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Tree Shading Factor as input for thermal model through hemispherical photography

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Abstract

Solar irradiation contributes to heat gain through building envelopes and has a significant impact on building energy consumption. Trees help reduce incident irradiation and need to be considered as exterior obstructions in energy models. Deploying robust models in early design stages is integral to designing energy efficient buildings. The challenge lies with the limited research on individual tree shade characteristics, in the domain of building energy simulation. A simplified methodology considering tree shade factors incorporating the essence of the complex underlying geometry – without compromising on data accuracy for detailed energy estimation in various engines – is thus required. This work presents Shading Factor (SHF) as a dynamic temporal schedule, calculated using data measured from on-site hemispherical photographs and simulations performed in Honeybee tools in Rhino Grasshopper, for modellers to use as alternative to arbitrary shading values.

Key Innovations

- Provides an easy methodology for various simulation engines to incorporate site trees and make informed decisions adhering to a site.
- Reduces computational power and time in complex tree modeling for architects and energy analysts.

Practical Implications

The tree data presented is specific to the trees studied and is not representative of their entire species. To form a 'SHF library', input of at least 20 trees in a climate is representative of a specie's characteristics. Individual crown shade traits could further influence the selection of tree for future landscape plantations.

Introduction

While the influence of static external obstructions towards estimation of lighting energy use in built environment is well understood (Yoon, Y., 2006), the understanding of trees towards shade contribution is limited. Trees directly affect solar heat gain component of building energy use estimation (Villalba, A., 2014; Akbari, 1997), but the available energy simulation tools do not consider trees as exterior obstructions, due to complexity and time invested in modelling these dynamic shading devices. Tree shading over a building – especially windows – significantly impacts building energy use (Berkeley L., 2019), by influencing the cooling and heating loads – through shading, obstructing wind flow and evapotranspiration (Laband, D. N., 2009; Akbari, H., 2001; Wang, Y., 2014). Parameters that impact shading quantity and quality are determined by tree species, canopy area, crown volume and shape, foliation period, leaf area and density, leaf reflectance, tree location and orientation with respect to building element (Abdel-Aziz, 2015; Hsieh, 2018). A single tree provides significant shade even in winters and these results are applicable wherever the studied tree species are common (Konarska, J., 2013). While different species impact building loads differently (Hes, D., 2011), the effect due to an individual species is somewhat uniform: a medium-size deciduous tree can reduce irradiance on south façade by 80% and 40%, with and without leaf cover, respectively (Heisler, G. M. 1986). Integration of tree shading into dynamic energy models has been proposed (Sattler, 1987), considering geometry, transmissivity, and location with respect to a building as the three influencing parameters (Abdel-Aziz, 2015). While evergreen trees with dense crowns are effective in reducing annual heat gain, deciduous trees provide shade in summers yet allow solar ingress in fall and winter seasons (Kamal, M. A., 2012). A tree acts simultaneously as a mesh, awning and louvre, and helps diffuse, reflect and obstruct irradiation and daylight (Villalba, A., 2014) entering a space. The geometrical tree representations are complex, since they require inputs like leaf area, density, distribution, and reflectivity which are difficult to accurately model, and it is crucial to simplify tree modelling without compromising on data accuracy for accurate energy estimation.

Existing tools incorporate diverse methodologies for modelling the tree-influences. The DOE-2 building energy simulation tool calculates direct effect of trees by

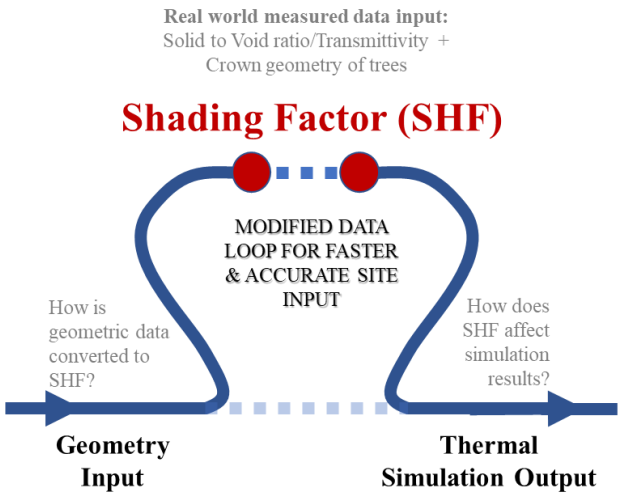


Figure 1: The Linear Simulation loop.

