solar azimuths and altitudes and where the curves radiating away from the south represent the solar time (Fig. 2). This projection is advantageous for studies of facade elements like windows and shading devices since the sun’s projection is viewed “parallel” to the building facade.

Traditional methods have some limitations: their accuracy is limited by the size of the charts and they yield shading devices that are larger than necessary since they are only capable of returning a “binary” answer (Etzion, 1992). This is due to the fact that they indicate an “unshaded” condition even when a small area of the opening is lit by direct sun and a “shaded” condition the rest of the time.

Fig. 1 Solar path diagram used by the Olgyays (1957).

Fig. 2 Solar path diagram used by Mazria (1979).
Despite these limitations, traditional methods are still used and taught in many schools of architecture and a number of computer programs based on these methods have been developed recently (Bouchlaghem, 1996; Oh and Haberl, 1997; Kensek et al., 1996). Methods based on charts have the advantage of being simple and straightforward: they show the relationship between the solar path, the overheating period and the required shade in one single picture.

1.2 Computer tools
Many computer design tools for shading have been developed during the past decades. These tools are in essence similar to traditional tools but have the main advantage that the shading device geometry is automatically "generated" by the program.

One of the first computer design tools for shading was proposed by Shaviv (1975, 1984). This program indicates the shape of the shading device that prevents direct radiation from reaching the window during each month. A similar program, which provides one annual solution by subtracting a summer from a winter design day funnel, was later proposed by Arumi-Noé (1996). More recently, a program combining simulation, generation and optimisation routines was developed by Kabre (1999). This program provides a 3D image of the optimum exterior fixed shading device, which is determined by weighting the "shading" versus "heating" efficiency of the window-shade combination. The optimum solution is determined from the results of energy simulations and a Pareto optimisation.

1.3 Limitations of the existing tools
One limitation of most existing design tools is that they are based on the incident (not transmitted) solar radiation on the window. The only one who considered the window transmission and absorption properties is Petherbridge (1965). However, he used horizontal projections of the solar path (similar to the Olgyays) and presented the window transmittance and absorptance separately, which make it difficult to use his charts in practice. Kabre (1999) also considered the window transmittance. However, his program takes this parameter into consideration in the simulation routine after the shading devices have been generated based on the incident sun.

Considering incident instead of transmitted radiation is equivalent to attributing an equal “weight” to all angles of incidence. This will invariably yield shading devices larger than necessary since all angles of incidence must be covered. In reality, incidence angles close to the window normal usually have more impact on the building’s annual energy use since a surface perpendicular to the sun receives the maximum amount of solar radiation and since the window total solar transmittance is maximum around the window normal.

Oversized shading devices are less economical and reduce both the view out through the window and the daylighting in the building. It is well known that a reduction in interior daylighting levels usually yields an increase in the use of artificial lighting, which results in an increase in the cooling load to remove the internal heat gains from lights.

In this article, a simple chart relating the solar path to the window solar angle dependent properties is presented. The chart, which is based on Mazria’s (1979) solar path projections, can be used at an early design stage to identify the hours during the day and year when solar radiation is likely to cause overheating in the building.

This article presents the new chart and shows how it can be used in practice by providing an example where the geometry of an awning is defined for a south- and west-oriented office room in Stockholm (Sweden). In this example, the awning’s geometry is further studied using dynamic energy simulations. The aim of the simulations is to identify with precision the optimum awning geometry and compare it with the geometry suggested by the chart.

2. METHOD
This section is divided in two parts. The first part explains how the new chart was developed while the second part describes the method and simulations used in the example.

2.1 A new chart for the design of shading devices
Although both direct and diffuse solar radiation are responsible for solar heat gains through windows, in most cold and temperate climates, it is preferable to define shading devices according to direct radiation since
1) diffuse radiation is desirable most of time as a source of daylighting in the building;
2) direct radiation is dominant on clear days when shading is needed.

