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Integrating the cellular method for shading design with a thermal simulation

E. Kaftan
Research & EcoDesign, Israel

A. Marsh
Welsh School of Architecture, Cardiff University, United Kingdom

ABSTRACT

The cellular method for optimal shading design recently has been implemented as a plug-in for the Ecotect software (Fig. 1). This is a significant step since it enables designers to optimize shading devices based on predicted indoor hourly thermal requirements for shading and solar gain. These requirements are determined from predicted hourly heating and cooling loads or fluctuating internal comfort levels. The method comprises a unique process of projecting and accumulating this information onto numerous theoretical cells of proposed shading devices or any other outdoor locations. Then, different regions of the proposed shading devices or outdoor space can be graded with the overall degree of importance to provide either shading or solar penetration.

Linking the cellular shading method directly to a thermal analysis engine provides for an unprecedented level of shading optimization - tailoring the shape and transparency of each shading device to its local climate, specific window, and associated thermal space. This level of accuracy in shading design is essential if the increasingly stringent levels of energy conservation required by future building regulations around the world are to be met.

1. INTRODUCTION

Nowadays, computer capabilities enable re-approaching the significant dilemma of optimal shading; refining shading optimization methods.

The optimal shading dilemma - ensuring both solar shading during overheated periods and solar gain during under-heated periods - is commonly approached with simple calculation methods. Key methods comprise Olgyay's and Olgyay’s shading mask (1957), Shaviv's method (Givoni, 1974), Etzion's one point method (1985), and Saleh's shading template (1988). These methods generate an excess of shading since they primarily account for the need of shading, rather than also for the necessity of winter solar gains.

Other approaches, McCluney's algorithm (1990), Etzion's tool (1992), Grau and Johnsen polygon clipping (1995), and Maradaljevic's STIMAP (2003), all focus on evaluating shading performance. Indirectly they can assist optimizing shading devices shape, however only by a process of trial-and-error. Recent attempts at developing methods for generating optimal shading devices include Marsh's cut-off date projection and point-cloud ray-trace (2003); and Kaftan's cellular shading method (2001).

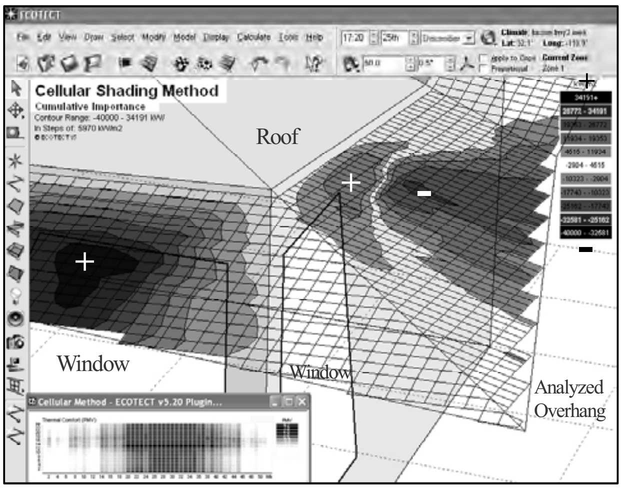

Figure 1: The cellular method as per Ecotect's plug-in.

2. THE CELLULAR SHADING METHOD

The cellular method for optimal shading design was developed by Kaftan at the University of Arizona (2001). It is currently a US patent pending. The method's core notion comprises the optimization of shading devices, utilizing the evaluation of numerous theoretical cells of proposed shading devices or other outdoor locations. The method includes a calculation procedure to determine the *overall shading importance* of each cell (Fig. 2). The cell's *overall shading importance* indicates the final degree of importance of this location to provide either shading or solar penetration during a period (season, year, etc.). Accordingly, designers can redefine or design optimal shading devices.

The cell's *overall shading importance* is calculated by accumulating *momentary shading importance* data for numerous short time segments (for instance, hourly). *Momentary shading importance* indicates the degree of importance of this location to provide either shading or solar penetration during a particular short time segment. Each cell's *momentary shading importance* can be determined by evaluating its *shading effect*, *shading necessity*, and *shading relevancy*.

Shading effect would be either the admitted or the eliminated potential solar radiation according to the decision to include a particular cell in the final shape of the shading device. *Shading necessity* is the determination if solar radiation is beneficial or undesirable to the associated thermal space during a particular time segment, according to thermal and visual comfort conditions. *Shading relevancy* is the potentiality of a particular theoretical cell to shade the preferred shaded space during a particular time segment, according to geometrical solar analysis.