simulating buildings with and without trees using typical weather data, where indirect effects are calculated by modifying weather data to account for urban microclimate (Akbari H, 2001). Energy Plus calculates shading factor through homogeneous coordinate procedure, which couples sunlit area with irradiation data from ASHRAE clear sky model (2005). While the effect of reflected radiation on obstructions is kept simple, still it requires detailed inputs for considering multiple bounces through each obstruction (Cascone, Y., 2011). Recent developments include hemispherical imagery for modelling trees, as inputs for daylighting and thermal simulations (Balakrishnan, 2019): where high dynamic image-based data is used to assess the void ratio or SVF (Al-Sallal, 2012).

The existing methods to model trees in thermal models comprise of complex geometry and boundary conditions and can be broadly divided into TYPE-1 and TYPE-2 categories, based on how they model trees as shading element, and the type of site data needed for simulation. TYPE 1 requires geometrical input of shading device in the form of coordinates apart from defining a transmissivity value or a schedule for simulation engines to consider a variable external source. Simulation engines that require Transmissivity schedule are: Energy plus (Design Builder and Open Studio), IESVE and e-QUEST.

TYPE 2 does not require geometrical input to consider external shading device for simulation engines, therefore Shading Factor (SHF) for the building element can be defined as a schedule. Simulation engine that allows direct input of SHF schedule is EDSL Tas.

A methodology to avoid the need of creating complex tree geometries in thermal models is highly needed, where shading factors of native trees are used to generalize shading factor for different tree species. This will aid energy analysts and modelers alike in faster simulations while incorporating the advantages offered by surrounding vegetation. Therefore, this paper proposes a way to avoid complex geometry yet consider trees, i.e. as a numeric input without compromising on the readily available site data. The comparison between the proposed methodology and the existing techniques is demonstrated in Fig.3.

Although several studies state that shading factor of a tree would change with seasons, only the Leaf Area Index (LAI) is considered (Eiko K., 2011) in assessing transmissivity of trees, and not the Plant Area Index (PAI). However, since tree trunk and branches also contribute to tree shadow, PAI should be considered instead, and this is addressed in this paper. Further, shading is temporally divided: summer shading includes leaves along with tree branches and trunk, while winter periods will consider shading from branches and trunk. Shading factor is identified as:

Shading Factor= Void area/Projected Non-void area

Owing to various underlying factors, tree transmittance depends on specie, climate and direction of view. SHF depends on solar altitude for most tree species in summer while it is constant for winters. Therefore, the calculation of SHF would require both solar altitude and tree geometry (Tregenza p., N.D.). This paper addresses this through providing SHF, which has spatial geometric dependence, and the data provided as temporally dynamic.

Methodology

The methodology for this work includes data measured through processing hemispherical High Dynamic Range (HDR) photography of representative tree samples, along with parameters simulated using honeybee modules in Rhino Grasshopper. For measurements, two evergreen trees – Neem (Azadirachta indica) and Banyan (Ficus bengalensis), and a deciduous tree - Peepal (Ficus religios) native to hot-and-dry climate of India are selected. In continuation, irradiation data with- and without- a tree scenario is simulated for annual, monthly and seasonal basis using location-specific weather files.

For a holistic study, at least one year of site-measured data comprising of information like transmissivity, Leaf area index, and seasonal canopy density is desirable to assess shading input of a specie. The scope of disconnecting the streamlined approach of geometry modeling in established tools was identified, to allow for piping-in real-world data and derived metrics in Figure 1. Simultaneously, it was assessed if transmissivity (τ) data of a tree could be added as a model input for different tree species. Since various simulation engines cause data loss by considering trees as external shading devices and

