THERMODYNAMICS OF THE MICROCLIMATE:
EFFECTS OF EXTERNAL ELEMENTS ON INTERNAL HEAT GAINS

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ABSTRACT

Urban energy concerns caused by phenomenon such as the heat island effect are increasing in importance and can no longer be ignored. Energy consumption in such urban areas is being adversely affected by local environmental conditions. Previous research has shown that the microclimate has a measured impact on a building’s internal energy performance. This research focuses on modeling aspects of the external microclimate for building energy consumption using a combination of simulation tools and manual calculations. Specifically, the development of a Visual Basic tool to study the effects of landscape on building fenestration is described.

The authors have identified the following issues as part of the study boundary: sun angles, shading and insolation; vegetation placement and characteristics; paving and roofing materials; windows and building assemblies. Field experiments with handheld instruments were done to study behavior of material properties when exposed to solar radiation in the external environment. Using a case study approach, simulations utilized a number of existing software tools based on the strengths of each program. The results from measured data and software predictions were compared for validation and to form initial conclusions. Some of the key recommendations of the ongoing research focus on strategic interventions around buildings and large paved areas such as parking lots.

ANALYSIS OF SOLAR HEAT GAIN

This paper is an attempt to identify the thermal analyses required on the exterior of a building in order to reduce heating, ventilating, air conditioning and refrigeration loads inside the building. This is a step towards a performance based approach as against a purely systems based approach to achieve thermal comfort. Through the medium of this paper, the authors argue that passive design principles can be objectively applied in a project specific context to not only make a building energy efficient, but to also help mitigate urban conditions such as the heat island effect. Specifically, through the use of strategically placed landscape elements, mutual shading of buildings, reflective coatings on rooftops, and careful selection of building and paving materials; a better thermal environment can be achieved. The processes described here are for the benefit of modern designers who are surrounded by a plethora of simulation tools that can be used to produce meaningful analysis. They form a roadmap to be followed to utilize the given site and climate conditions to the best advantage through informed decisions at the drawing board.

Other complementary analyses used during this process are also helpful in improving the design and performance of a building. For example a daylight distribution study can be done while evaluating the solar heat gain on a facade, which is used for determining the appropriate shading system and thus also provide a better daylight distribution in the building – balancing light, shade and external views at the same time. Reducing non-porous pavement areas to plant more landscape elements helps reduce heat absorbing surfaces in the exterior environment as well as allowing more water to be able to percolate through the soils – recharging the aquifers. An insolation analysis to determine the amount of incident radiation on a surface also helps decide the best possible locations for photovoltaic panels.
It is based on such results that the methodology of conducting a comprehensive study including the internal thermal comfort analysis and the external microclimatic thermal analysis is proposed.

**Solar Angles, Shading, and Insolation**

Solar heating loads are a major contributor to the heating up of the built environment. It is imperative that the building orientation and geometry are location specific. Additionally, plotting solar azimuth angles for different times of the year is an indispensable tool for determining the location of windows and openings. Shading structures including overhangs, fins and louvers are recommended for reducing excessive heat inside the building. A ratio of louver spacing to depth of 1:1 was found to be the most effective in balancing solar shading with daylight distribution on a horizontal louvered facade.

Another important aspect is mutual shading of buildings. While plotting the insolation available on the exposed surfaces of a building in an urban setting, it was found that with mutual shading of buildings overheating effects can be significantly reduced. The insolation analysis also showed the locations where potential photovoltaic panel installations could occur along with the availability of sunlight on them.

Field measurements were done through hand-held instruments in addition to comparing values from existing databases for material properties that can be used directly for such analysis. Quantities such as albedo, emittance, reflectance and Solar Reflectance Index have the most impact and were measured or calculated.

<table>
<thead>
<tr>
<th>Point</th>
<th>Air Temperature (°F)</th>
<th>Surface Type</th>
<th>Material</th>
<th>Emittance</th>
<th>Reflectance (%)</th>
<th>SRI</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>-</td>
<td>Parking Lot</td>
<td>Asphalt</td>
<td>0.95</td>
<td>24.14</td>
<td>27</td>
</tr>
<tr>
<td>B</td>
<td>-</td>
<td>Car on Parking Lot</td>
<td>Metal</td>
<td>0.2</td>
<td>44.34</td>
<td>16</td>
</tr>
</tbody>
</table>