The chart proposed in this paper is therefore based on direct solar radiation. However, in more extreme climates (hot humid), shading from diffuse radiation might also be desirable and should be considered in the design of shading devices. The diffuse component should also be considered when the shading device is mainly used for glare control.

When direct solar radiation hits a window, two factors contribute in reducing the amount of energy admitted into the building: the incidence angle between the sun beam and the window surface and the window total solar energy transmittance (also called the g-value or solar heat gain coefficient), which is also a solar angle dependent property.

2.1.1 The incidence angle
A surface perpendicular to the sun beam receives the greatest amount of energy. As the sun beam moves away from the window normal, the energy received by the surface decreases. The intensity (Iθ) of solar radiation on
the window surface can be determined from the intensity of the direct normal radiation (I_{DN}) according to:

\[ I_\theta = I_{DN} \cos \theta \] (1)

where \( \theta \) is the angle of incidence of the sun beam. Since the relationship between \( I_\theta \) and \( I_{DN} \) is a constant \( (k_\theta) \) for a given angle of incidence \( (\theta) \), the following can be written:

\[ k_\theta = I_\theta / I_{DN} = \cos \theta \] (2)

Note that this relationship holds for all directions with respect to the window surface.

2.1.2 The window g-value
The window g-value indicates which portion of the incident solar radiation is absorbed and transmitted by the window and becomes heat in the building. It includes both the primary and secondary transmittance i.e. the energy absorbed by the glazing and reradiated to the building interior.

The g-value varies according to the sun’s incidence angle with respect to the window normal. For most ordinary glazings, the transmittance is maximum around the normal, starts declining at 50° and reaches a minimum at 90° as shown in Fig. 3.

![Fig. 3 The g-value \( (g_\theta) \) for single-, double- and triple-pane clear glass windows as a function of the angle of incidence (calculated according to Karlsson & Roos, 1999).](image)

The solar angle dependent g-value can be imagined as a cone valid for each point of the window (Fig. 4). Since for each cone or angle of incidence \( (\theta) \) corresponds a specific g-value \( (g_\theta) \), the set of solar altitudes (ALT) and azimuths (AZ) corresponding to a specific g can be calculated using the fundamental geometrical relationship:

\[ \cos(ALT) \cdot \cos(AZ - \phi) = \cos(\theta) \] (3)

where \( \phi \) is the orientation of the facade (or facade normal) from the same reference direction as the solar azimuth (AZ). Note that the sun is behind the facade when \( |AZ - \phi| > 90 \).

The set of solar altitudes and azimuths obtained for each specific \( g_\theta \) can be plotted according to Mazria’s solar projection and superimposed on the solar path diagram. This superposition is shown in Fig. 5 for a vertical, south-oriented, triple-pane, clear glass window. Fig. 5 shows a set of concentric, distorted circles, where the centre represents any point at the surface of the window. If the g-value is normalised using \( g = g_\theta / g_0 \), the inner circle delimits the solar positions for which \( g > 0.9 \); the second circle delimits the solar positions for which \( g > 0.8 \); the third circle is for \( g > 0.7 \), etc.

![Fig. 4 The window’s solar angle dependent g-value \( (g_\theta) \) can be imagined as a series of cones valid for each point of the window surface.](image)

2.1.3 A cosine weighted g-value
For convenience, the k- and g-values introduced in the previous sections can be combined into one single value, which we will call the Gcos-value or cosine weighted solar angle-dependent g-value. The Gcos-value \( (G_{cos_\theta}) \) at incidence angle \( \theta \) can be calculated as follows:

\[ G_{cos_\theta} = k_\theta \cdot g_\theta \] (4)

Since \( G_{cos_\theta} \) is a constant for a given angle of incidence \( (\theta) \), it can thus also be imagined as a series of cones pointing towards the window. The projection of these cones onto Mazria’s solar path diagram yields Fig. 6. Assuming that the Gcos-value is normalised using \( G_{cos} = G_{cos_\theta} / G_{cos_0} \), the inner circle encompasses the region of maximum values \( (G_{cos} > 0.9) \); the next circle is for \( G_{cos} > 0.8 \); the third circle is for \( G_{cos} > 0.7 \), etc.
Fig. 5 Chart showing the normalised g-values for a vertical, south-oriented, triple-pane, clear glass window. The chart is superimposed on the solar path diagram for latitude 59°N.

