SHADING/ENERGY GENERATING SKIN INSPIRED FROM NATURAL SYSTEMS

Lidia BADARNAH¹
Ulrich KNAACK Prof.Dr.Eng.²

¹ Building Technology, Delft University of Technology, Delft, Netherlands, l.badarnah@tudelft.nl
² Building Technology, Delft University of Technology, Delft, Netherlands, uk@pduk.de

Keywords: distribution, orientation, leaves, range of sun radiation, flexibility, azimuth, altitude, shading.

Summary
An adjustable shading system inspired by leaves is presented. Plants have developed unique mechanisms for specific climates and locations, where they can determine the amount of exposure for the efficient photosynthesis performance. Physiology and geometry are the most significant factors influencing light interception in plants, where leaf distribution, orientation and dynamics influence the exposure to sun radiation. Based on principles and methods extracted and abstracted from plants, a shading system was designed that has the ability to track the range of sun radiation throughout a day. Computer simulations checked the performance of the shading system through three critical days throughout the year, where azimuth and altitude angles were considered. The simulations resulted in showing different patterns of shading areas. The combination of azimuth and altitude angles determined the distribution of the shading system elements. Due to the flexibility of the system in orienting to different directions and repositioning through the day, it provides continuous shading all over the desired plane at the envelope. With the system it is possible to achieve maximum required shaded area with loose density of shade planes and avoiding self-shading, or shading with high density of shade planes for maximum energy gaining, due to their position normal to sun rays.

1. Introduction
Shading devices can be attached to building envelopes internally or externally, where they control the amount of light that permeates through the envelope. Adding shading devices to the envelope is important for reducing peak heat loads in the building, reducing cooling requirements, and improving natural lighting and more external visual contact than other standard shading devises. Energy-efficient building design is influenced significantly by the shading device. Current shading devices include solid shadings, canvas awning, roller shades, blinds and louvers. These shading technologies basically deal with extensions either vertically or horizontally, or by adding an extra cladding to protect against radiation from glazed openings, while leaving some amount of light to penetrate inside. These technologies have limited adjustability, while they are designed for the extreme situations of solar radiation and not for the whole range of solar radiation exposure (Badarnah et al. 2008).

Plants are organisms that have a significant relation with sun radiation. The relation between light and plant’s leaves has been investigated and reported by numerous biologists (e.g. Ehleringer et al. 1980, Brunig 1976, and Loomis et al. 1971). Organizational features in plants offer various solutions for tracking sun radiation, either paraheliotropic or diapheliotropic. Plants have developed unique mechanics for specific climates and locations, where they can determine the amount of exposure for efficient performance. Physiology and geometry are the most important factors that influence light interception in plants (Badarnah et al. 2008). Therefore, looking at nature’s solutions is a method for developing efficient technical systems for building envelopes. The structural geometry of the shade elements for The Singapore Lyceum Theater was inspired by nature, like sunflowers, fish scales etc. The intention of the architects (DP Architects) was, that the enveloping façade system changes pattern to suit the orientation of the sun, providing solar shading and controlling the internal environment of the pavilions (www.geocities.com). However, the individual shading devices are not adjusting themselves throughout the day or seasons according to sun-ray angles.

This paper introduces a shading system inspired by organizational features in leaves, where location and inclination were considered in the study and the developed system. The focus is on external shading elements, because of their effectiveness in blocking solar radiation before reaching the indoor environment (Ologyay 1992). Section 2 presents the background for leaves responding to sun radiation, and it is based on the work done by Badarnah et al. (2008). Based on this section, the main principles were transformed into technical solutions for a shading system (section 3). In order to evaluate the performance of the shading system throughout the day and seasons, computer simulations were carried out (section 4), and with these

simulations, the different shading patterns of the same system where studied (section 5). Finally, a discussion and the conclusions are presented in section 6.

2. Background

From summarizing the techniques used in plants for reacting to sun radiation, three main categories were recognized for maximum and minimum light exposure. Leaf distribution, orientation and dynamics play a significant role in influencing the exposure to sun radiation. Principles from the different categories influence the plant to track the sun effectively. Morphological and physiological factors influence light interception in plants (Brunig 1976), where it affects photosynthesis and rate of plant productivity (Loomis et al. 1971).