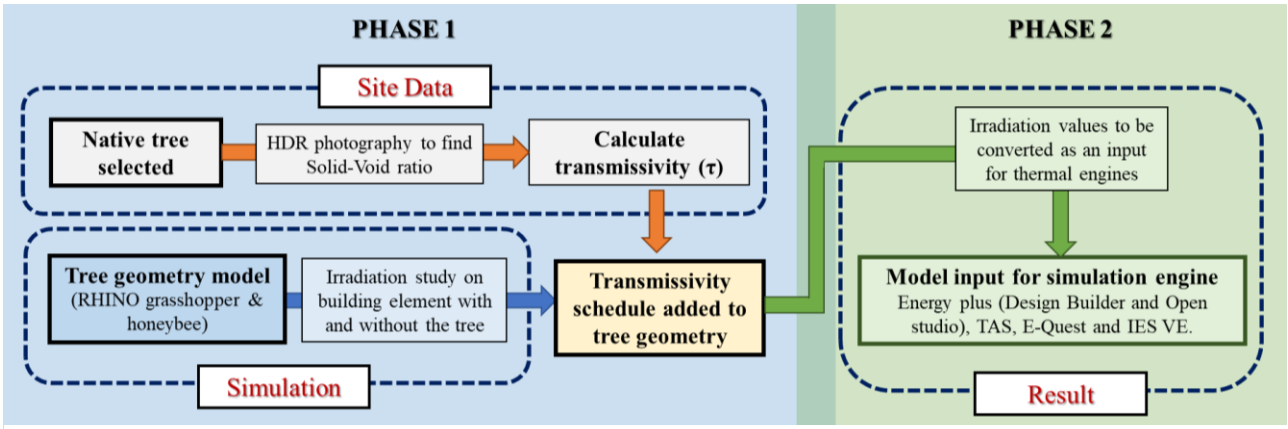


Figure 2: Research Methodology comprising of both simulated and site data.

Simulation Engine	Energy modeling software	Existing method to model a tree as Shading element	
Energy plus	Design Builder	• Geometry based: Component block for shading surface – Transmittance schedule value (0 to 1) added.	Type 1
	Open Studio + Sketchup	• Geometric input: Shading surface with coordinates in Sketchup – Transmittance schedule defined	
APACHE SIM	IES VE	• Modeled as shading objects (**Model It** Room Type Local Shade, Adjacent Building or Topographical Shade) and then run with **Sun Cast** solar shading prior to any thermal simulations.	
DOE 2	e-QUEST	• Adjacent building shading set by coordinates; dimensions assigned to building with simple geometry. • Shade-Schedule for seasonal variation in transmittance. Daylighting assumes TRANSMITTANCE = 0.	
EDSL	Tas	• Direct SHF through Feature shading: surface height + width, shading depth + offset + transmittance. • Simulation defined for 365 days when geometry is exported from 3D Modeler to Building Simulator. • For partially transmitting obstructions, the possibility of double transmission is considered.	Type 2
Proposed Methodology in this paper		• existing simulation engines model trees as static shading element • tree geometry granularity is generally comprised with, to save on computation and simulation time at the modeling level • considers tree data as a numeric input without compromising on the readily available site data.	

Figure 3: Simulation engines and their respective inputs required to simulate external shading devices

simplifying complex tree geometry – where the granularity in measured data is reduced to save computation and simulation time, this study aimed to pre-process the detailed measured inputs to a numeric input. This temporally dynamic numeric input could be piped-in to the simulation engines, without compromising quality of the originally measured data. A methodology framework to achieve the purpose of this research is derived.

Figure 2 explains various ways by which site data is collected, with two most widely used site instruments. Preference is given to photographic method over Pyranometer, due to reported accuracy of its realistic data acquisition. This is further used to derive tree canopy Transmissivity, which when collected over the span of a year, would yield a schedule. This schedule could be combined with geometric input of simulated tree models to yield a Shading factor schedule. This would follow a similar timeline as obtained through Transmissivity. The resultant schedules would involve both site and simulated data and would be used as input into energy modeling softwares.

The finalized research methodology is segregated into two phases as discussed in the objectives earlier. Briefly, the former deals with tree data collection and modeling while the latter deals with ways to input the results obtained in suitable simulation models. The First phase involves hemispherical photography of selected tree to calculate Void ratio or canopy transmissivity, followed by modeling a geometric tree within Honeybee modules to obtain Irradiation data for with- and without-tree scenarios for a building element. Set of parameters or algorithms required for tree shadowing could help in evaluation of geometrical tree representation, shading projection, and solar radiation data. The Second phase consists of finding easiest pathway to incorporate the collected first phase tree data into various simulation engines like – Energy plus (Design Builder and Open studio), Tas, eQUEST and IESVE by deriving parameters that affect the input results for thermal models. The result of second phase is analysed to form an appropriate schedule as input for both TYPE 1 and TYPE 2 simulation engines.