Fig. 6 Chart showing the normalised Gcos-values for a vertical, south-oriented, triple-pane, clear glass window. The chart is superimposed on the solar path diagram for latitude 59°N.
Fig. 7 Chart of the normalised Gcos-values for a vertical, south-oriented, triple pane, clear glass window superimposed on the solar path diagram for latitude 59°N showing the intensity of the direct normal solar radiation (I_{DN}) for clear days in Stockholm (W/m²).

Fig. 8 Chart of the normalised Gcos-values for a vertical, west-oriented, triple pane, clear glass window superimposed on the solar path diagram for latitude 59°N showing the intensity of the direct normal solar radiation (I_{DN}) for clear days in Stockholm (W/m²).
2.1.4 The intensity of solar radiation

The intensity of solar radiation varies throughout the day and the year. This parameter can also be included in the previous figures using points of different sizes as shown in Fig. 7-8. These figures show the relationship between the solar position (and time), the intensity of the direct normal radiation on clear days (calculated according to Brown & Isfält, 1969) and the window Geos-values. Fig. 7 shows the correct superposition for a vertical, south-oriented, triple pane, clear glass window. Fig. 8 is for the same window oriented towards the west direction.

These charts can be used to calculate the solar gain (Q_{sol}) in the building due to direct solar radiation using:

\[ Q_{sol} = I_{DN} \cdot \text{Geos} \cdot A \]  \hspace{1cm} (5)

where A is the window area.

Note that since the intensity of the direct normal solar radiation is not symmetrical about the solstice, each point in Fig. 7-8 is an average of the values for two symmetrical months. A more precise approach would consist of having two charts, one for each half year.

2.2 Examples: Design of an awning

In order to show how the charts introduced in the previous sections can be used in practice, we present two specific examples where an awning must be defined for a south- and west-oriented office room in Stockholm (latitude 59.35° N, longitude 18.07° E). In these examples, the awning is to be used continuously only during the cooling season, which is from early May to the end of September according to a previous analysis of annual cooling loads for the same room (Dubois, 1999). A dark blue (85% absorpt., 1% transm.) awning with a slope of 30° with respect to the building facade is assumed for both orientations.

The following procedure was used to determine the optimum awning geometry:

Step 1 Charts were produced for the relevant latitude (59.35° N) and window type (triple pane, clear glass).

Step 2 From the charts produced in step 1, the critical solar angles were identified and some shading hypotheses were made.

Step 3 The shading device geometry was determined for each shading hypothesis identified in step 2.

Step 4 Energy simulations were carried out to determine which of the shading hypotheses defined in step 3 was optimum in terms of annual energy use.

2.2.1 Energy simulations

The energy simulation program Derob-LTH was used in the examples to determine which of the shading hypotheses was optimum in terms of annual energy use (step 4). Derob-LTH, which is an acronym for Dynamic Energy Response of Buildings, originates from the University of Texas (Arumi-Noé, 1979) but has been under continuous development at Lund University’s Department of Building Science (Kvist, 1998; Källblad, 1999). The program uses hourly data for the exterior temperature and solar radiation intensity and updates the solar position four times every month. The window and shading models have the following characteristics:

- Coarse ray tracing and Fresnel calculation of the direct radiation.
- View factor and Fresnel calculation of the diffuse radiation.
- One thermal node for each pane.
- Shading device transmits and reflects diffusely.
- One thermal node approximating the thermal balance for all shading devices.
- Long wave sky radiation included.