2.1 Distribution

The combination of arrangement and density of leaves affects leaf distribution in plants for photosynthesis efficiency (Ehleringer et al. 1980). Therefore, there are two ways for photosynthesis efficiency: leaves distributed in a single-layer with high density or multi-layer distribution with loose density (Horn 1971). Leaf density of plants, influences the plant’s projected area, which affects sunlight interception capability (Niklas 1988). Form and proportion are additional factors affecting photosynthesis efficiency (Kriegh 2003). Some plants have special arrangements that could be described mathematically, e.g. Fibonacci series, which are adopted for compact and dense packing of members.

2.2 Orientation

In plants, sun tracking is achieved in two ways: leaves move perpendicular to the direct sun rays, which are called diaphototropic leaves, and leaves move parallel to the direct sun rays, called paraheliotropic (Ehleringer et al. 1980). Heat load, leaf temperature and transpiration rate are reduced with paraheliotropic movements (Forseth 1980). Diaphototropic movements, fig. 1, allow a high solar irradiation and result in maximal rates of photosynthesis throughout the day (Mooney 1978). Regulation of leaf inclination is one of the mechanisms to avoid shading by neighbors (Mullen et al. 2006), fig. 1.

2.3 Dynamics

Plasticity in response to sun light is one of the dominant aspects of plant architecture (Pearcy et al. 2005). This plasticity is recognized when leaflets shift from a vertical position to a horizontal position. In this process plants increase their internodes and petiole length, and leaves increase their area while reducing mass per unit area. Dynamics in plants are generated via their nastic structure (Bar-Cohen 2006); it has different functions, such as rapid bending, which is recognized at the Venus flytrap. Its closure is achieved through the property differences at the exterior and interior surface of the wing, fig. 2. The inner surface is able to extend 5%, while the outer surface extension is 20%. Another function is orienting horizontally or vertically, this property is adapted basically to track sun radiation. The centralization of vascular bundles in the leaf stalk allows the leaf to bend.

Figure 1  (a-c) The angle of incidence determines energy density. (a) leaves normal to sun rays for maximum energy gain. (b) the effect of different inclination on the projection. (c) top, front and projection view. (d,e) lower layers of leaves bend for maximum light perception. (d) lower leaves get bigger with smaller inclination ($\beta < \gamma$). (e) the effect of inclination, preventing self-shading.

Figure 2  Venus flytrap. At right, a cross section showing different extensibilities for the inner and outer surfaces.
2.4 Summary of techniques used in light-responsive plants

Table 1 Summary of main organizational features in leaves for maximum light exposure.

<table>
<thead>
<tr>
<th>Distribution/position</th>
<th>Orientation/inclination</th>
<th>Dynamics</th>
</tr>
</thead>
<tbody>
<tr>
<td>loose distribution at multi-layer</td>
<td>perpendicular to sun-rays (Diaphototropic)</td>
<td>increasing internode and petiole length</td>
</tr>
<tr>
<td>dense distribution at mono-layer</td>
<td>facing east for maximum exposure at morning and afternoon</td>
<td>increasing leaf area combined with reducing mass per unit</td>
</tr>
<tr>
<td>maximum projected area</td>
<td>facing south/north for maximum exposure at winter noon’s</td>
<td>plasticity, nastic structure</td>
</tr>
<tr>
<td>Fibonacci series for compact pattern packing</td>
<td></td>
<td>different flexibilities of the sides of a blade</td>
</tr>
<tr>
<td>extending stem</td>
<td></td>
<td>special surface properties- uncoated cell clusters (for flexibility)</td>
</tr>
<tr>
<td>horizontal expansion</td>
<td></td>
<td>convex surface shape</td>
</tr>
</tbody>
</table>

3. Principles Transformation

Leaves in plants have unique properties in order to track sun radiation. For maximum exposure, leaves tend to have a clear organization and distribution with an adaptive inclination and relatively high plasticity in the plant’s body (Table 1). At minimum exposure, plants are less dynamic and reorient when having high exposure, e.g. at noon, also they tend to have low leaf inclinations, preventing conditions such as normal to rays. Furthermore, in order to achieve dynamics, the structural geometry is very significant. Geometry is a major aspect for determining the distribution, inclination and dynamics. Based on principles and methods extracted and abstracted from plants, a shading system was designed. For the design process we referred to the following (extracted from Table 1):