**Paving and Roofing Materials**

Highly reflective roofs reduce the amount of heat absorbed and keep the building cool. Green roofs absorb the heat and through evapotranspiration convert the sensible heat to latent heat of fusion, thereby reducing temperatures. Depending on the climate type, a thermal lag may be desirable. However, surfaces that absorb a lot of heat also increase the amount of heat transmitted through them – causing higher temperatures both outside and inside. This factor needs to be controlled for the heat balance to work in favor of energy efficiency and excessive overheating of the exterior environment.
The same principal applies to paving materials in the urban environment. With less green areas and more paved areas, the amount of surfaces emitting heat increases and accordingly the temperature around them also increases. Thermal properties of paved materials can make a huge difference. For example, asphalt tarmac can emit a lot more heat than a concrete pavement.

**Window and Building Assemblies**

The envelope of the building is the separation between the inside and the outside. However harsh the conditions outside, the objective of any designer is to maintain comfortable conditions on the inside. This requires an evaluation of the physical and thermal properties of an external wall section as well as individual components such as the windows and the different walling materials. A set of building assemblies was evaluated using IES-VE© to study the effects of thermal mass, time lag and heat transfer.

![Figure 5: Thermal loads across a building assembly](image)

This analysis also tells us how much heat is reflected, absorbed, transmitted and emitted by the building surfaces. This is important to evaluate the thermal conditions of the inside as well as the outside of a building. Product selections for walls, roofs and windows can be greatly influenced by such material properties.

Following this methodology of studying different heat retaining components in and around buildings, the authors concluded that the microclimate around a building can benefit the most from cooling sources, notably from vegetation nearby. Vegetation provides much needed shade and evapotranspiration based cooling. This helps reduce the impact of solar gain on built surfaces and provides a cooling effect in the external microclimate. A simulation tool was developed to study the benefits of vegetation. The remainder of the paper describes the development of this tool.

**SIMULATION TOOL FOR VEGETATION**

As building energy consumption, performance analysis and simulation software tools become increasingly prominent in the industry, surprisingly few programs incorporate the effects of landscape on a building’s energy performance. It is clear from previous research that landscape can have a significant impact on a building’s energy use.

In the United States, buildings account for roughly 40% of the total energy consumption, with residential buildings comprising roughly 55% of that total (US EPA, 2004). Considering these statistics, the residential market presents a viable segment for a computer-based tool that evaluates the effectiveness of landscape on reducing solar loads. Such a tool can become a valuable resource for individuals and designers who seek to adopt or suggest alternative and passive strategies around a residential property.

**Scope and Boundary**

The authors focused the scope of the tool on existing low-rise residential buildings in the United States. Specifically for the tool, single story single-family detached homes in the boundary of the hot-arid climate of Los Angeles were studied. Energy efficient landscape for this particular climate prescribes shading (for subsequent reduction of solar energy and heat gain) as the primary objective. It was found that in particular, insolation gained through fenestration surfaces presents the main area of improvement in using shade trees.

**Program Development and Structure**

Visual Basic was selected as the program development language since it is an event-driven programming language, meaning that the operation of the program is determined by events. This is suitable since the execution of the program requires the user to provide inputs and make selections that, in turn, cause the program to execute algorithms. The program was developed in a linear manner, with each successive user interface using inputs from previous screens and obtaining information from the user to be used later. The following image identifies the interaction between the program forms, modules, and databases.
Information required for calculations that is not provided by the user, such as climate data (in the form of TMY3 weather data files) is stored and called from a database.

In order to determine the savings that can be achieved from the shade provided by trees, it is necessary to determine the shade pattern cast by the tree(s), to compute the shaded and unshaded areas on the window surface, and finally to calculate the instantaneous heat gain through fenestration surfaces.

The user is guided through a series of screens prompting them to input information on building dimensions, fenestration construction, window placement, as well as tree selection and tree placement adjacent to the house. The user is provided with a list of pre-determined tree species, native to Los Angeles. Information for these trees, such as transmissivity, mature tree height, and canopy size are also stored in a database. Variable transmissivity values are also necessary since the trees selected are deciduous and thus without leaves for roughly half of the year.

Two separate sets of cooling load calculations are performed for each window: instantaneous loads without shade and instantaneous loads with (if any) shade. Both sets of calculations are performed hourly based on TMY3 data using values for direct normal irradiation. The instantaneous load calculations without shade are performed using the same value for direct normal irradiation, given for the particular hour, over the entire area of the window. The instantaneous load calculations that consider shading from the tree incorporate a scanline algorithm to determine which portions of the window are in shade and thus which portions are receiving less direct normal irradiation due to this shade.