Calculations to determine these values can vary according to the level of accuracy needed. For instance, *shading effect* can be determined by calculating general reductions in radiation occurring between the Sun and the associated thermal space. Prime reductions needed to be considered occur in the phases of extraterrestrial radiation, atmospheric penetration, solar obstructions, incidence angle, and glass solar optical. *Shading necessity* can be determined through various high-quality indexes (PMV, etc). In general, if the associated thermal space, without mechanical cooling or heating, is cold then shading is undesirable; otherwise, shading is beneficial. *Shading relevancy* can be determined by simple geometrical projections, considering solar angles; and the spatial relationship among theoretical cells, proposed shaded objects, and solar obstructions.

Mathematically, *shading effect* can be represented with the units of $W/m^2/h$; *shading-necessity* by a positive sign (+) when shading is beneficial and a negative sign (-) when shading is undesirable. Several coefficients can be attached to this sign (as daylight saving, etc.). *Shading relevancy* value can be represented by the value of 1 (relevant) or 0 (non-relevant).
Then, *momentary shading importance* can be determined multiplying these values as follow:

$$[(W/m^2/h) \times (+\% \text{ or } -\%) \times (0 \text{ or } 1)] = \pm W/m^2/h.$$

Finally, the *overall shading importance* of each theoretical cell can be calculated by accumulating all its *momentary shading importance* values. Adding positive and negative values, the sum is the mathematical difference. Higher difference represents higher degree of importance to provide either shade (-) or solar penetration (+).

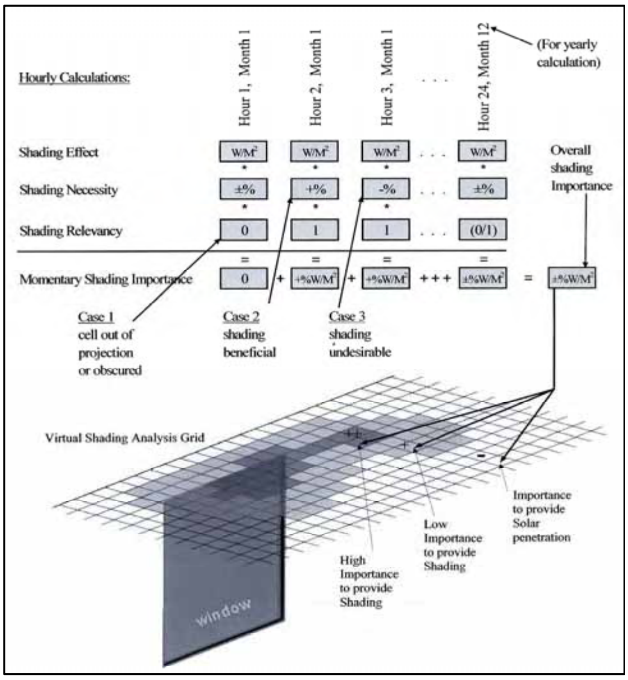

Figure 2: The cellular shading method model.

3. INTEGRATION WITH ECOTECT

The *cellular method* for optimal shading design recently has been implemented within the Ecotect software - a dynamic thermal analysis simulation tools which integrates a 3D modeling interface with a wide range of performance and shading analysis.

3.1 Direct Integration

Ecotect's Project Shading Potential tool based on the point cloud ray-trace method (Marsh, 2003) was extended to include the *cellular method's* concept of accumulating shading information within small theoretical cells. This is accomplished by an analysis grid assigned to proposed shading objects or outdoor space. During a selected period, the grid accumulates a weekly average of recorded direct and diffuse values of hourly solar radiation passing through these theoretical cells and reaching selected shaded objects (windows, walls, etc.). Each hourly time step, the radiation intensity is added to the grid cells included within the projection of the selected shaded objects towards the Sun. The data for solar radiation can be obtained either from the attached weather file or from ideal clear sky data. The numeric results, stored in their three dimensional locations, generate a colored scaled map indicating areas with different relative shading potential (Fig. 3). Areas of high solar intensity indicate a higher requirement to provide shading; whereas lower intensity areas enable designers also to make judgments based on other design factors.

