Designing the Window to Fit a Shading Device : A Reversed Method for Optimizing Energy Efficient Fenestration

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Abstract. Solar radiation penetrating a window Increases cooling loads and energy use, especially in hot climates. Most energy efficiency CAAD tools help designers to optimize a shading device protecting a given window, usually a rectangle. It is hard to protect some window parts, such as lower corners. Enlarging shading device to protect them Increases lighting and heating loads, as well as their complexity, visual impact and cost. Changing the shape of the window by cutting these corners may reduce the size of the shading device considerably, which opens way to a different – or even a reversed - approach : "Designing the window to fit a shading device instead of designing the shading device to fit a window !". This approach has several potential applications. The building form itself sometimes works implicitly as a shading device. For example, a building of U shape plan shades parts of its walls, the window can be designed to fit the shadow pattern caused by the building, changes in the building profile gives similar shadow. Conceptually, this approach makes energy efficiency a form giving attribute, helping to create innovative facades, while giving an energy efficient configuration of window and shading device. CAAD tools can help designers adopt this approach, by proposing the window shape that suits an arbitrary shading device.
This paper validates the approach and introduces a method for developing a software module to be integrated with current CAAD tools; handling complexity of solar geometry and intensity, and the geometry of the window and shading device.
1. Introduction

Solar radiation passing through a window contributes significantly to cooling loads and energy consumption, especially in hot climates. Most CAAD tools that handle energy efficiency aim to help designers in defining the optimal configuration of the shading device that protects a window of a certain shape, which is typically rectangular. However, some parts of the typical rectangular windows (e.g. the lower corners) become hard to protect unless the shading device becomes very large. This, in turn, results in unnecessary over-shading of the other parts of the window, increasing lighting and heating loads. As well as the complexity, visual impact and cost of the shading device.

Earlier shading design methods adopted an analytic/graphic approach. Olgyay [1] used a graphical method that utilized sun path diagrams in defining the optimal shape of shading devices. It is based on evaluating the climate of the location to predict thermal comfort and to define the under heated periods requiring solar penetration. The shading device is configured to shade the window during the rest of the year. This design approach was further developed by several researchers.

Computer modeling and simulation tools helped introduce sophisticated design methods and allowed the evaluation of complex shading device configurations. Examples of this approach include the work of McCluney [3], Etzion [4], Grau and Johnsen [5], and Maradaljevic [6]. Search methods were used to derive the optimum shading device by exhaustive trials of a large set of alternative designs, evaluating their effect on energy use and comfort conditions of the shaded spaces. These methods usually address the efficiency of the shading device for a certain case. It searches for the optimum shading device configuration that fits a certain window shape of in a certain geographic location. However, this provides little guidance to the designer in proposing optimum shading device configurations that suit other cases.

Use of the cut off dates along the sun path for defining the configuration of the shading devices was explored by many researchers. A form generating method that uses computer simulation for generating the optimal shading device configuration was introduced by Arumi-Noe [7]. A method for constructing a shading device that suits any polygonal window was explored. It used the solar path of a winter design day to create a "solar funnel" that was later clipped with the solar path of summer design day to identify the shading device edge configuration.

Andrew March [8] proposed a design method for shaping the shading device based on defining a certain cut-off date on which complete shading is required. This can be either the first or the last day of the year. The sun path was tracked onto the shading plane throughout the day for each of the corner points of the window. Integrating this method with the Ecotect software provided the ability to
generate optimized shading devices. Given a rectangular shape of a window, it was possible to derive the exact shape of the shading device required to completely shade the window up until a specified date and time. The edge of the clipped funnel represented the minimal shading device required to satisfy both winter and summer conditions. This gave the designer an identification of the scale and extent of the shading element required. Figures 1 and 2 illustrate the often complex shading device configurations that were generated by use of cut-off date and cut-off time approach.

Kaftan [9] introduced "The Cellular Shading Method" which divided a shading device into finite cells, shading importance of each cell was calculated, indicating the degree of importance of each cell in providing shading or solar penetration during a certain period (season, year, etc.). This enabled the designers to refine the design of the shading devices. It was later integrated with the Ecotect to provide easy application [10].

