Urban vegetation design recommendation for improving outdoor thermal comfort in tropical and temperate climates

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Abstract
This paper evaluates seasonal outdoor thermal comfort of urban streets with three distinct aspect ratios in temperate and tropical climates. Native evergreen and deciduous vegetations are analysed as the mitigation strategy for each configuration. A hybrid simulation workflow that integrates the Ladybug tool and OpenFoam is employed to assess the Physiological Equivalent Temperature (PET) level. Additional microclimate corrections are performed to capture the effects of vegetation transpiration on air temperature and humidity. Results indicate that vegetation is not always conducive to improving outdoor thermal comfort in every climate. For climates experiencing hot and dry summer such as Lisbon and Riyadh, deciduous trees with large crown size (10m), and higher trunks (8m) are recommended on the leeward side of buildings. In winter, wind protection is essential in Lisbon, narrow street with aspect ratio 2:1 can help reduce air movement onsite. However, vegetation are not recommended due to side effect of shading and transpiration adding more cold stress. In Riyadh’s wintertime, ensuring the solar exposure and air movement can create a comfortable space. Vegetations are only recommended in wind stagnant areas that are fully exposed to the sun. For hot and humid climates such as Singapore, which experience constant high temperature and humidity and moderate solar radiation throughout the year, evergreen vegetation with bigger crown size, lower Leaf Area Index (LAI), and higher trunks are recommended in well-ventilated areas, even though the evaporative cooling benefit from tree transpiration is negligible due to high ambient humidity.

Introduction
The study of outdoor thermal comfort is important because it can help us design outdoor spaces that promote physical and mental health, enhance urban design, address the impacts of climate change, and improve the tourism and recreation industries. By understanding the factors that influence outdoor thermal comfort, such as temperature, humidity, wind, and solar radiation, designers are able to create outdoor environments that are more comfortable and enjoyable for users.

Outdoor Comfort in Urban Area in Temperate and Tropic Climate
Recently many outdoor thermal comfort studies have been conducted in tropical and temperate climates, as these regions often experience extreme weather conditions that can impact human comfort and wellbeing. An objective assessment in Bhopal, India highlights the importance of shade and radiation reduction in attaining thermal comfort in the urban open spaces during the afternoon [1]. Wind activity which facilitates evaporation (heat transfer from the human body to the environment through sweating mechanism) is important too in improving outdoor comfort levels in hot and humid climate [2]. Urban wind speed ranging from 1.0 to 2.0 m/s is recommended for pedestrian comfort in summer [3]. Users can be more sensitive to humidity in certain conditions [4].

For temperate climate, air temperature is typically the most important parameter affecting outdoor comfort, followed by solar radiation and wind speed. Relative humidity and clothing insulation also play a role but to a lesser extent. In summer, PET shows more relevance to the mean radiant temperature. Even though with a lower ambient temperature, exposed to solar radiation still increase the heat stress [5]. The same conclusion has been given by a study in the Netherlands, stating the duration of direct sun and mean radiant temperature plays the most important role in thermal comfort [6].

Urban Vegetation Impact in Outdoor Comfort
Vegetation can provide several benefits in improving outdoor thermal comfort [7,8,9]. Trees and other plants can provide shade against direct solar radiation. In hot and dry climate, trees are capable of cooling down the surrounding area by releasing water through their leaves, which then evaporates to the ambient air and removes heat. Deciduous trees can protect against the direct radiation, thus protecting against the extreme heat stress in hot seasons. During the winter season the situation is the opposite. Leafless trees reduce the extreme cold stress since the incoming radiation at low angles can reach the surface unhampered [10]. Vegetation canopies also block air movement. In tropic climates human thermal comfort is more sensitive to humidity and wind speed, hence the benefit of vegetation needs to be further investigated [11]. Another study focusing on vegetation impact on outdoor thermal comfort has same observation that increasing the vegetation coverage reduces more heat stress then other
parameters (i.e. tree height, Leaf Area Index etc.). However, the increasing humidity related to plant transpiration prevents further reduction of heat stress [12].