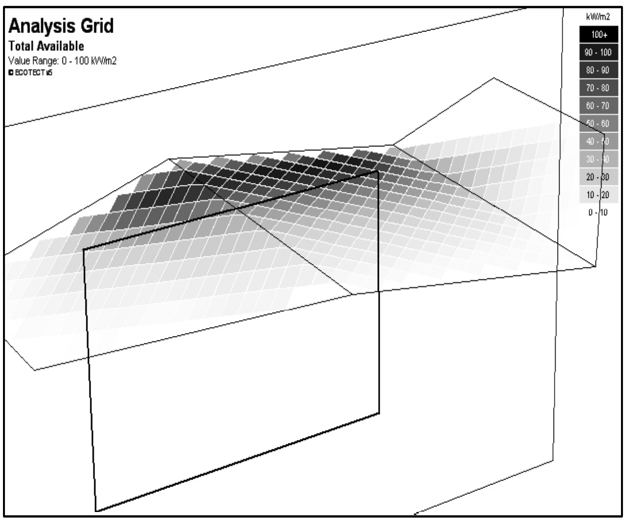

Figure 3: Direct integration within Ecotect.

3.2 Plug-In

Beside the *cellular method's* direct integration, an external plug-in was developed, further extending Ecotect’s capabilities. The *cellular shading method plug-in* enables designers to account for indoor hourly thermal requirements of shading and solar penetration. These requirements can be determined from predicted hourly heating and cooling loads or from fluctuating internal comfort levels. As a result, shading device optimization ensures a weighted optimal solution, accounting for both needs for solar shading during overheated periods and solar penetration during under-heated periods. The plug-in connects to Ecotect and performs a calculation procedure in three major steps, *solar potential, shading need*, and *shading projection*.

The first step of *solar potential* calculates the potential direct (and/or diffuse) solar radiation admitted through selected windows (or received on other selected shaded objects such walls). This amount of solar would be later either admitted or eliminated according to the decision to include the particular theoretical cell in the final shape of the shading device. Data is collected for all time steps in different tables (hours/weeks) assigned for each selected shaded object (Fig. 4). Such tables also enable the plug-in to import external data. *Solar potential* is not accounting for the shading effect of proposed shading devices and other obstructions. As a result, it reflects the full solar potential. Such an approach is important since as long as we do not finalize the shading devices shape, the full solar/shading potential is still relevant.

Calculations include hourly direct radiation from a weather file multiplied by the cosines of solar incidence angle with the selected shaded objects. In case the selected object is glass, it is also modified by its transmittance and refractive index according to incidence angle.

The second step of *shading need* evaluates if solar radiation is beneficial or undesirable to the selected zone during a particular hourly time step, according to one of the following criteria: heat gain and losses, thermal comfort, and zone temperatures. It utilizes Ecotect's thermal simulation and one of the following indexes: comfort PMV (N.DR and D.R), thermal neutrality, adaptive free run, adaptive average, and percent dissatisfaction. The data is arranged in a table (hours/weeks) (Fig. 5), which can also be imported from external data generated in other thermal simulations tools. This step accounts for all solar obstructions, including the shading effect of proposed shading devices. *Shading need* is assigned with a positive sign (+) when shading is beneficial and a negative sign (-) when shading is undesirable.

The third step of *shading projection* projects shading requirements from steps 1 and 2, *solar potential* and *shading need*, onto Ecotect's shading analysis grid. Each time step, a geometrical analysis is conducted to determine the relevant grid cells. Relevant cells are those which would shade the selected objects during this particular time step if they were included within the final shading devices shape. They are located by projecting numerous vectors from the selected objects towards the sun and finding their intersections with the grid cells. In addition, these vectors accumulate the transparency level of the surrounding solar obstructions along their path; not accounting for the proposed shading devices. Each relevant grid cell is assigned with the cumulative transparency level of its relevant solar obstructions (from 0 for complete obstruction to 1 for complete exposure). Then, at each hourly time step, all relevant grid cells are assigned with *solar potential* and *shading need* values stored in the relevant tables (according to the selected shaded object which the vector is initiating from). At this point, *shading need* values can be adjusted with a coefficient accounting for the difference in energy usage between cooling and heating. Upcoming developments would enable the application of other coefficients, accounting for daylight saving, partial shading, occupancy schedule, etc.

The process of step 3 is repeated for all time steps of the analyzed period (Fig. 6), while data accumulation is taking place at each grid cell. The grid cells final data is presented as a color-mapped surface. One color indicates the importance of providing shade and whilst the other color indicates the importance of allowing solar penetration. The cells' color intensity is interpolated between the two based on its value.

For better results, after redefining or designing the proposed shading devices, the entire process, starting from step 1, should be re-run several times, since each time the *shading need* in step 2 is refined according to the new shading effect of the redefined proposed shading devices.