![Fig. 1. Sun path tracked throughout the day for each of the window corner points, to reach the shape required to shade the window in the specified cut-off date, by Intersecting solar path funnels with the shading device [2].](image1)

![Fig. 2. Examples of optimized shading devices generated by Ecotect to provide complete shade in a specific Time and date [3].](image2)

It is apparent that the literature on this topic predominantly concentrated on the design of a shading device that fits a predefined shape of the window - usually a rectangular shaped window - to prevent summer sun and allow winter sun. The methods generated efficient shading devices with complicated configurations, which may generate excessive shading that obstructed view from the window and the diffuse radiation required for daylighting. A more efficient approach could lie
in reversing the design logic where the window would be formed to suit the shading pattern of a shading device.

The proposed approach could prove useful to architectural design as it allows architects to perceive the shading systems as integral parts of the building design, not as additions to the building after the window and façade designs were shaped. It is common to design the window then to design a shading device that fits it, but it is also possible to start by the shading device then design a window to fit it. Or even using an iterative approach where several rounds of design window - optimize shade - optimize window. Take place to reach an optimal configuration achieving the energy conservation objectives, including minimizing solar penetration during overheated periods, maximizing solar radiation during under-heated periods and maximizing the visible diffuse radiation for daylighting.

2. Objective

The objective of this paper is to explore the potential of using simulation software such as Ecotect in defining the optimum shape of windows that suit certain shading systems. Conceptually, this approach makes energy efficiency a form giving attribute, helping to create innovative building facades, while giving an energy efficient configuration for both window and its shading device.

3. The shaded-points window design method

The suggested method is rather reversed; the designer starts by the shading device, then designs the optimal window that suits that shading. This paper introduces this concept, and demonstrates how and when it could be implemented, and its benefits.

The method is based on identifying the shadow pattern resulting from use of the shading device on a building surface where a window could be located. The shadow pattern is drawn in overlays, each representing one of the time steps of the shading period. The amount of solar Insolation reaching any point of the surface for each time step is calculated. The total energy reaching each point throughout the shading period is determined by adding the values calculated for each of the overlays. This defines the amount of energy that will potentially add to the cooling loads if it passes into the space through the window. The points having minimal overall exposure to solar Insolation could be considered more "shaded" in comparison with the points that have higher exposure. This could be used to define the maximum accepted energy the designer would allow his window to receive. It also differentiates between shaded points (that would be part of the window) and exposed points (that should remain opaque). The
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boundary between the shaded points and the exposed points defines the edge of the "shadable area" in which the window is better located.

The proposed method could be summarized as follows :

• Model the surface where the window will be located.
• Model the shading device, or the building part that acts as a shading device (Figure 3-a).
• Model any adjacent buildings that have a significant shading effect on the surface.
• Define the shading period (the times when shade is needed).
• Draw the shadow pattern resulting from use of the shading device on the surface for each time step of a typical day that represents each of the shading period months (Figures 3-b, 3-c, 3-d and 3-e).
• Overlay all these shadow patterns to arrive at an overall shadow density for the whole year (Figures 3-f).
• Subdivide the surface into finite elements having a suitable size, either by intersecting the shadow patterns generated in each time step or by using an analysis grid.
• For each finite element define the solar radiation reaching the point, the intensity of the direct component multiplied by a Boolean indicator of shading, cosine of the angle of incidence and transmittance of glass to this angle, in addition to a diffuse component multiplied by sky view factor.
• Accumulate all energy reaching each finite element during the shading period.
• Assign the incident solar energy values of the elements in an Array representing the analysis grid nodes – or an appropriate data structure if intersecting polygons are used - and plot these values on a graph.
• Draw the contour lines representing iso-values of solar energy intensity, either in absolute values in KW/Hr or relative values (percentage of the maximum energy reaching the exposed elements).
• Define the energy or shading percentage limits accepted for the window, the consequent contour line will be the binding envelope of the window.
• Draw the window outline according to the boundaries of the contour line to create the shaded window.
• Calculate the sum of energy passing through the Window – or the average shading percentage - to confirm that the design falls within the accepted limits.
4. Quantitative performance of the window-shade configuration

This section proves the validity of the concept by applying it a case study of a horizontal overhang fixed on a south facing façade of a sample building located in an arid desert location (Cairo, Egypt Lat 30°N- Long 31°E) which is cooling dominated. Shading is required for 9 months / year; from 21st February to 21st October [2].