The shading and window models in Derob-LTH have been validated experimentally using two full-scale guarded hot boxes exposed to the natural climate. A comparison between measured and simulated energy for a dark and a light awning has shown a maximum error of 3% with respect to the incident solar radiation (Källblad & Wallentén, 1999).

2.2.2 Office room

The Stockholm office was a 2.9-m wide by 4.2-m deep rectangular room (Fig. 9). The room had a 1.8-m wide by 1.3-m high, triple-pane, clear glass window with a U-value of 1.88 W/m²K and a normal g-value (g₀) of 0.67.

The exterior wall was a standard construction with respect to Swedish norms with a U-value of 0.18 W/m²K. The room was assumed to be surrounded by office space at the...
same temperature. Thus, all “interior” walls were modelled
as adiabatic surfaces. A free horizon with no obstruction
and a ground reflectance of 20% were assumed.

The room had constant infiltration (0.1 ach) and
ventilation (10 l/s) rates and internal heat gains from one
occupant (90 W), a computer and monitor (120 W) and
energy-efficient lighting (10 W/m²). These gains were only
assumed during weekdays at normal office hours (8-17).
The temperature set points were 20°C (heating) or 24°C
(cooling) during work hours and 18°C (heating) or 28°C
(cooling) the rest of the time.

3. RESULTS

3.1 Optimum awning geometry, south orientation
The solar path diagram for Stockholm and the chart of
Gcos-values for a south-oriented, triple-pane, clear glass
window were produced and are shown in Fig. 7. This
figure shows that September is the month with the lowest
solar altitudes among the cooling months (May, June,
July, August, September). It is also the month when the
solar path is within a region of high Gcos-values (> 0.8)
around noon when the intensity of solar radiation is high
(> 800 W/m²). For other months with high solar radiation
intensity (May, June and July), the Gcos-value is never
higher than 0.6, which means that the window itself
reduces the intensity of the incident radiation by at least
60% (100(1-Gcos·g0)) during these months.

While the awning’s length can be defined according
to the solar altitude in September, its width will depend
on the required period of shading during the day. The
building is only occupied from 08.00-17.00 and this
period can thus be accepted as the maximum period of
shading required. Since the work hours are asymmetrical
with respect to the solar path1, and since a symmetrical
awning (about the window) is assumed, 17.00 hours
becomes the design hour. The minimum shading period is
11.00-13.00 hours, which falls within the region of
highest Gcos-values and high solar radiation intensity.

Considering the solar path and awning symmetry
about the window, there are thus 5 shading schemes to be
considered: 07.00-17.00, 08.00-16.00, 09.00-15.00,
10.00-14.00 and 11.00-13.00 hours. The awning’s
dimensions (assuming a slope of 30°) were calculated for
these 5 shading schemes and are presented in Table 1.

Table 1 shows that the definition of the shading
period over one day significantly affects the size of the
awning. Shading schemes 1-3 yield unrealistically wide
awnings. Since the Gcos-values and the intensity of solar
radiation are lower before 10.00 hours and after 14.00
hours (Fig. 7), and since partial shading will be provided
even for hours falling outside each shading scheme,
shading schemes 1-3 can be eliminated. The design
problem then consists of choosing between two
alternatives: shading schemes 4 or 5.

![Figure 10](image)

Table 1: Awning dimensions according to 5 shading
schemes, south orientation.