Outdoor Thermal Comfort Modelling

Envi-met is a well-established and widely used microclimate simulation software that has been validated through various field experiments [13,14,15,16]. It uses a high-resolution numerical model to simulate the complex interactions between air temperature, solar radiation, wind and humidity. One advanced feature is to model the transpiration of vegetation [17]. However, the excessive simulation time and expensive license are two main drawbacks of ENVI-met.

In the context of the iterative design process, a simulation tool that allows for fast parametric simulation and design optimization is necessary. As a plugin from grasshopper, Ladybug tool harness the parametric capabilities of Grasshopper for Rhino 3D [18] to manipulate multiple design parameters and iterate different geometry configurations. Previous studies have compared the accuracy of calculating Mean Radiant Temperature from different software, Ladybug tool has been proved as most accurate to simulate human body, shortwave radiation and view factors, among other available outdoor thermal comfort tools as CitySim Pro, ENVI-met, RayMan and Autodesk CFD [19]. Accuracy of the longwave radiation depends on the surface temperature of the ground. Ladybug Tools accounts for reciprocity between buildings, and takes into account freestanding objects, and models the ground as an EnergyPlus thermal zone [20]. Material absorption is able to be customized to capture the accurate thermal absorption and radiation from the ground. Compared to ENVI-met, Ladybug tool provides reliable results in a reasonable computational time and is less expensive. It can also optimize design for wind control strategies by incorporating other software capabilities in Grasshopper. [21,22,23,24,25]

Knowledge Gap

There is lack of a systematic study using the same threshold and criteria to evaluate the outdoor thermal comfort in both tropic and temperate climates, and therefore defining the parameters with the most significant effect on outdoor thermal comfort, to aid in providing design optimization strategies.

Meanwhile an improved hybrid simulation workflow is developed and employed to simulate the PET results. Comparing with traditional ENVI-met and Ladybug tool, this workflow is capable to accurately model the vegetation’s impact on wind speed, air temperature and humidity within reduced simulation time and costs

Aim and Objective

This paper presents a hybrid and fast simulation workflow that integrates the Ladybug tool and OpenFoam to analyse the Physiological Equivalent Temperature (PET) levels of the urban streets of three distinct aspect ratios and the potential impact of vegetation under both temperate and tropical climates. The simulation results offer valuable insights for architectural and urban planning, providing guidance on building design and landscaping strategies for outdoor thermal comfort. This approach can inform the iterative design process and enable designers to quickly evaluate various design parameters for effective design optimization.

Methodology

This study uses a hybrid workflow integrating OpenFoam and Ladybug Tool to simulate the Physiological Equivalent Temperature (PET) of the urban streets, innovatively implementing correction methods to capture the transpiration and wind impact of different vegetation species.

Computational Fluid Dynamics by OpenFoam

Computational fluid dynamics is used to simulate wind conditions. A cylindrical fluid domain is selected as per the advantage in saving meshing time [26]. The cylinder’s diameter is 1040m, height is 70m (2.5 times of building height).

![Figure 1 CFD simulation domain](image)

The surface roughness is kept constant for all cases at 0.003. The k-ε turbulence model is used as per its proven ability to accurately predict the average wind flow through buildings [26]. Vegetation is integrated in the CFD model as a porous zone. The porosity is added to the simulation using the Darcy-Forchheimer coefficients, which are calculated from the tree’s Leaf Area Index (LAI) [27,28]. According to OpenFoam terminology, the pressure loss across the trees due to porosity can be calculated using the Darcy-Forchheimer equation:

\[
\frac{\Delta p}{\Delta x} = -\mu U - \rho \frac{|U|}{2} f U \quad (1)
\]

Where \( \mu \) is the air viscosity, \( U \) the air velocity, \( \rho \) the air density and \( d \) and \( f \) respectively the Darcy and the Forchheimer coefficients.

