A MODELLING METHOD TO ASSESS THE EFFECT OF TREE SHADING FOR BUILDING PERFORMANCE SIMULATION

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ABSTRACT

Increasing urban tree numbers is a simple but effective means to provide climate change adaptation to the urban environment by reducing the thermal load on buildings. To better communicate and value the importance of urban trees it is necessary to quantify these benefits and to understand the properties and processes that influence the magnitude of these benefits. For this we need verified and effective ways of modelling the trees in modelling software.

This paper presents the results and problems encountered when trying to model trees effectively. The aim is to present our approach which was to treat the shade as a shading co-efficient on the wall. This allows for the consideration of the benefits of deciduous versus evergreen species. A modelling method to assess the effect of tree shading was developed and presented in this paper.

Key words: thermal simulation, solar thermal load, modelling of tree shading

INTRODUCTION

There are three studies that provide significant precedents with specific regard to the cooling energy savings achieved through tree shade. These include the 1996 simulated study by Simpson and McPherson, the Akbari et al. 1997 small-scale study of two houses in California, and the 2009 study of 460 single family homes in California by Donovan and Butry. Nikoofard et al. 2011 recommended that external shading effects need to be accounted for in modelling residential energy consumption. These studies document the impact of tree shade on the cooling energy demand through theoretical and empirical data across small, medium and large scales.

The results correlate well and provide evidence that data obtained from both controlled studies and from simulations is relatively consistent and can potentially provide the basis for reliable forecasting of the value of strategic tree planting within the urban environment.

Akbari, Bretz and Hanford showed seasonal cooling energy savings of 30% (4 kWh per day) and estimated peak demand savings of 0.7 kW per house in their study (Akbari, 1997). Simpson and McPherson reported that shading on the west side of houses showed the highest reduction in cooling energy demand and that adding two shade trees on the west and one on the east of a house would reduce annual cooling costs for the house by between 10-50% (Simpson 1996).

Donavan and Butry provide data that supports simulations and previous studies in this area. A simulated application of their method to the Akbari et al. study in California shows forecasted savings to be consistent with measured savings. They stated that morning shade is of little value as it is provided during hours when air-conditioning is not typically required while western shade offers the greatest value (Donovan and Butry 2009). This assumption discounts the value of eastern surface temperature reductions, which may contribute significantly to the daily reductions. Given the nature of our study we will be able to quantify the value of east façade shading in relation to the total daily reductions and to peak energy demand. Donavan’s study also considers crown size and distances of trees from the buildings in order to determine their impact on energy reduction. A system was required to normalize the classification of buildings, sites and tree cover as they measured the benefits of existing tress at some 460 locations. As this study was intended to close the gap between large-scale simulations and small scale empirical testing it is understandable that the complexity of the study required much assumption and extrapolation of collected data. It presents good evidence that simulated results provide realistic forecasts for actual energy savings achieved through strategic planting of shade trees.

Akbari et al. conducted an experiment where 16 deciduous trees, eight at 6 meters tall and eight at 2.4 meters tall, were placed on the east and west of two similar houses in California. Data included air conditioning electricity use, indoor and outdoor dry bulb temp and humidity, roof and ceiling surface temperatures, inside and outside wall temperatures,
insulation, and wind speed and direction. They reported up to 25% reductions in outside surface temperatures as a result of shading and a reduction in wind speeds of up to 16%. The experiment produced 96 days of complete data out of the 129 days of measuring. Air conditioners were continuously on, windows were always closed, and lighting electricity use was strictly controlled. They identified two major flaws in their data collection. Firstly, thermocouples would lose adhesion with external surfaces, which meant that temperature readings were not of the surface but of the pocket of air that formed between the thermal couple and surface material. The second flaw was that ceiling mounted sensors indicated rising temperatures even after the outside temperature was falling or the air conditioning was operational. This was due to direct solar gain and/or convection, depending on the placement of the sensors. This study is very close in nature to our own and therefore will provide a valuable point of reference against which to compare results and findings.

The precedents highlight the importance of isolating the effects of tree shade in order to quantify the energy savings. A possible flaw in existing data is human behavior as the actual energy consumption was measured. As we have removed the human element there is an opportunity to have significantly more control over the test environment and consequently, to obtain more specific information about the internal temperatures and energy demands.