<table>
<thead>
<tr>
<th>Shading scheme</th>
<th>Shading period, Sept. 21 (hours)</th>
<th>Length L (m)</th>
<th>Width W (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>07.00-17.00</td>
<td>1.13</td>
<td>6.65</td>
</tr>
<tr>
<td>2</td>
<td>08.00-16.00</td>
<td>1.12</td>
<td>4.05</td>
</tr>
<tr>
<td>3</td>
<td>09.00-15.00</td>
<td>1.12</td>
<td>3.10</td>
</tr>
<tr>
<td>4</td>
<td>10.00-14.00</td>
<td>1.12</td>
<td>2.55</td>
</tr>
<tr>
<td>5</td>
<td>11.00-13.00</td>
<td>1.12</td>
<td>2.15</td>
</tr>
</tbody>
</table>

The impact on energy use of the shading schemes
defined using the chart was studied using energy
simulations. Although only 2 schemes were proposed, a
total of 8 simulations were carried out in order to show
the impact of various alternatives. The awning’s length
was 1.12 m for all the cases studied (from Table 1) and
the width was varied from 0 to 5 m. The incremental
annual energy use for cooling and heating the room as
well as the annual peak heating and cooling loads are
presented in Fig. 10.

![Figure 10](image)

1 In this study, daylight savings time was not used.
Fig. 10a shows that the annual cooling demand decreased almost linearly as the awning’s width increased from 0 to 1.8 m. However, little additional cooling savings were obtained over 2.15 m. The curve stabilised into a straight horizontal line from this point. The same occurred with heating loads although the increase in the heating demand was not as steep as the reduction in cooling between 0 and 1.8 m.

Fig. 10b shows that the peak cooling demand was reduced by almost 50% with the 1.8-m wide awning but that no significant reductions occurred over 1.8 m. The peak heating load was unaffected by the awning’s size, which is normal since the highest heating loads occur at night and outside the cooling season.

According to Fig. 10, the optimal awning dimension was thus around 2 m considering the cooling demand and annual energy use. This solution corresponds to shading scheme 5, which was the one covering only the region of highest Gcos-values (> 0.8).

3.3 Optimum awning geometry, west orientation

Fig. 8 shows the correct superposition of the Gcos-values and the solar path diagram for the west orientation. This figure shows that:

1) September has the lowest solar altitudes among the overheating months;
2) the sun is within the region of highest Gcos-values at the end of the day i.e. around 17.00 hours but the intensity of solar radiation is lower at this time;
3) the period 12.00-13.00 hours can be neglected since the sun is within a region of low Gcos-values (< 0.1).

As for the south orientation, 5 shading schemes remain after the periods before 13.00 hours and after 17.00 hours are eliminated. Table 2 shows the awning dimensions for these 5 shading schemes assuming an awning’s slope of 30° for all the cases. Note that the awning’s length was determined according to the solar altitude at 17.00 hours while the width was determined according to the beginning of the shading period.

Table 2. Awning dimensions according to 5 shading schemes, west orientation.

<table>
<thead>
<tr>
<th>Shading scheme</th>
<th>Shading period, Sept 21 (hours)</th>
<th>Length (m)</th>
<th>Width (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>13.00-17.00</td>
<td>1.39</td>
<td>4.11</td>
</tr>
<tr>
<td>2</td>
<td>14.00-17.00</td>
<td>1.39</td>
<td>3.29</td>
</tr>
<tr>
<td>3</td>
<td>15.00-17.00</td>
<td>1.39</td>
<td>2.80</td>
</tr>
<tr>
<td>4</td>
<td>16.00-17.00</td>
<td>1.39</td>
<td>2.44</td>
</tr>
<tr>
<td>5</td>
<td>17.00-17.00</td>
<td>1.39</td>
<td>2.12</td>
</tr>
</tbody>
</table>

Table 2 shows that shading schemes 1-2 yield unrealistically wide awnings. Since partial shading will be provided even for hours falling outside each shading scheme and since shading schemes 1-2 cover Gcos-values lower than 0.7 (which means that the window itself will reduce the incident radiation by at least 53%), these shading schemes can be eliminated. The design problem then consists of choosing between three alternatives: shading schemes 3, 4 or 5.

The impact on energy use of these shading schemes was studied using computer simulations. The awning’s length was 1.39 m (from Table 2) for all the cases and the width was varied from 0 to 4.11 m. The incremental annual energy use for cooling and heating the room as well as the annual peak heating and cooling loads are presented in Fig. 11.