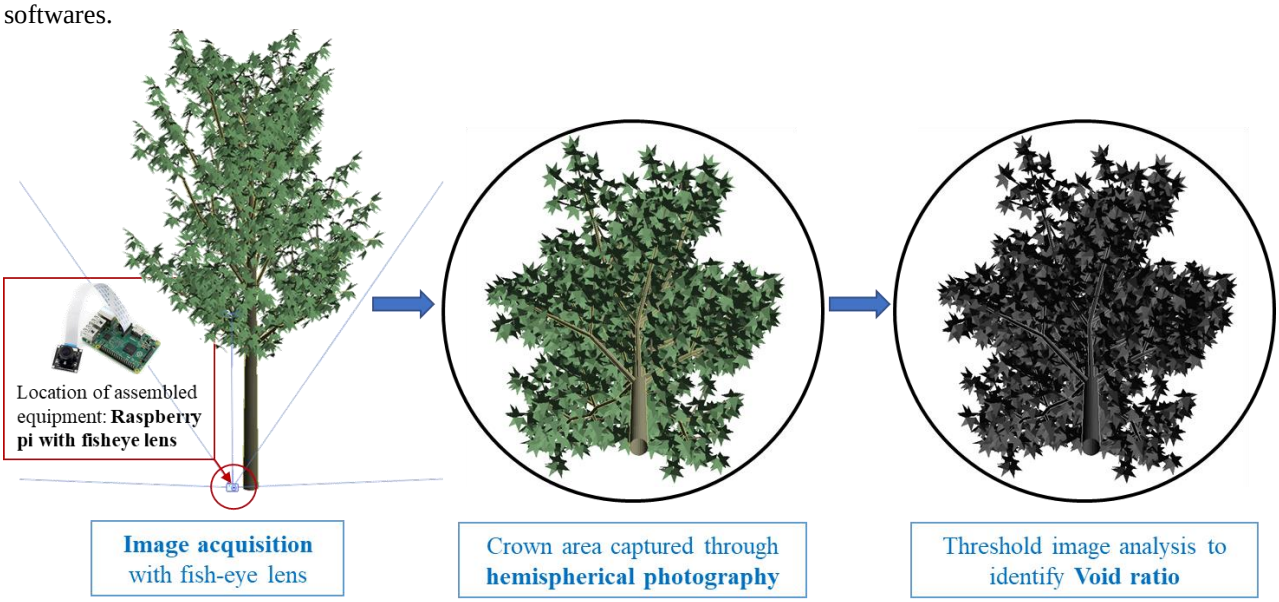


Figure 4: Hemispherical image acquisition steps on site for selected tree to calculate void ratio.

In the measurement segment of Phase 1, Hemispherical HDR imagery coupled with image processing technique is used to identify Void ratio of a given tree species, as presented in Figure 4. A Raspberry-pi coupled with a fisheye module is used for the measurements. The fisheye lens has a viewing angle of 180- and 135-degrees for the long- and short-edge respectively and can effectively capture the canopy of a tree. HDR images are generated by stitching 8 images captured at increasing exposures [1/8000, 1/4000, 1/2000, 1/1000, 1/500, 1/250, 1/125 and 1/100] through a custom Python script. The colored channels are flattened to capture grayscale images, by using factors of 0.2989, 0.5870 and 0.1140 respectively for the red, green and blue channels.

The HDR pixel-data is then converted to luminance map using single point calibration, cropped, and resized to 800x800 pixels, and exported to CSV for post-processing. This technique is capable of capturing data of high resolution as compared to spot-measurement through a luminance gun.

For the simulation part of Phase 1, a geometrical model of the tree canopy is created along with the building element to be studied, using RHINO grasshopper, and radiation analysis is done using Honeybee through visual scripting. The Visual script developed in honeybee-grasshopper obtains SHF in 3 steps. In step-1, the inputs of the site-measured tree data obtained through hemispherical HDRi is incorporated, and tree parameters consisting of Bole radius & height, crown radius are added: Tree transmissivity obtained from the site is matched with the mesh model made in the script. The shape of tree canopy is determined by capturing a vertical image of the entire tree shape. From options, of circular, conical, and cuboidal, the appropriate one is selected in a custom Grasshopper recipe, and the model is generated in Rhino workspace. Modifications in the options for different tree shapes can be incorporated by connecting a different shape, for example, the trees in hilly regions have a tapered canopy shape, and replacing the spherical shape with a conical shape can make the desired changes in the model. Other parameters inputs – bole (trunk) height, bole radius, crown radius and Transmissivity of the tree obtained from the site are incorporated.