**Program Function and Calculations**

For each hour, the building is rotated through a set of matrix transformations using sun altitude and azimuth so that it is in line with the sun. This yields a model and calculating problem in only 2-dimensions as opposed to 3-dimensions. The building is represented as a cubic/rectangular volume defined by a set of 8 distinct points, with each window being defined by a set of 4 points, each having specific (x,y,z) coordinates. The points are first rotated about the z-axis via application of a matrix transformation based on solar azimuth angle, and then tilted around the x-axis via application of a second matrix transformation involving the solar altitude angle. These calculations are as follows:

**Azimuth transformation:**

\[
[M1] = \begin{bmatrix}
\cos(\Phi) & -\sin(\Phi) \\
\sin(\Phi) & \cos(\Phi)
\end{bmatrix}
\]

**Altitude transformation:**

\[
[M2] = \begin{bmatrix}
\cos(\beta) & -\sin(\beta) \\
\sin(\beta) & \cos(\beta)
\end{bmatrix}
\]

In the above equations, \( \sqrt{\gamma} \) represents the solar azimuth angle, and \( \Psi \) represents the solar altitude angle. The same transformations are used to rotate the points defining the tree polygon.

Next it is necessary to determine whether or not each respective wall plane is facing the sun. It is possible to obtain this information through the use of the surface solar azimuth angle, given as follows:

\[
\gamma = \Phi - \Psi
\]

In the above equation, \( \gamma \) is the surface solar azimuth angle, \( \Phi \) is the solar azimuth angle, and \( \Psi \) is the surface...
azimuth angle. If the surface solar azimuth angle is greater than 90° or less than -90° then the surface is in the shade, and thus the wall surface is not facing the sun. Since the sun’s position is constantly changing as it rotates around the house, it is necessary to evaluate the surface solar azimuth for each wall plane at every hour.

Once it has been established whether a particular wall plane is facing the sun, it is necessary to map the projection of the shadow created by the tree onto the wall in order to determine if the window is shaded or unshaded. Since the building and the tree have been rotated to be in line with the sun, the tree canopy and window become a set of two-dimensional overlapping polygons. The scanline algorithm then scans across these polygons in a series of horizontal slices to determine the percentage of tree canopy shadow falling on the fenestration surface. The process is essentially like approximating the area of polygon via the use of an integral. The concept is shown in the following image.

Hourly instantaneous heat gain for both the unshaded and shaded scenarios are then calculated over the course of the entire TMY3 data year to determine annual energy reduction from the presence of tree shade. The instantaneous heat gain calculation is as follows:

\[
Q_{\text{Shaded}} = U \times A_{\text{Total}} \times (T_{\text{out}} - T_{\text{in}}) + \text{SHGC} \times A_{\text{Shaded}} \times \tau \times ((E_{\text{DN}} \times \cos(\Theta)) + E_d) + \text{SHGC} \times (A_{\text{Total}} - A_{\text{Shaded}}) \times ((E_{\text{DN}} \times \cos(\Theta)) + E_d)
\]

where:
- \(Q_{\text{Shaded}}\) = instantaneous energy flow (Btu/h)
- \(U\) = overall coefficient of heat transfer (Btu/h*ft²*°F)
- \(T_{\text{in}}\) = interior air temperature (°F)
- \(T_{\text{out}}\) = exterior air temperature (°F)
- \(A_{\text{Total}}\) = total projected area of fenestration (ft²)
- \(A_{\text{Shaded}}\) = total projected shaded area of fenestration (ft²)
- \(\text{SHGC}\) = solar heat gain coefficient
- \(\tau\) = transmissivity
- \(E_{\text{DN}}\) = direct normal radiation (Btu/h*ft²)
- \(E_d\) = diffuse sky radiation (Btu/h*ft²)

The final screen in the program displays expected annual savings. The screen shows both unshaded and shaded scenarios on a color coded graph, along with a numerical value for estimated energy savings. The screen is shown in the following image.

SOFTWARE RESULTS VERIFICATION

The program code and outputs were verified through a series of exercises comparing code function and outputs to previously published research as well as industry standard software, such as Microsoft Excel, HEED®, MATLAB, and Ecotect®.