Assuming high permeability, \( d=0 \) and therefore:

\[
\frac{\Delta p}{\Delta x} = -\rho \frac{|U|}{2} f U \quad (2)
\]

Where \( f \) can be calculated as:

\[
f = 2 \frac{LAI}{h} C_d \quad (3)
\]

Where LAI is the leaf area index of the tree, \( h \) its height and \( C_d \) its drag coefficient.

Mean Radiant Temperature by Ladybug Tool

Mean radiant temperature (MRT) quantifies the exchange of radiant heat between a human and their surrounding environment [29]. The approach used to calculate MRT in this study is based on ASHRAE Standard 55 by using
Ladbug 1.6.0 which considers both shortwave and longwave radiation as presented in Equation (4) [30].

\[ MRT = MRT_{sky} + MRT_{short,dir} + MRT_{long,surface} \] (4)

The longwave radiant exchange with the sky depends on both sky temperature and sky view factor, which is specified by Equation (5) [31,32,33]

\[ MRT_{sky} = f_{svf} \left[ \frac{I_v}{\alpha_{lw}} \cdot \sigma \left( T_e^4 - 273.15 \right) \right] \] (5)

Where \( f_{svf} \) is the fraction of sky view in the occupants’ view. \( I_v \) is horizontal infrared radiation intensity (W/m²). \( \sigma \) is Stefan-Boltzmann constant = 5.6697e-8 W/m²K⁴. \( \alpha_{lw} \) is body emissivity (assumed to be 0.95).

Short-wave mean radiant temperature represents radiant temperature from short-wave direct and diffuse solar radiation [34], as shown in Equation (6)

\[ MRT_{short,dir} = \frac{E_{R_{solar}}}{f_{eff}} \cdot \frac{1}{h_c} \] (6)

Where \( E_{R_{solar}} \) is the effective radiant field, which specifies the net radiant energy flux to or from the human body, including both direct and diffuse radiation. \( f_{eff} \) is the fraction of the body surface exposed to environment (0.725 for a standing person). \( h_c \) is the radiation heat transfer coefficient (6.012 W/m²K).

The \( MRT_{long,surface} \) is the overall effect of the surface temperature, as estimated by Equation (7) [35]. Due to limited time and computational resource, this study assumes the surface temperature same to air temperature for fast simulation.

\[ MRT_{long,surface} = T_{air}^4 \cdot F_{P-1} + T_{air}^4 \cdot F_{P-2} + \cdots + T_{air}^4 \cdot F_{P-n} \] (7)

Correction on climate data due to vegetation transpiration

Since the Ladybug tool lacks the ability to simulate the vegetation’s transpiration process, an extra correction step is implemented to adjust the air temperature and humidity. Taking transpiration process as a simple humidification process, psychrometric chart is used to calculate for the ‘treated’ air condition.

![Figure 2 Transpiration process on air temperature and humidity](image)

Physiological Equivalent Temperature by Ladybug Tool 1.6.0

Hoppe [36] defined the PET as the air temperature that maintains thermal equilibrium for a typical internal human condition, assuming consistent core and skin temperatures with the original situation. This index is based on the Munich Energy-balance Model for Individuals (MEMI), which originates from the 2-node model by Gagge et al [37] and incorporates the heat balance equation for the human body.

The heat balance equation for the human body is interpreted by using Equation (5):

\[ M + W + R + C + E_D + E_{Re} + E_{Sw} + S = 0 \] (8)

Where \( M \) is the metabolic heat production (W/m²), \( W \) is the physical work output (W/m²), \( R \) represents net radiation of the body (W/m²), \( C \) is the convective heat flow (W/m²), \( E_D \) is the latent heat flow to evaporate water into water vapour diffusing through the skin, \( E_{Re} \) is the sum of heat flows for heating and humidifying the inspired air (W/m²), \( E_{Sw} \) is the heat flow caused by sweat evaporation (W/m²) and \( S \) is the storage heat flow for heating/cooling the body mass (W/m²).