The Ecotect software was used as the primary tool for calculation and visualization. It includes most of the features required for applying the shaded-points method proposed in this study. Also, it gives access to numerical data of total solar energy reaching each node of the analysis grid in the design surface during the defined shading period.
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Fig. 4. Combined shadow pattern of a horizontal shading device.

Fig. 5. Relative Exposure (RE) of each node in the Analysis grid.
Figure 4 illustrates the combined shadow pattern, while Figure 5 includes the relative numerical values associated with this shadow pattern. The values represent Relative Exposure (RE), which is the ratio between actual total direct radiation on the node and the maximum total direct radiation reaching the exposed points of the surface. The maximum total direct radiation on the south wall was 868kW.hr/m$^2$. Several points of the area directly beneath the shading device were in total shade. Their grid nodes had an incident Insolation of Zero or 8kW.hr/m$^2$ (<1% of the maximum total direct radiation).

The first contour line defines the area with RE of 0-10%, which gives an impression that 10% of the maximum radiations reaches this area, but actually most nodes in that area received negligible amounts of radiation.

By calculating a weighted average of the radiation reaching the area proved that the average RE was only 2.1% of the maximum value. The second contour line which marked the maximum RE of 20% enclosed an area with an average RE of 5.3%.

All the points having RE values between 0 and 50% were counted and a weighted average curve was plotted against the maximum value (Figure 6) exact average RE for selected maximum RE values are listed in Table 1.

The proposed algorithm proposes the form, calculates the Average RE, modifies the boundaries if it exceeds the RE average limit defined by user.

Fig 6. Average Relative Exposure corresponding to maximum RE, fitted to second order polynomial curve.
Table 1. Average relative exposure corresponding to maximum RE.

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5. The form of the window-shade configuration

The form of the window is defined by many factors. Energy conservation is one of them. The proposed method inspires the designer to define a form influenced by the shading efficiency not forced by it. Design modulation, style, use of spaces and the construction techniques or materials are some of that factors that are typically considered by the architect in designing the window; thus, flexibility is extremely important.
The proposed method facilitates adopting a wide range of window configurations that would fit within the boundaries of the overall shade pattern (Figure 7-a). They could take one of the following configurations:

1. The exact path of the specified contour line: the boundary becomes a curve (arc, parabola, etc.). A Bezier curve is usually flexible enough to represent any form of contour line, the designer can define the number of vertices and control points or the software tool may use its defaults (Figure 7-b).

2. A polygonal shape that approximates the original curve, vertices can be defined by the pane width or the design module, or the number of vertices (Figure 7-c and 7-d).
3. A stepped form of rectangular panes, number of steps, min. step dimension and the relation between steps and contour line can be defined by the designer (Figure 7-f).

4. A rectangular window within the boundaries of the contour line, or intersecting it with definite performance constrains (Figure 7-g).

5. A rectangular window larger than the boundaries of the contour line, in which the contour line divides the window into 2 portions: within the shading contour line low cost clear glass is used, outside the contour line protection shall be provided to the glass, either a dark or reflective glass is used, or solar screens may protect these portions, (Figure 7-h). This solution could be easily adopted in the retrofit of existing buildings that have inefficient or unplanned shading devices.

The above window configurations follow a 20% maximum RE contour line. The window with Bezier curve has exactly average RE of 5.3. Other geometrical approximations vary between 4% and 5.3%.

The Selection between these forms will depend on several architectural Issues such as aesthetics of facades. For example, if the designer uses a curvy building form, the parabolic alternative Figure 7-b would be matching. If the building form is rectilinear, a rectangular window inside the boundaries (Figure 7-f.g) can be used. interior planning and detailing constraints may not encourage a window with a curved sill, in such a case, a polygonal approximation can solve some of the problems (Figure 7-c.d), or a rectangular window can be used. Shading the window allows the use of clear glass which gives a better visual relationship between interior and exterior, and allows better daylighting, with a lower glazing cost.