Tree Polygon and Scanline Verification

Microsoft Excel was used to verify tree polygon formation and scanline algorithm function. A square box of 6 x 6 dimensions was plotted along with the tree polygon. The square window polygon was then moved around to various locations to test the performance of the scanline algorithm by comparing calculated shaded area values in Excel to those produced in Visual Basic. The images below show a sample test.
MATLAB was used to verify the function of the matrix transformations (azimuth and altitude rotations). A rectangular volume defined by 8 points in 3-dimensional space was rotated through various angle rotations. The results in MATLAB were compared to those outputs provided by Visual Basic and hence confirmed the functionality of the program.

**Instantaneous Heat Gain Verification**

The software program HEED (Home Energy Efficient Design) was used to verify the instantaneous heat gain calculations through unshaded fenestration surfaces. Buildings of similar dimension and construction were modeled in both HEED and the Visual Basic program. Annual and single day heat gain outputs of both programs were compared for east, west, and south-facing fenestration. The images below show sample output graphs for HEED (above) and the Visual Basic program (below) for a south-facing window.

![Figure 10: Program Scanline Algorithm Test](image)

![Figure 11: HEED Annual Energy Gain for South Window](image)

The two graphs are comparable in shape as well as in peak heat gain (4.38 kBtu/hr for HEED compared to 4.5 kBtu/hr output by the Visual Basic program).

**Tree Shading Analysis Verification**

The verification of tree shading analysis was done using Ecotect. The shadow casting capabilities of Ecotect were used to verify the percentage shading of overlapping tree and window polygons after the matrix rotations were applied. The image below shows a sample test comparing a projection formed in Excel to one produced in Ecotect.

![Figure 13: Program vs Ecotect Shading Verification](image)

These tests yielded similar visual results and shaded percentages, verifying that the Visual Basic program function was acceptable. Finally, Ecotect was also used to verify insolation (or solar heat gain) through window surfaces. The table below shows a comparison between Ecotect and the Visual Basic program for 3 different window surfaces for 3 different days.

<table>
<thead>
<tr>
<th></th>
<th>ECOTECT</th>
<th>VISUAL BASIC</th>
<th>ECOTECT</th>
<th>VISUAL BASIC</th>
<th>ECOTECT</th>
<th>VISUAL BASIC</th>
<th>ECOTECT</th>
<th>VISUAL BASIC</th>
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</thead>
<tbody>
<tr>
<td>ROOF</td>
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<td>5.954</td>
<td>5.727</td>
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<td>5.727</td>
<td>5.954</td>
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</tr>
<tr>
<td>SOUTH</td>
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<td>7.062</td>
<td>7.382</td>
<td>7.062</td>
<td>7.382</td>
<td>7.062</td>
<td>7.382</td>
<td>7.062</td>
</tr>
</tbody>
</table>

![Table 2: Program vs Ecotect Insolation Analysis](image)

Results were, again, comparable which further verified program function.

**Savings Verification**

Finally, the program savings outputs were compared to previous written research publications (McPherson, 1993, McPherson et al., 1996, and Akbari et al., 1987). Studies were chosen that evaluated the effects of single trees on single-story residential buildings in hot-arid
climates. Although slight differences existed in the method of simulation analysis, for instance one study utilized DOE2.1-C so trees were approximated as exterior shades (Akbari et al., 1987), the results are still useful for verification. Percentage savings were calculated for a number of tree locations and results examined. Percentage savings values for the all three research studies were comparable to the program’s outputs, with trends in increased or decreased savings based on tree locations being very similar. Any discrepancies existing could be due to different algorithms, capabilities for simulation, or assumptions and methodology used.

From the above verification exercises presented in this section, it can be concluded that the Visual Basic program performed an accurate and acceptable analysis.

Finally, the program has the capability of being expanding to include more climate zones, species, and also to accommodate a greater number of windows and trees in the yard.

CONCLUSIONS
This paper summarized the research efforts of the authors to evaluate the effectiveness of simulation tools and field measurements on quantifying the impact of various passive design principles to reduce building solar loads and hence energy consumption. The results and measurements obtained, along with the Visual Basic tool developed, contribute to and further expand the growing field of academic work and research that supports the viability of passive design in energy conservation.

The above research clearly shows the effectiveness of passive strategies such as landscaping, shading, as well as choice of building and paving materials to demonstrate a need for further application and development. This research is a work in progress and the authors aim to continue their work for passive design analysis.

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