- Mono-layer at dense distribution for maximum light capture
- Plasticity, in order to adapt to different inclinations
- Different inclinations of leaves in relation to sun rays, the generated projected area could be maximized
- Leaves normal (perpendicular) to sun-rays
- Special surface properties, for flexibility
- Increasing leaf area combined with reducing mass per unit, for better photosynthesis process
- Petioles extension, in order to prevent self-shading
- Stem elongation for maximum light capture

These principles and methods are the base-line for the shading system development. The transformation of these principles and methods resulted in a shading system for building envelopes that has adjustability for different inclinations. In this complex transformation process, plant's mechanisms and building envelope’s demands need to be integrated. Based on the unique shape and structure of plant’s leaves, which provide them the desired flexibilities induced by sun light, it is possible to develop a system providing shading and also energy generation. The side of the sheets facing radiation has integrated cells for gaining energy and by that provides shade for underneath.

3.1 The shading system

The system consists of shading sheets, tubular members and profiles. The shading sheets are connected to the tubular supporting members via an elastic membrane for flexibility. The profiles create a grid, which allows the tubular members to roll over and control their position according to shading requirements. For sun radiation blocking, the shading sheets are flexible and can be adjusted to different inclinations, more explanation in the following sections.

Figure 3 The shading system. (a) front view, shading sheets and profiles in the back. (b) side view, shading sheets connected to the tubular member via the elastic membrane. (c) perspective view.
This system is designed for the whole sun radiation path throughout all the days of the year, where azimuth and altitude angles are considered (Figure 4). The system blocks the sun radiation at a specific angle and allows the indirect light to penetrate between the sheets. When the sheets are normal to sun rays, their position in the depth could be different (Figure 5). In this case, indirect light reflected from the surrounding environment reaches behind the system and keeps the interior space with good quality of light. Additionally, shading sheets being normal to sun rays is the best orientation for radiation gaining, where photovoltaic cells are attached to the surface facing sun.

**Figure 4** Azimuth (θ) and Altitude (ω) angles determine the position of sun. The hatched surface presents the sun radiation path throughout a specific day.

**Figure 5** The same projection area for two different surfaces of shading sheets normal to sun rays. (a) the shading sheet flat and normal to sun rays. (b) the shading sheet is divided to smaller pieces and positioned in different depths of ray direction.

### 3.2 The shading component

The shading component consists of a sheet attached to a supporting tubular member with the property of elongation (Figure 6d). This elongation is important to avoid shading by neighbors. The sheet is able to have different inclinations as shown in Figure 6(a-c), where it covers and blocks the sun radiation path, which is determined by azimuth and altitude angles, throughout a day.

**Figure 6** The shading sheets inclination and their support elongation. (a.-c.) showing different inclinations of the sheet connected to the support member by an elastic membrane. (d) the support tubular member elongation.

The shading component is connected to the grid of profiles allowing the components to move and change position according to users shading requirements. Four elastic wires are attached to each sheet at their corners, when one of the wires is stretched the sheet will rotate and change its inclination. The specific required inclination for a sheet is controlled via these four wires (Figure 7). The components are controlled separately with considering each other's position and inclination in order to have the maximum variation of shading patterns.

**Figure 7** The shading component. (a) four strings attached on the sheet, reaching the corners and inserted into the tubular member. (b) a close-up to the four strings interring the tubular member.
3.3 The system implementation

The system could be applied on a flat envelope or on a freeform envelope due to its grid pattern. The scale and size of the grid depends on the specific envelope to be applied on. In cases where the envelope has a freeform layout, the grid has smaller dimensions than at a flat envelope. The shading components are controlled to move over the grid and pack under each other, in cases like cloudy days, where no shading is required and by that the visual contact to the outside is more open (Figure 8).

![Figure 8](image)

Shading components movement over the grid. (a) Shading components positioned to cover the radiation. (b) Shading components moved to the edges of the grid providing free visual contact and packing under each other.