In step-2, relation between the tree and the area under investigation: the location of the tree with respect to the resultant wall, the direction, orientation, and location of building element to be studied is determined and incorporated into the visual script. Also, for the surface under investigation, the size of the building element, the angle at which the tree is positioned with respect to it, and the vertical and horizontal distances are incorporated in further defining the model. With appropriate modifications, the floor-wise SHF may be obtained by altering shape and size of a building element. In step 3, the temporal assessment is done, where the weather file of a location is added, and dynamic SHF is derived by changing the time period from months to annual basis. The final irradiation output is achieved by averaging the grid size of the entire building wall element. The data-series thus generated is exported as CSV output, as a ready to use SHF schedule.

The Void ratio obtained from the HDRi-based site study is then incorporated to the simulations, and the resulting decrease in solar irradiation is mapped and calculated to obtain SHF of a given tree.

Radiation analysis is done for the with- and without-tree scenario for various parametric options, and this process is repeated for various distance from the building element. The irradiation data is exported to a workbook to determine monthly and annual SHF of a tree element through post-processing, and data collected for various independent trees of same species is averaged to obtain SHF for a given tree species.

Each outcome of this dataset is specific at a given distance from the building element, based on the physical parameters of the tree as on-site. Since most of the trees are found in clusters at any given site, averaging out SHF

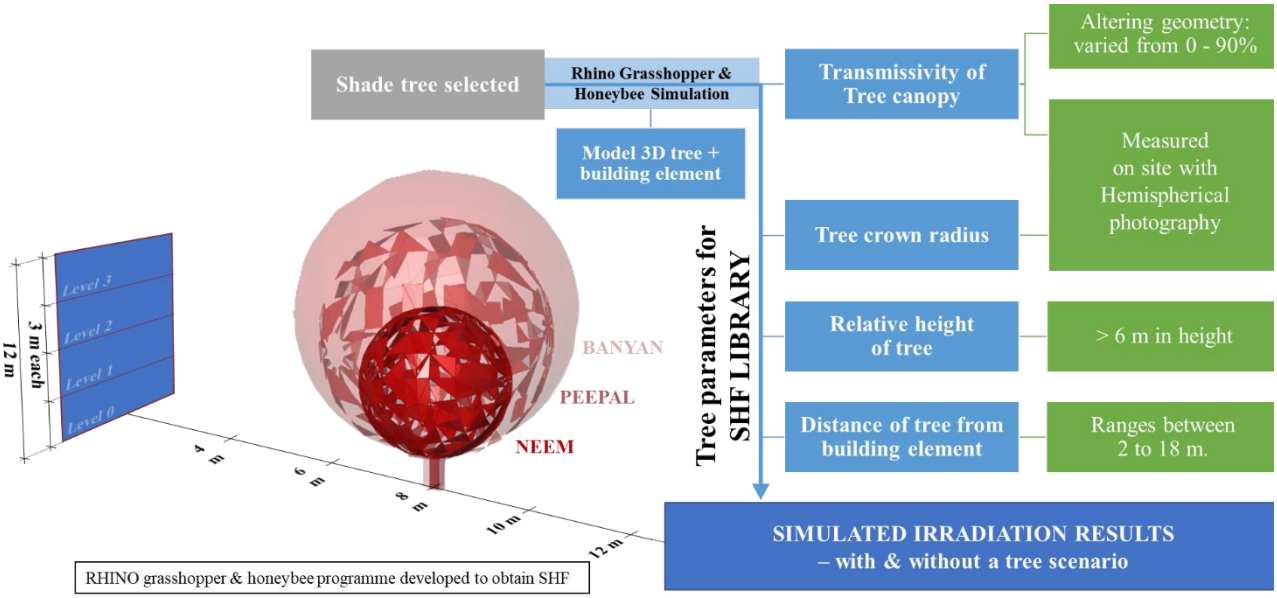


Figure 5: Workflow to derive SHF of different tree species from site-based parameters.

of all the tree species in each direction could give the resulting SHF required for the building element. The process in Fig.5 can be deployed to map SHF of various trees with parameters as listed here. This representational seasonal variation can be added as schedule-input in simulation-based-optimization of building elements.