The value of shade during summer was relatively consistent between the studies, with all reporting or forecasting an average annual energy saving of around 30%. These studies took place in Sacramento, California, which is a Mediterranean climate (Koppen Csa) and typically produces hotter summers and colder winters when compared to the climate of Melbourne. It can be assumed that the same study taken place in a Melbourne would produce lower energy savings due to lower cooling and heating demands. It is commonly understood that energy savings range significantly between tree species, with deciduous trees providing the greatest annual benefit, permitting solar gain during the winter months. The assumption is made that reported benefits of tree shade in these studies refer to the use of deciduous species when referring to annual benefits.

Simulations by Akbari et al. performed in parallel to their field tests indicated that energy savings were consistently underestimated by up to 50% when compared to measured data. This is an indication of the complexity of modelling environmental factors such as tree shade and how assumptions and approximations can significantly affect the simulation results. It is unclear as to the expected margin of error in other simulated studies, however value of simulations in our context lies primarily in the verification of trends within measured data. Used in conjunction with data from controlled field tests, computer simulations provide the opportunity to develop effective predictive modelling and a tool for strategic planting of urban environments.

The investigation into effective methods of tree shade simulation shown here have been undertaken in the context of a field test where a comprehensive data set has been, and continues to be collected for the purpose of long term studies of the effect of shade on annual heating and cooling energy use. A basic explanation of this experiment and its methodology is presented here to define the context within which the field test data is produced. The approach of simulating trees as three dimensional objects has been used in an effort to simplify the input process while allowing the software to account for the shading effects as well as the reduction of wind velocities due to the presence of trees, which can have a significant effect on building surface temperatures. An alternative method of adjusting shading coefficients on the walls to represent the shading effect is also presented, and forms the basis for this paper. The results, methods and limitations of each approach are discussed below.

**METHOD**

The site for this study located in Eastern metropolitan Melbourne with coordinates 37°48′49″S, 144°57′47″E. The moderate oceanic climate results in significant residential heating and cooling loads throughout the year and is an ideal climate for passive design principles. The site context was modelled with test buildings being unshaded in order to compare simulation results against field test data for the purpose of calibrating the digital model and to assess the impact of local shade on each building’s internal temperature. It was found that the small difference in amounts of early morning shade had a negligible impact on the internal temperatures of the buildings. For the purpose of simplifying the computer model and eliminating the influence of varied environmental factors on simulated results it was deemed appropriate to exclude the surrounding trees and buildings from the simulations (Figure 1a and 1b).

![Figure 1a Site model](Image 309x114 to 524x259)
The next challenge was to effectively model the proposed shade trees within Integrated Environmental Solutions’ Virtual Environment software (IES-VE) and to generate realistic results that would be confirmed by measured data. It should be noted that the IES-VE software, while powerful and intuitive, has not been used for detailed studies on external shading at the time of this paper so significant experimentation was necessary in order to establish the appropriate method required to produce the required output. Given the complex geometry of a single tree, and the inherent variations even within trees of the same size and species, it is necessary to abstract their physical form. Limitations within the software required the vector count for modelled ‘trees’ to be as low as possible while our experiment demanded the most accurate representation achievable. It was also necessary to ensure that the effect of indirect solar radiation reflecting off leaf surfaces was included. The solution was to represent a tree canopy with two single circular planes intersecting each other at right angles (refer to Figures 2a, 2b and 3a, 3b).

Solid planes would represent full shade similar to the Golden Ash trees during summer while small perforations amounting to approximately 50% of the surface area of the circular planes would represent the Red Ironbark trees throughout the year. While the perforation areas of 50% and 0% appear arbitrary, they are a reasonable approximation of the shading effect of our test trees during summer and provide a good point of reference upon which conclusion can be drawn and recommendations made.

The properties of building materials, building envelope and operation factors such as blinds, infiltration, ventilation and internal heat gains where modelled to replicate those of the field test with the greatest degree of accuracy possible. Figure 4 illustrates the geometry and materials of the field test buildings while Table 1 lists the critical properties that have been measured, predetermined or assumed, and are consistent between the field test and simulations.
As environmental properties between the field test and computer simulations needed to be consistent it was necessary to construct a weather file from the collected data that could be used within IES-VE. Climate data for the IES-VE software is based on a typical weather year (TWY) however this did not correlate well with the actual weather experienced during the data collection period (an unusually cold and wet summer). This made direct comparisons between simulated results and collected data difficult and often misleading. Once the weather file was constructed calibration of the digital model was confirmed and the necessary adjustments made.

The calibration process is critical as it provides a reference point from which to compare various shading conditions as well as providing the link between empirical and simulated data. Previous studies of this nature have had the element of human behaviour and the variations between subject buildings to consider, and both impact on the ability to quantify the value of shade.(Simpson 1996, Akbari 1997) As these factors have essentially been excluded from our experiment it is reasonable to suggest that with a well-calibrated model meaningful and relevant data will be produced.