<table>
<thead>
<tr>
<th>PET/°C</th>
<th>Thermo perception</th>
<th>Grade of physiological stress</th>
</tr>
</thead>
<tbody>
<tr>
<td>≤20</td>
<td>Very cold</td>
<td>Extreme cold stress</td>
</tr>
<tr>
<td>21-4.0</td>
<td>Cold</td>
<td>Strong cold stress</td>
</tr>
<tr>
<td>4.1-1.0</td>
<td>Moderate</td>
<td>Moderate cold stress</td>
</tr>
<tr>
<td>1.1-10</td>
<td>Slightly cool</td>
<td>Slight cold stress</td>
</tr>
<tr>
<td>10.1-2.0</td>
<td>Comfortable/Neutral</td>
<td>No thermal stress</td>
</tr>
<tr>
<td>2.1-2.9</td>
<td>Slightly warm</td>
<td>Slight heat stress</td>
</tr>
<tr>
<td>3.0-3.5</td>
<td>Warm</td>
<td>Moderate heat stress</td>
</tr>
<tr>
<td>3.5-4.0</td>
<td>Hot</td>
<td>Strong heat stress</td>
</tr>
<tr>
<td>4.1-5.0</td>
<td>Very hot</td>
<td>Extreme heat stress</td>
</tr>
</tbody>
</table>

Source: Matzarakis and Mincer (1997)

![Figure 3 PET and thermal perception](image)

Ladybug tool 1.6.0 is used to calculate Physiological Equivalent Temperature (PET) through several inputs. Inputs such as air temperature and humidity are imported from weather file or adjusted by psychrometric chart if the cases include vegetation. Point-by-point pedestrian wind speed on the tested ground surface is exported from Open Foam, meanwhile MRT is simulated by Ladybug tool 1.6.0.

![Figure 4 An improved hybrid simulation workflow](image)

**Simulation Setup**

- **Building models**
  After investigating typical urban grids [38], building height of 28m was chosen, with aspect ratios (height to street width) of 1:1, 2:1, 1:1.5. The test surface is a ground plane measuring 150m x 150m.
Vegetation species and model:
Following research on the native tree species, five species are selected across the tested climates, considering both evergreen and deciduous tree types.

<table>
<thead>
<tr>
<th>Location</th>
<th>Date</th>
<th>Hour</th>
<th>Air temperature</th>
<th>Humidity</th>
<th>Wind-speed</th>
<th>Wind-direction</th>
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<td>57</td>
<td>3.7</td>
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<td>20.4</td>
<td>46</td>
<td>3.7</td>
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<td>37</td>
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<tr>
<td></td>
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<td>11.6</td>
<td>58</td>
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<td>NE</td>
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<td>30</td>
<td>70</td>
<td>3.9</td>
<td>S</td>
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<tr>
<td></td>
<td>Feb 15th</td>
<td>9</td>
<td>33.4</td>
<td>9</td>
<td>3.3</td>
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<td>15</td>
<td>21.2</td>
<td>3</td>
<td>2.6</td>
<td>SS</td>
</tr>
</tbody>
</table>

Table 1 Vegetations as selected for each climate

Table 2 Simulation inputs

Results Discussion

Lisbon

Wind

In Winter, both N-S and E-W streets are ventilated. Narrow streets (Aspect ratio 2:1) provide more wind sheltered area at the SW corner of the site due to more wind blockage. In summer, narrow streets (Aspect ratio 2:1) promote funnelling effects of North prevailing wind on N-S street, reaching up to 5 m/s. Downstream of the first row of buildings causes stagnant area between the two rows.

As expected, oak trees reduce wind speed in most areas during both winter and summer cases, apart from the windward area. Especially for the accelerated wind in N-S street and the West and East corners of first row buildings in Summer. It’s worth noting that mild funnelling happens in the very narrow gap between the trees and buildings on N-S street, similar results was also observed by Miao et al. [52].