Fig. 11a shows that the cooling demand decreased as the awning’s width increased from 0 to 2.12 m. However, little additional cooling savings were obtained over 2.12 m. As for the south orientation, the heating loads increased linearly as the awning’s width increased from 0 to 1.8 m but little change occurred over 2.12 m.

As for the south orientation, the peak cooling load (Fig 11b) was reduced by almost 50% when the awning’s width increased from 0 to 1.8 m but increasing the width over 1.8 m had little effect on the peak cooling load. The heating and cooling loads were added up in a 1:1 ratio.
peak heating load was unaffected by an increase in the awning’s width.

Fig 11 thus shows that the optimum width was around 2 m, as for the south orientation. This corresponds to shading scheme 5, which only provides complete shading at 17.00 hours. Note that it is the time when the sun is within the region of highest Gcos-values (> 0.9).

4. DISCUSSION

The example shows that the chart provides meaningful information about the window properties. This information can be used to restrict the early design hypotheses for the shading device. In this case, many shading schemes were included in the analysis although some of them covered regions with low Gcos-values. However, the energy simulations indicated that the optimum awning dimensions corresponded to the less strict shading scheme i.e. the one that only covered regions with the highest Gcos-values. This suggests that the initial shading hypotheses could have been even more restrictive.

It was shown that relatively narrow awnings (~ 2 m) could provide efficient shading both for a south- and a west-oriented office in Stockholm. This indicates that solar radiation coming from the sides of the awning has a relatively negligible importance with respect to annual energy use. The most important is to shade the window when the sun is within a region of high Gcos-values i.e. around the window normal.

However, since narrow awnings will let the direct radiation hit the window at certain hours, it is essential to provide the building occupant with an extra shading device like a curtain, an interior screen or a venetian blind. A shading device will in any case be necessary during the winter to avoid glare problems. This extra shading device should be manually adjustable and preferably located on the interior side of the window. Interior shading devices have a poor shading coefficient, which means that they will only affect the solar heat gains in a negligible way during the heating season. Littlefair (1999) also suggested to use a hybrid approach— with an exterior device to control summer heat and internal blinds for glare—in buildings where both heat and glare control are important. He observed that while external shading systems are very efficient at preventing overheating, only sophisticated external louver systems are really effective at controlling both solar gains and sun glare.

5. CONCLUSIONS

A simple chart to define the optimum geometry of shading devices was presented. The chart, which is complementary to Mazria’s (1979) solar path diagram, provides additional information about the window solar angle dependent properties and the window’s geometrical relationship to the sun beam. This additional information allows to identify the periods when solar radiation is most likely to cause overheating in the building.

The main advantage of the proposed chart is its simplicity. One figure shows the relationship between the solar position, the intensity of the direct normal radiation and the window angular properties.

Another advantage of the chart is its generality. For a given window type, the shape of the overlay describing the window properties (Gcos-values) is the same for any orientation or latitude.

Two examples were provided where the chart was used to define the geometry of an awning installed on a south- and west-oriented office room in Stockholm. The dimensions of the awning obtained using the chart and further specified with the energy simulations were small compared to the ones obtained if we had only considered the incident sun and the hours of occupation of the building. Such an approach yielded an awning three times wider than necessary on the south facade and double as wide as necessary on the west facade.

This study shows that, even at an early design stage and with simple tools, it is possible to define the optimum geometry of a shading device quite accurately just by considering the window properties. This will permit to restrict the number of iterations in the computer simulations used at a later stage in the design process. When computer simulations are not available, the proposed method will avoid oversizing shading devices, which is not economical, reduces daylighting and blocks a larger portion of the window view.

The proposed chart is solely based on considerations of energy use for heating and cooling buildings. In a real context, it is paramount to also consider the relationship between the shading device, daylighting and visual comfort.

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