In this study, two evergreen trees – Neem (Azadirachta indica) and Banyan (Ficus benghalensis), and a deciduous tree - Peepal (Ficus religios) are selected for the hot-dry climate of Ahmedabad. Following the process presented, the SHFs are derived. Transmissivity is obtained from site study for TYPE 1 simulation engine input. The TYPE 2 analysis consists of mapping resulting decrease in solar irradiation and calculating SHF of a given tree for a given distance from the building element. This process would be used to find SHF for annual, monthly, and seasonal basis under uniformly overcast or clear sky conditions. The resultant trendline is added as a schedule to the given simulation engine as an optimization for building element. The individual tree canopy in Figure 6(1), is captured by placing the Raspberry Pi fisheye camera right below the tree's canopy on flat ground, and data is captured for both North and South directions as shown in Figure 6(2). The resulting HDR image is converted into workbook data (.csv format) through the custom script. A threshold value is used to separate the background, after single-point calibration of electronic data received on the camera sensor, which helps identify the minor voids in the tree canopy. The full tree canopy is further formed by combining two HDR hemispherical images of North and South directions, as shown in Figure 6(3). Since the tree

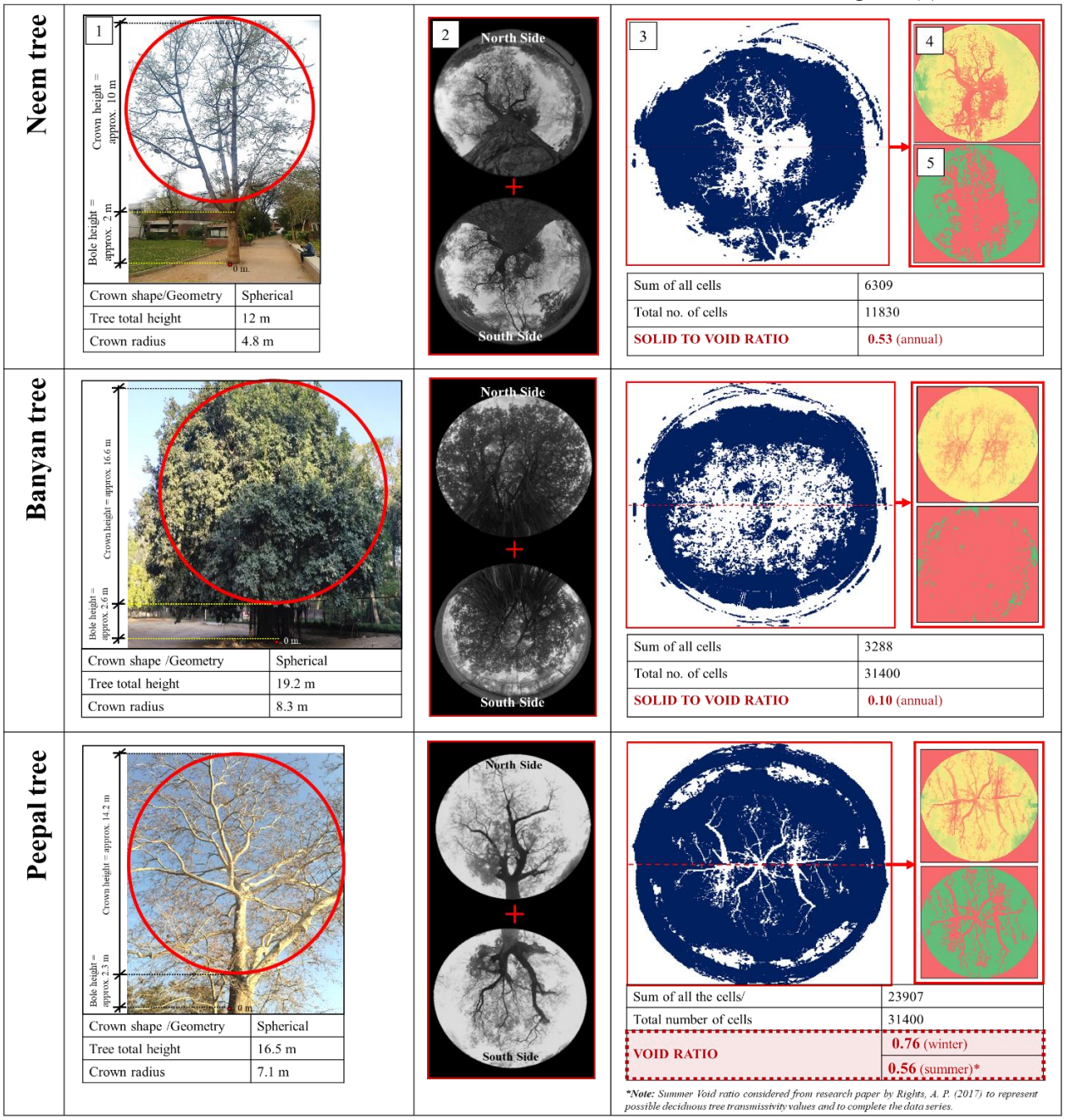


Figure 6: Steps followed to obtain transmissivity value of selected trees in Ahmedabad.

canopy obtained includes the irrelevant surrounding data captured by the hemispherical lens, a circular 'sky mask' is applied to the CSV file with the sky image threshold as shown in Figure 6(4). By flattering the foregroung and background to binary values of 1 and 0, a count of the number of cells representing the cells of the foreground with those of the background generates the solid-to-void ratio for a given tree at a given location and direction. Similarly, a count of the cells representing the background, along with count of all the cells in the mask yields the void ratio, This helps generate the transmissivity data to be added to the script used for creating the mesh geometry.

Results

Figure 7 presents the outcome – a temporally varying SHF for the studies trees. A brief comparison between the two studied evergreen trees, shows that Neem behaves as a semi-evergreen tree in harsh weather and drought-like conditions, demonstrating reduced foliage density which varies across topographical and geographical locations. The foliage density of Banyan tree varies by less than than 3% throughout the year. Repercussions of this in building domain is this, that dense foliage of Banyan would not allow sunlight penetration across seasons, while the semi-evergreen Neem could allow winter sun through reduced foliage in the season.