4. Simulations

The main aim of the simulations is to check the ability of the shading system to track sun radiation throughout a day. These simulations refer to a specific location which is Delft at 52°0'54"N 4°21'24"E (Figure 9), with considering three critical days throughout the year, where noon hour was determined (Table 1). The tested side of the envelope is south with 90° inclination.

![Figure 9](image)

The shading system location, inclination and orientation.

In this paper, the focus is on the principle of the new shading system, where size of grid and amount of elements does not affect the way the shade is generated on the envelope. The dynamic projection of shading sheets, caused by sun radiation, on the envelope was studied. The values in table 1 and 2 are generated from an online calculator for sun angles (www.susdesign.com). The path of sun radiation is determined by altitude and azimuth angles. These angles change throughout the day and differ from day to day. In this paper we refer to morning and noon azimuth and altitude angles, since noon and afternoon need the same treatment but mirrored because of their similarity in relation to south (Table 2), more explanation will follow in results section.

For these simulations we refer to a system that has an initial status as in Figure 8a. It consists of 67 shading sheets distributed as a single layer all over the grid. The aim was to shade the grid with minimum shading sheets and preventing situations where two sheets shade the same spot (self-shading). In the results where sheets less than 67 are shown, means that the other sheets are moved over the rails and packed under the major shading generating sheets.

<table>
<thead>
<tr>
<th>Reference Date</th>
<th>Sun duration (hours)</th>
<th>Sunrise</th>
<th>Sunset</th>
<th>Noon</th>
</tr>
</thead>
<tbody>
<tr>
<td>September 21</td>
<td>12:20</td>
<td>06:27</td>
<td>18:47</td>
<td>12:37</td>
</tr>
<tr>
<td>December 21</td>
<td>7:45</td>
<td>08:49</td>
<td>16:34</td>
<td>12:42</td>
</tr>
<tr>
<td>June 21</td>
<td>16:44</td>
<td>04:23</td>
<td>21:07</td>
<td>12:45</td>
</tr>
</tbody>
</table>
Table 3  Morning, noon and afternoon altitude and azimuth angles for three days in Delft.

<table>
<thead>
<tr>
<th>Time</th>
<th>September 21</th>
<th>December 21</th>
<th>June 21</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>08:00</td>
<td>10:00</td>
<td>09:00</td>
</tr>
<tr>
<td>Altitude</td>
<td>13.16°</td>
<td>6.67°</td>
<td>38.74°</td>
</tr>
<tr>
<td>Azimuth</td>
<td>73.86°</td>
<td>36.86°</td>
<td>78.54°</td>
</tr>
<tr>
<td>Time</td>
<td>12:37</td>
<td>12:42</td>
<td>12:45</td>
</tr>
<tr>
<td>Altitude</td>
<td>38.66°</td>
<td>14.56°</td>
<td>61.44°</td>
</tr>
<tr>
<td>Azimuth</td>
<td>0.03°</td>
<td>0.01°</td>
<td>0.36°</td>
</tr>
<tr>
<td>Time</td>
<td>17:00</td>
<td>15:00</td>
<td>18:00</td>
</tr>
<tr>
<td>Altitude</td>
<td>15.13°</td>
<td>8.75°</td>
<td>34.40°</td>
</tr>
<tr>
<td>Azimuth</td>
<td>-70.80°</td>
<td>-31.71°</td>
<td>-84.64°</td>
</tr>
</tbody>
</table>

5. Results

In this section, shading simulations for three selected days (Table 3), introduced in the previous section, in Delft are presented. For each day two simulations were carried out, one at noon and the other one in the morning.

Figure 10  Shading results for the system located in Delft and facing south. (a) on the 21st of June at noon (left) and at morning (right). (b) on the 21st of September at noon (left) and at morning (right). (c) on the 21st of December at noon (left) and morning (right).
On the 21st of June, sun rays have high altitude angle at noon, which resulted in shading the surface with few shading sheets normal to sun rays (Figure 10a left). In this case the sheets have the same inclination, but the rows of shading sheets are not at the same distance from the shaded surface, this is important in order to avoid shading by neighbors. In the morning (Figure 10a right), when sun radiation reaches the southern façade then it will have already moderate altitude angle but with high azimuth, and resulted in shading with different organization and less sheets but with more surface area of shade.