Ash tree shows limited benefit in wind protection in winter as it sheds leaves seasonally. In summer, lower wind reduction is observed as per lower LAI. Furthermore, higher trunk height of ash at 8m, compared to 2m for the oak, has less of a wind blocking effect at the pedestrian height.

Air Temperature

Typical seasonal variation is observed, slightly cool winter and hot summer. Transpiration of Oak is able to reduce the air temperature by 2-3 degrees both in winter and summer, while Ash causes 1 degree drop in summer.

MRT

Seasonal changes in solar angle cause shaded areas to occur to the north of buildings in winter and beside buildings in summer, resulting in a lower mean radiant temperature (MRT) around 18–40 degrees compared to exposed areas. Oak provides constant solar shading,
while Ash offers greater shading benefits in the summer due to its larger LAI and crown width. **PET**

Most of the tested area in Lisbon is experiencing slight to moderate cold stress in winter. Wind protection and solar exposure are essential to remain a comfortable outdoor space in winter. Narrow street (aspect ratio 2:1) creates a comfortable zone at the South of the site, as per lower wind speed and continuous solar exposure. Vegetations cause overcooling in winter due to side effect of evaporative cooling and solar protection, even though it reduces wind speed in general.

Summer in Lisbon is quite hot. Passive design strategies such as massing self-shadows and vegetation are unlikely to create a comfortable space on the test day. However, vegetation can mitigate the moderate and extreme heat stress. Oak can improve up to 18% of moderate hot area to acceptable slightly warm condition, while ash is less effective with 7% improvement. Furthermore, compared to the exposed case with 10% extreme hot area, oak can maximumly reduce to 2%, followed by ash to 6%.

**Singapore**

**Wind**

In winter, the site is well ventilated by Northeast prevailing wind, accelerated wind appears at the NW and SE corners of the buildings, and W-E street. Wider streets encourage overall more air movement through the site, and more areas of accelerated flow. In summer, narrow streets (Aspect ratio 2:1) promote the funnelling effect of the South prevailing wind on N-S street, however there are stagnant zones downstream of the first row of on the E-W street. Wider street options show improved air movement on E-W street with higher wind speed up to 1.5 m/s.

Eucalyptus trees reduce the wind speed in both summer and winter. The funnelling effect is observed again between trees and buildings on N-S street in summer. Melia as a deciduous tree, blocks wind only in summer.

**Air Temperature**

As a tropic rainforest climate, Singapore has uniform temperature and high humidity through the year. Due to the high humidity (up to 92% for tested hours), transpirations of Eucalyptus and Melia could not effectively cool down surrounding air, only reducing by 0.5 degrees.

**MRT**

Constant moderate solar radiation is happening throughout the year. The seasonal variation of the solar angle causes shaded areas occurring to the North of buildings in winter and South in summer. The mean radiant temperature (MRT) of shaded areas is notably lower than that of exposed areas, measuring around 20–36 degrees in winter and 20–42 degrees in summer. Eucalyptus provides a constant solar shading annually. **PET**

Outdoor spaces experience continuously moderate to strong heat stress in Singapore. Providing solar protection is most important throughout the year, followed by good ventilation. In winter, it is unlikely to mitigate heat stress in any tested case. Even though some accelerated zones occur at the NW and SE corners of the buildings, and W-E street, solar exposure still causing moderate heat stress. Vegetations is not able to remove heat stress. In summer, benefit from solar angle and prevailing wind direction, South of buildings is experiencing slightly warm condition, which is acceptable to occupants as per Yang et al.’s previous research [5]. Vegetations unexpectedly cause 5% more area extremely hot, as per blocking the air movement, overriding the shading and evaporative cooling benefits.

**Riyadh**

**Wind**
Winter prevailing wind is slightly lower, at only 2.6 m/s. Large areas of stagnation occur to the NE of buildings particularly in the case of narrower streets. In Summer, narrow streets (Aspect ratio 2:1) promote funnelling effects of North prevailing wind on N-S street. Downstream of the first row of buildings stagnation zones occur on the E-W street. Wider street options show improved air movement on E-W street with higher wind speed up to 2 m/s.