Limitations of IES-VE

The IES-VE is a building energy modelling software package intended to inform the design of both buildings and environmental systems across a range of project scales. As its focus is on controlling internal building conditions the use of this software to predict effects of an external and dynamic element such as shade is problematic and requires considerable simplification in the modelling process. The value of the software for our application is in the forecasting the energy savings achieved through a range of shading conditions, extending the empirical research to different scales, densities and contexts.

There are two reasonable approaches that can be used. The first, described above, consisted of abstracting the ‘trees’ producing approximated shading of external surfaces. The shortfall of this method is the lack of accuracy with which the amount of shading is determined. Factors such as leaf reflectivity and emissivity, leaf positions, evapotranspiration and canopy density are not scientifically calculated and represented leading to potential error due to over or under estimation. This is why the values of 0%, 50% and 100% shading were used for the ‘trees’ within the IES model.

Shading coefficients of trees

The second method was to consider the effect of shading as a shading coefficient for the wall receiving shade. The use of shading coefficients for the purpose of simulating the effect of shade has been tested by Jim and He (2011) in their study of estimating the heat flux transmission of green walls and by McPherson and Simpson (1996) in their broad simulated study of the energy saving benefits of urban tree shade. It appears that McPherson and Simpson simulated tree shade by modelling abstracted trees and applying an appropriate shading coefficient to each tree canopy. While there are clear advantages of this approach, an alternative method of simulating shading effect is presented here in the interests of establishing a predictive modelling tool that can be applied to a broader range of situations. By applying a similar approach to Jim and He, average hourly shading coefficients of both the Ironbark and Golden Ash trees from the field test data can be used to establish an adjusted solar absorptance value for external surfaces. This adjusted solar absorptance value mimics the effect of tree shade on external wall surfaces. In order to account for the variation of incident solar radiation throughout the day hourly average data is applied. In the context of IES this is a simple procedure however, separate simulations need to be run for each adjusted solar absorptance value in order to reflect the changes in incident radiation to wall surfaces. The simulated data provides a relatively accurate representation of daily cooling energy use and an effective comparison between species and location of trees is possible.

Shading coefficients of two species of tree were estimated by using ‘Sol-Air Temperature’ (\(T_c\)) for vertical surfaces equation (ASHRAE Handbook 2009).

\[
T_c = T_o + \frac{\alpha E_t}{h_o}
\]  
Eq (1)

Where:

- \(T_o\) = outdoor air temperature
- \(\alpha\) = absorptance of surface for solar radiation
- \(E_t\) = total solar radiation incident on surface
- \(h_o\) = outside air convective heat transfer coefficient

Equation (1) can be rewritten as follows for the wall with tree shade.
Where:
\[ T_{es} = T_o + \frac{\alpha E_i (1 - SC)}{h_o} \quad \text{Eq (2)} \]

The equation can be obtained by combining Equations (1) and (2).

\[ SC = \frac{T_{es} - T_o}{T_o - T_e} \quad \text{Eq (3)} \]

The measured outside wall temperatures were assumed to be same as Sol-Air Temperatures and the time varying shading coefficients were calculated (see Table 2).

The following table lists the adjusted solar absorptance values that were applied to the external walls of the simulated buildings. The unshaded control building (Shed B) has a solar absorptance value of 0.6 for external walls and adjusted values were calculated using the following method:

\[ \text{Adjusted Solar Absorptance} = 0.6 \times (1 - \text{Shading Coefficient}) \quad \text{Eq (4)} \]

**Table 2**

<table>
<thead>
<tr>
<th>Time (Hour)</th>
<th>Ironbark Shed A</th>
<th>Golden Ash Shed C</th>
</tr>
</thead>
<tbody>
<tr>
<td>9:00</td>
<td>0.378</td>
<td>0.360</td>
</tr>
<tr>
<td>10:00</td>
<td>0.426</td>
<td>0.408</td>
</tr>
<tr>
<td>11:00</td>
<td>0.462</td>
<td>0.438</td>
</tr>
<tr>
<td>12:00</td>
<td>0.486</td>
<td>0.450</td>
</tr>
<tr>
<td>13:00</td>
<td>0.498</td>
<td>0.450</td>
</tr>
<tr>
<td>14:00</td>
<td>0.498</td>
<td>0.438</td>
</tr>
<tr>
<td>15:00</td>
<td>0.480</td>
<td>0.408</td>
</tr>
<tr>
<td>16:00</td>
<td>0.450</td>
<td>0.360</td>
</tr>
<tr>
<td>17:00</td>
<td>0.402</td>
<td>0.300</td>
</tr>
<tr>
<td>18:00</td>
<td>0.348</td>
<td>0.222</td>
</tr>
</tbody>
</table>