Architects may find rectangular windows easier to Handle for several reasons, the reversed Approach can still be applied even on rectangular windows larger than the parabolic shaded area, using a clear glass pane in the shaded parabolic area allows better view and daylighting, while the exposed parts (lower corners) may be of a dark or reflective glass to reduce solar penetration, or they may be protected by solar screens, still allowing more daylighting (Figure 7-h), the possible combinations are infinite, and open to designers creativity.

This approach could be further explored by changing the angle of rotation and shape of the shading device in parallel with designing the shape of the window. This allows for innovative forms and more improved energy performance. An example is illustrated in Figure 8, where a simple square horizontal overhang draws a large skewed parabolic form on the 10% RE contour line, which the window can follow generating non familiar form of window. The shallower overhang generates a chamfered rectangle window. Rotating the square overhang 30 degrees gives a wider window, while the shallow rotated over hang gives a rotated window.
Fig. 8. Innovative window configurations resulting from simultaneous design of the shading device and the window.

The angle of rotation could be complemented by changing the proportion of the overhang shading device. Figure 9 illustrates the various shade patterns, and thus window configurations that could result.
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Fig. 9. Change of window shape as a result of changing the angle of rotation and proportion of the overhang.
U shaped building facing south creates a shading pattern. Figure 10, locating the windows in the shaded areas reduces energy passing through windows. Figure 10-b represents the RE pattern. Figure 10-c proposes the preferred fenestration. Addition of an overhang in the exposed middle area creates shadow for a potential window which follows the shadow pattern to look compatible with the form of other windows (Figure 10-d,e).

6. Implementation potential

The proposed method could be applied manually using any conventional CAD or 3D modeling software depending on guided integration of existing features of modeling solar geometry and visualization. Image processing software could handle the overlying process and calculating intensities and generating contour lines. The designers would take their decisions visually with minimal calculations. Complex forms could be handled this way during the conceptual design phase.
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The concept would be better applied if energy conscious software such as Ecotect is used, where calculations of shading could be conducted and visualized for a wide range of building forms and shading devices could also be reported in numerical forms for more processing.

The proposed method would be better applied in through an automated solution by developing an intelligent module that can work independently or preferably added as a plug in to Ecotect or similar software. The module could automatically or interactively develop the design of the window according to the shadow intensity, and inserts that window into the model. If the designer’s primary concept is green architecture where the dominant form-giving attribute is energy conservation, the tool could automatically define the optimum window shape by following the energy contour lines. If the designer wants to integrate some other design aspects, he could then make some compromises. The tool would then be flexible to allow alternative near-optimal forms, and interactively quantify the energy loads resulting from using these forms.

7. Ongoing developments and future research

The concepts needs more refinement, performance assessment of sample building in this paper concentrated on quantifying shading during the overheated period, this is usually the most critical aspect in desert climates which are cooling dominated. However, generalization to moderate climates requires careful assessment of the reduction in solar radiation during the under heated period. The impact on daylighting could be included. It is understood that the method is meant to define potentially efficient forms during the conceptual and schematic design phases. Use of the energy simulation tools such as the Energy Plus for simulation of the overall energy performance could prove useful in validating the proposed design method. Finally, development of the detailed algorithms of the software tool is currently underway.

8. Conclusion

The paper addressed a new approach for designing building facades. It proposed a reversed approach: “Designing the window to fit a shading device instead of designing the shading device to fit the window!”.

In order to achieve this objective the Shaded-Points Method was proposed. It has several advantages. These are:

1. It facilitates the achievement of required shading by use of smaller and simpler shading devices. These would sufficient for protecting the window
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from overheating, hence allowing better winter solar exposure and improved diffuse radiation required for daylighting. It also improves the external view of windows.

2. It gives the designer a chance to reach new limits of performance by designing the 2 elements of the shaded window system instead of assuming an inefficient window form and forcing the shading device to solve the problems created by the window form.

3. It utilizes the actual building forms for improving the energy conservation by selecting right places and forms for windows in the parts that are self shaded by the building edges.

4. It facilitates new creative forms for windows that can help label and symbolize the energy saving architecture.

5. It defines the parts of the windows that faces problems in the retrofit of existing buildings, and solves it using smaller and less costly solutions.

References


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