Due to the relatively high trunk height, palm trees have small effects on air movement in both winter and summer.

**Air Temperature**

Seasonal temperature variation is observed, with warm to extremely hot throughout the year. As an evergreen tree, Palm remains a constant LAI throughout the year. However, Oil palm leaves have limited transpiration due to their waxy coating, which only reduces ambient temperature by 0.5 degrees.

**MRT**

Solar radiation in Riyadh is quite strong all year around, due to low altitude and very little cloud coverage. The seasonal variation of the solar angle causes shaded areas occurring to the North of buildings in winter and South in summer. The mean radiant temperature (MRT) of shaded areas is notably lower than that of exposed areas, measuring around 30–48 degrees in winter and 25–31 degrees in summer.

Oil Palm provides a constant solar shading throughout the year.

**PET**

 Ensuring adequate solar exposure and air movement can create a comfortable space in winter, while for shaded areas to the North of the buildings, wind protection is important. Increasing building distance (Aspect ratio 1:1.5) can reduce the self-shading impact and improve the air movement on E-W street, creating 4% more comfortable area compared to narrowest street (2:1). Vegetations aggravates the cold stress for areas to the shaded areas at South and West of the buildings, causing 2 to 7% more cold area, while reducing the hot stress for the wind stagnant areas at the South of the windward buildings that are fully exposed to the sun.

In summer, outdoor space is experiencing moderate to heavy heat stress, especially the leeward side of buildings with low air speed. Vegetations reduce the wind speed, especially at the W-E streets for wider massing options (aspect ratio 1:1 and 2:1). However, benefit from the shading and evaporative cooling effect, extremely hot area is reduced from 40% to 20% compared to exposed case.

**Figure 10 Simulation Results for 2:1 massing in Riyadh**

Winter

Summer

**Figure 11 Seasonal PET Area Percentage**
Conclusion

Lisbon
Controlling air movement is essential to improve winter outdoor comfort in Lisbon. Vegetation is not recommended to block the wind, as the side effect from shading and evaporative cooling adds extra cold stress. Designing first row of buildings in parallel with winter prevailing wind can potentially protect the area behind. Denser massing (Aspect ratio 2:1) can help reduce the air movement.

Summer in Lisbon is quite hot. Reducing ambient air temperature, protecting from solar heat and encouraging air movement of the outdoor open space are all critical. Deciduous vegetation is recommended all around buildings even though wind speed is slightly reduced. Species with larger crown size, higher LAI, and higher trunk height are recommended to the well-ventilated areas, which can provide constant solar protection with less wind block on pedestrian height.

Riyadh
Ensuring the solar exposure and moderate air movement can create a very comfortable space in winter. Wider massing (aspect ratio 1:1.5) ensures less self-shadowing and higher wind speed on E-W street. Vegetations are only recommended to the solar exposed areas experiencing the wind stagnation.

In summer, reducing solar heat gain and ambient air temperature are more critical. Even though oil palm has a relatively low LAI and transpiration rate, the shading and evaporative cooling benefit play essential roles in mitigating extreme heat stress.

Limitation and future recommendation
The biggest limitations of this study are related to the assumptions and inputs of the vegetations:
1. Size and transpiration rate of vegetations are based on literature review
2. Location of vegetations is only tested as 15m away from building, 20m apart from each other
3. For fast approach, corrected air temperature and humidity are assigned for full testing ground instead of crown projection area only, assuming no heat transfer between different ground areas

Hence, several recommendations for future research can be made:
1. A greater variety of vegetation species and arrangement can be investigated
2. The microclimate correction methodology used in this study can be further investigated, by comparing detailed microclimate modelling results from Envi-met and potentially field measurement
3. Same approach can be explored in different climates and testing period to enlarge the database.

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