**RESULTS**

The complexity of accurately representing shading effects through computer modelling is evident in this investigation and it is clear that more work is required in order to produce definitive results across the year. Because of the limitations of the field testing and simulation it is assumed that, like previous studies, the energy saving benefits are underestimated to a some degree. Without the support of extended field test data it is not possible to speculate as to the extent that savings are underestimated here. The research is continuing for the next 2 years to try to reduce these uncertainties.

**IES - VE Simulations**

Using the percentage coverage approach the data shows an increase in winter time heating energy use of 2.1% for the 50% shading and a 4.5% increase for the 100% shading. During the cooling months, from November to March, we saw a reduction of cooling energy by 8.5% for the 50% shading and 11.2% for the 100% shading.

Using the shading co-efficient approach, the simulated data shows the effect on cooling loads of each adjusted absorptance value with reference to the unshaded control building, illustrated by the Figure 6. It is apparent that shade provided to the west faced has almost double the effect on cooling energy reduction than shading to the North and East façade. Surprisingly there is only a marginal reduction in cooling energy use with the denser Golden Ash canopy as compared to the Ironbark trees (Figure 5). However, in the context of annual energy consumption the presence of shade through the use of an evergreen species such as the Ironbark tree has a significant effect on heating energy during winter months as the passive heating effects of solar gain are reduced.

**Figure 5 – showing the decreased cooling requirements for the shaded buildings (7 January 2011)**

The summary of field test results below are achieved from a culmination of both methods. They represent a starting point for further investigation and are assumed to be conservative average energy saving reductions. The dynamic nature of the ‘real world’ result in greater maximum saving and this will undoubtedly be supported by future field test data.

**Calibration of the model**

In order to simulate the impact of tree shade on cooling and heating energy use throughout the year a reliable predictive model is required. The approach taken in this research was to run consecutive studies of both computer simulations and of empirical data collected from controlled field tests. It was assumed that the two studies would validate one another while providing the basis for a predictive model that could be applied to a broader context. However, the complexity of modelling the effects of trees on internal temperatures is significant and output is often only useful in the support of a notional ideas and concepts. Since the study of tree shade is largely an exercise in proving the obvious, it is necessary to develop a specific and relatively accurate predictive modelling tool that can be used to determine actual...
savings to space conditioning energy use through the presence of tree shade.

Calibrating the model raised additional questions about methodology and the appropriate tools for measuring shading effects in the context of this experiment, and without long-term field test data an accurate assessment of the software and inputs cannot be made.

Field test inside temperature data was the control used to calibrate the computer model. The graph in Figure 6 shows inside temperatures of building B from the field test and simulation and indicates some variation between data sources with the IES simulation producing warmer temperatures during warm times and cooler temperatures during cool times. An explanation for this is that while the field test temperature represents a single point in the room the simulation temperature is an average of the whole room. As this includes air adjacent to windows and doors we see a greater variation in overall temperature. The fields test data showed that the location of the sensor was very influential on the reported inside temperature and so it is reasonable to accept these simulated results as rational. Again, it will be necessary to review this against future data and particularly through varied climatic conditions in order to verify its accuracy.

Figure 6. A comparison between simulated and field test inside air temperatures of the unshaded building B. It has been calibrated and variations are due to average overall room temperatures of the simulations.

Sensitivity analysis of increasing the insulation levels
Thermal resistance for the fiberglass batt applied in the test sheds were unknown. It was estimated by using the on-site measured data. The following hourly average measured data were used for the estimations.

- Heat flux across the wall [Wm⁻²] measured at the interface between Fiberglass batt and Masonite board (Sensor: Omega Thin Film Heat Flux Sensor, HFS 4)
- Surface temperature of the outside wall [°C] (Sensor: Omega Infrared Thermocouple, Type K, OS36)

- Indoor air temperature [°C] (Sensor: Type T thermocouple, 30 AWG, Neoflon PFA insulated)

The total thermal resistance of layers 1 to 5 (Table 3) was estimated by using Equation 5.