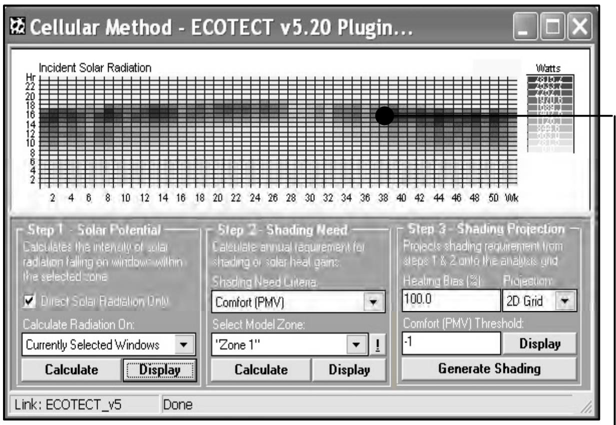

Figure 4: Plug-in's first step of solar potential.

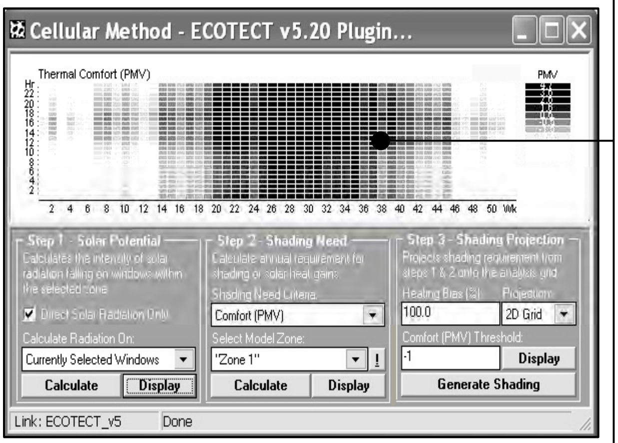

Figure 5: Plug-in's second step of shading needs.

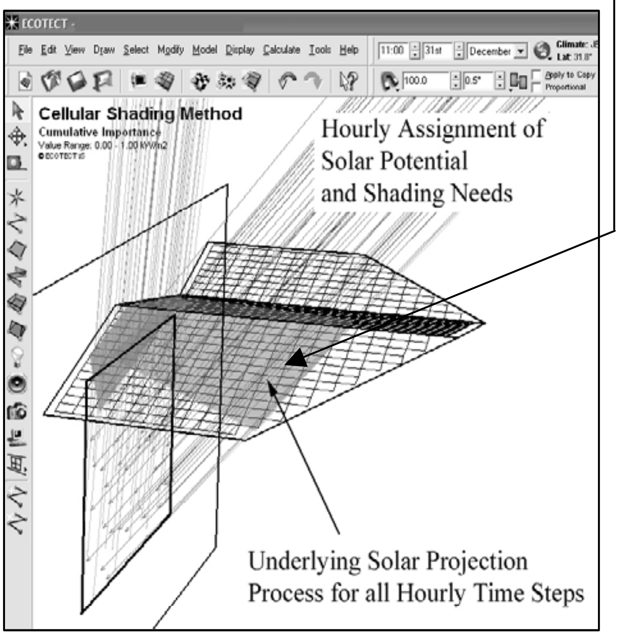

Figure 6: Plug-in's third step of shading projection.

4. LEADING ADVANTAGES

4.1 Considering Shading and Solar Gain Needs

Integrating the cellular shading method with a thermal simulation tool enables consideration of both needs for shading and solar gain in any thermal space. Thus the over-shading problem generated by most methods - since they consider the need only for shading - is addressed. In many regions, winter heating and artificial lighting loads should greatly influence shading device shape. For example, conventional methods based on the cut-off date are designed to provide complete shading in hot periods. However, as a result they provide only partial solar gain in cold periods and reduce daylight.

The integration the cellular shading method with thermal simulation also allows matching the shading device optimization to the shading and solar gain requirements of any particular thermal space. This is very important since building properties (such as materials, geometry, orientation, internal gains, etc.) and occupants clothing and activities can significantly influence the needs for cooling and heating. Therefore, it is not always obvious exactly when solar gain may be desirable within a particular space and when it should be excluded. Furthermore, in complex buildings the thermal performance of many spaces can be often counter-intuitive.

The cellular shading method can also account for detailed schedules of shading requirements. In fact, the more time steps are evaluated, the more accurate the final shading devices shape.

4.2 Handling Complex Geometry

Integrating the cellular method with three dimensional solar simulations can accommodate geometries of any complexity, including multiple windows of any shape and any number of surrounding solar obstructions. This allows for exceptionally accurate shading device spatial forms, since outdoor spaces can be sampled with any level of precision. In fact, the more theoretical cells are examined in a space, the finer the resolution of the shading device shape.