On the 21st of September, sun rays have moderate altitude angle at noon, which needed more shading sheets to provide the required protection (Figure 10b left). In this case the sheets have the same inclination, but sheet rows are not at the same distance from the envelope, in order to avoid self-shading. In the morning, sun rays have high azimuth and low altitude which resulted in shading sheets concentration at east with relatively dense distribution (Figure 10b right).

And on the 21st of December, sun rays have low altitude angle at noon, where more dense distribution was needed to provide the required protection (Figure 10c left). In this case the sheets have the same inclination with different distances from the envelope, this was a way to provide a stronger visual contact with outside and lighten the perceived density of the shading system by creating the openings and division (the same principle as in Figure 5b). In the morning, sun rays have low altitude and moderate azimuth angles which resulted in having a large number of sheets, in order cover the required surface of the envelope, with high density (Figure 10c right). The same principle of distribution at noon was applied in the morning, where sheets have different distances from the envelope.

From these simulations, we notice that altitude angles, at envelopes facing south, affect significantly the density of shading sheets distribution. For low altitudes in the morning, sheets are more concentrated to the eastern side of the envelope with high or low density, depending on the azimuth angle. For different combinations of altitude and azimuth angles, different organizational patterns of the shading system are generated.

Current standard shading systems such as louver panels either vertical or horizontal, the sun radiation blocking is controlled by flipping the louvers to different angles. However, these louvers are not adapted, three-dimensionally, to track the exact sun radiation throughout the day. They tend to have the same angle of inclination when flipped, Figure 11. Venetian blinds, which consist of adjustable louvers, can be divided into separate parts, for controlling and adjusting them in different inclinations. This will control the sun radiation to get deeper in the room or reflecting it (Knaack et al. 2007). But still, this division has a limited adjustability, when the louvers are flipped they still have the same angle of inclination. The limited adjustability is due to their design principle, where louvers have their best performance at noon while facing south. This poor consideration results in cases where louvers are totally closed in order to block varied sun radiation, e.g. low altitude and high azimuth angles of radiations.

6. Conclusions

As a result of principles and methods transformation from leaves, a shading system was developed. This system is able to track sun radiation and provide shade for the desired plane of the envelope. It has flexible shading sheets that can rotate around their support. These supports are tubular members that can elongate and position the shading sheets in different distances from the envelope. The shading system is designed for the whole range of solar radiation throughout a day during the year. The simulations for performance testing refer to Delft at 52°05′44″N 4°21′24″E (Figure 9), where different azimuth and altitude combinations influenced the shaded area on the envelope.
From the results it is possible to conclude the high influence of altitude angles on sheets organization and their density, where azimuth angle has more influence at morning hours. The system is able to avoid self shading situation by elongating their support tubular members and by that they have different distances from the envelope, like leaves in plants elongate their petioles. If we compare it with existing shading systems, then we realize that current shading systems consider altitude angles or azimuth angles but not their combined influence (horizontal louvers for high Altitude angles or vertical louvers for low Altitudes in the morning or evening). This combination of altitude and azimuth is very important in order to cover the path radiation throughout the day, which is achieved in the designed system above. However, some improvements could be considered, the system was tested in one location for specific angles. Sometimes we have very high altitude angles and the system have some difficulties with shading the upper parts. A proper solution could be, allowing the sheets to fold and have better contact with the envelope (figure 12); in this case, the sheets don’t have the same inclination, where their inclination gets higher at higher positions.

Due to the flexibility of the system in orienting to different directions and repositioning through the day, it provides continuous shading all over the desired plane at the envelope in Delft. With the system it is possible to achieve maximum required shaded area with loose density of shade planes and avoiding self-shading, or shading with high density of shade planes for maximum energy gaining, due to their position normal to sun rays. Further investigation on the flexibility possibilities of the sheets is needed in order to adopt the system to different locations with different altitude and azimuth angles.

Acknowledgement

The authors would like to thank L. Voorbij for reviewing this work.

References