$$R_{1-5} = \frac{\Delta T_{1-5}}{Q/A}$$

Where:

$$R_{1-5} = \sum_{i=1}^{n} R_i$$

$$\Delta T_{1-5} = T_{wall} - T_{indoor}$$

$$Q/A = \text{heat flux [Wm}^{-2}]$$

<table>
<thead>
<tr>
<th>No</th>
<th>Construction</th>
<th>Thickness [m]</th>
<th>Conductivity [Wm⁻¹K⁻¹]</th>
<th>Conductance [Wm⁻¹K⁻¹]</th>
<th>Resistance [m²KW⁻¹]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Indoor air film</td>
<td>-</td>
<td>-</td>
<td>8.5</td>
<td>0.118</td>
</tr>
<tr>
<td>2</td>
<td>Masonite board</td>
<td>0.006</td>
<td>0.060</td>
<td>10.0</td>
<td>0.100</td>
</tr>
<tr>
<td>3</td>
<td>Fibreglass batts</td>
<td>0.050</td>
<td>0.049</td>
<td>0.98</td>
<td>1.020</td>
</tr>
<tr>
<td>4</td>
<td>Air space</td>
<td>0.030</td>
<td>-</td>
<td>-</td>
<td>0.030</td>
</tr>
<tr>
<td>5</td>
<td>Weather boards</td>
<td>0.020</td>
<td>0.220</td>
<td>11.0</td>
<td>0.091</td>
</tr>
<tr>
<td>6</td>
<td>Outside air film</td>
<td>-</td>
<td>-</td>
<td>24.0</td>
<td>0.042</td>
</tr>
</tbody>
</table>

Total resistance 1.401

The total thermal resistance calculated for the wall is 1.4m²K⁻¹W⁻¹. If we assumed the temperature difference 10°C between the inside room and the outside ambient temperature, the calculated steady state heat flux across the wall is 7.1 Wm⁻². The resultant temperature differences across the wall layers are shown in Table 4. It should be noted that the estimation of properties for the bulk insulation in the wall is critical since it provides about 73 % of the thermal resistance.

Table 4 Temperature differences across the wall layers (To-Ti=10°C)

<table>
<thead>
<tr>
<th>No</th>
<th>Construction</th>
<th>Resistance [m²KW⁻¹]</th>
<th>Temperature difference [°C]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Indoor air film</td>
<td>0.118</td>
<td>0.84</td>
</tr>
<tr>
<td>2</td>
<td>Masonite board</td>
<td>0.100</td>
<td>0.71</td>
</tr>
<tr>
<td>3</td>
<td>Fibreglass batts</td>
<td>1.020</td>
<td>7.28</td>
</tr>
<tr>
<td>4</td>
<td>Air space</td>
<td>0.030</td>
<td>0.21</td>
</tr>
<tr>
<td>5</td>
<td>Weather boards</td>
<td>0.091</td>
<td>0.65</td>
</tr>
<tr>
<td>6</td>
<td>Outside air film</td>
<td>0.042</td>
<td>0.30</td>
</tr>
</tbody>
</table>
Figure 7 shows that the increased insulation levels from R1.4 to R3 will reduce the impact of the shading by almost 20%, for the simulated day. Remembering that 0.6 was the solar absorptance of the unshaded building and 0.36 that of the Golden Ash were most shaded.

Thus, even though the impact is less it is still worthwhile to shade the walls with high solar incidence.

**Other benefits of trees**

Apart from potential energy savings from direct reduction of heat load on the external surfaces of buildings there are other benefits to trees. The first is the impact on the microclimate. Trees reduce the temperature of their general vicinity by evapotranspiration. Particularly relevant to the city where increased temperatures have seen increased physiologcal impact even death, this impact on the reduction of the Urban Heat Island effect is part of the ongoing research of this site (Rosenzweig et al., 2006; Rosenfeld et al., 1997).

Current research also shows that having access and contact with natural elements such as trees will affect the inhabitant positively. That is, they are psychologically, emotionally and physiologically healthier (Wilson, 1984; Kahn and Kellert 2002; Kellert 1993; Kellert, Heerwagen, Mador, 2008; Sternberg, 2009).

**CONCLUSION**

Field tests and simulations have helped to better understand the impact of tree shade on heating and cooling energy, however the broader goal of this research is to provide an effective predictive model with applications across a range of scales and shading conditions. The shading coefficient method presented here draws from empirical data and provides the foundations for such a predictive model, with simulated results correlating well with collected field data.

The research has also shown that there are potential energy savings using trees to shade the external surfaces of buildings, although the species of shade trees impacts heavily on annual heating and cooling loads. For climates such as Melbourne, these benefits are greatest using deciduous trees which allow sun to contribute to passive winter heating.

**REFERENCES**


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