4.3. Accounting for Detailed Climatic Settings

Integrating the cellular shading method with dynamic thermal simulation also allows the consideration of detailed local conditions such as regional, seasonal, and diurnal variations in received solar radiation. Such variations are especially important since fixed shading devices have both positive and negative effects, varied in their degree, on thermal and visual comfort as well as energy conservation. The use of hourly weather data, dynamic shading and thermal calculations in Ecotect mean that shading and solar gain needs can be closely matched against the local environment's ability to meet them.

4.4 Accounting for Variations in Shading Effects

The use of local hourly solar radiation data from weather files and Ecotect's dynamic solar calculations enables, through the cellular approach, accounting for variations in the potential shading effect among outdoor locations. Each outdoor location at each particular time holds different shading effect values, which are determined according to solar availability, geometrical configuration, materials properties of associated building envelope, and surrounding solar obstructions. The final graded mapping provides realistic information of localized shading importance.

4.5 Enabling Designer High Level of Flexibility

The cellular shading method operating with Ecotect's 3D interface and the graded mapping enables designers more flexibility in determining shading device shape. Such mapping enables designers including within the final shading devices shape areas with a high degree of importance to provide shade; while excluding areas with a high degree of importance to provide solar penetration. By these means, designers can apply other important considerations (structure, aesthetics, cost, etc.), yet obtaining a relatively high degree of thermal comfort and energy conservation. Furthermore, proposed shading devices can be modified and constantly re-evaluated by the cellular method, directing designers towards the optimum solution for their specific needs.

5. UNDERWAY DEVELOPMENTS

5.1 Space Shading Analysis

The cellular shading method analysis is not limited only for proposed shading devices; it can also be applied to a spatial volume. Analyzing a full 3D volume enables great flexibility in determining the shading device forms. In fact, once a given volume is evaluated, an infinite number of potential forms for shading device can be determined; still providing the same optimal shading performance. In order to establish a comprehensible visual presentation and a spatial design technique, a unique volumetric mapping is being developed. Such mapping involves generating iso-surfaces separating spaces with similar degrees of importance to provide either shade or solar penetration (Fig. 7-L). These surfaces are arranged naturally like onion layers. A navigator will enable designers to travel through separating surfaces. Geometric snapping to these surfaces would enable users to modify or create shading devices in a 3D virtual space according to grid data.

5.2 Shading Device Design Automation

An automatic optimization of a proposed shading device is also under development. This tool will perform localized optimization of each node in a proposed shading device, according to nearby theoretical cells evaluations (Fig. 7-R). Search distance would be able to be set. Then the auto-adjust process would move the selected nodes according the evolving evaluation results.

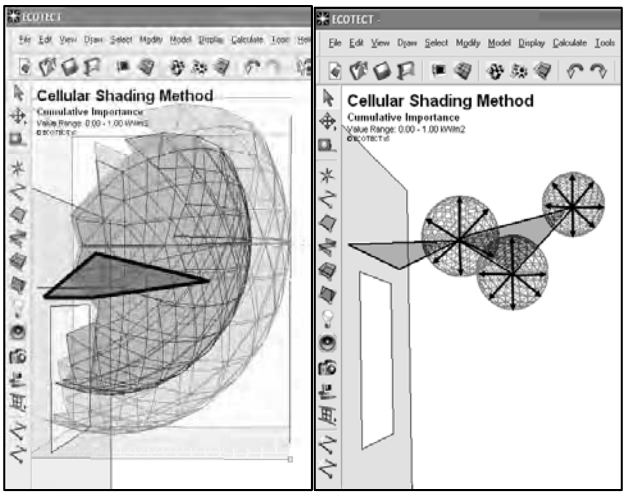

Figure 7: "Onion layers" diagram for space analysis (left); node automatic optimization diagram (right).

6. CONCLUSIONS

Linking the cellular shading method directly to a thermal analysis simulation provides for an unprecedented level of shading optimization - tailoring the shape and/or transparency of each area of a shading device to its specific window and associated space. The cellular approach enables consideration of numerous significant parameters which have not considered before.

As a result, the optimized shading device ensures an optimal weighted solution considering both needs for solar shading during the overheated period and solar penetration during the under-heated period.

The importance of such a development is that it provides an innovative performance-based design approach, guiding local envelope optimization for maximum energy conservation. Generative solutions to performance related design problems are an important step towards energy conservation and sustainability.

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