It is observed that shading factor decreases linearly as the building element is placed away from the evergreen tree for the Banyan tree, yet it varies slightly for the Neem tree. Transmissivity value obtained from hemispherical photography of Peepal tree is added to the simulation model with similar geometry to determine the percentage decrease in irradiation received at building element through a tree. Shading coefficient for deciduous tree is reported to range from 0.07 to 0.38 in summers, and from 0.27 to 0.89 in winters (Rights A. P, 2017), according to a study done in Tucson, Arizona, which has a similar climate as Ahmedabad, India (hot semi-arid climate) where the present study was conducted. The minimum difference observed between the two major seasons is roughly about 0.2, while the maximum is about 0.6. The minimum difference is selected to represent the worst-case scenario with less foliage growth to complete the data series for a deciduous tree in this research. As seen in Figure 7, the results obtained from this research can directly be directly integrated into the TYPE 1 simulation engines.

It is identified that tree transmissivity is a property of its canopy is not dependent on the direction, hence a schedule may be formed specific to the trees studied. The monthly average graph could also be plotted hourly as per requirement. This study can be taken forward and annual data may be recorded using the proposed methodology for more accurate results specific to tree type.

Conclusion

Traditionally, simulation tools do not categorise tree types, and a generic value is considered for all trees, even when it is understood that species hugely impact the built environment. This reinforces the importance of studying vegetation around a site for determining accurate tree impact. The mentioned methodology can be used to study various species of tree at a given site and its shading effect on the building element, provided that transmissivity data for all seasons is available. The timeline of this research was limited, which restricted year-long collection of selected tree-data. To fill-in the gaps, literature that reported approximate change in transmissivity values for deciduous and evergreen trees for summer season were referred. A general convergence was seen between measured outcomes of this study with those in literature, however, the site data collection was done for winter month – which denotes worst-case scenario of tree transmissivity with least shading factor. An average variation in void ratio of 2-3% on an average is considered for the evergreen trees as well, to account for new leaves and branches for a given mature tree. The stated percentage would vary within and between various species due to climate, environmental conditions, size,

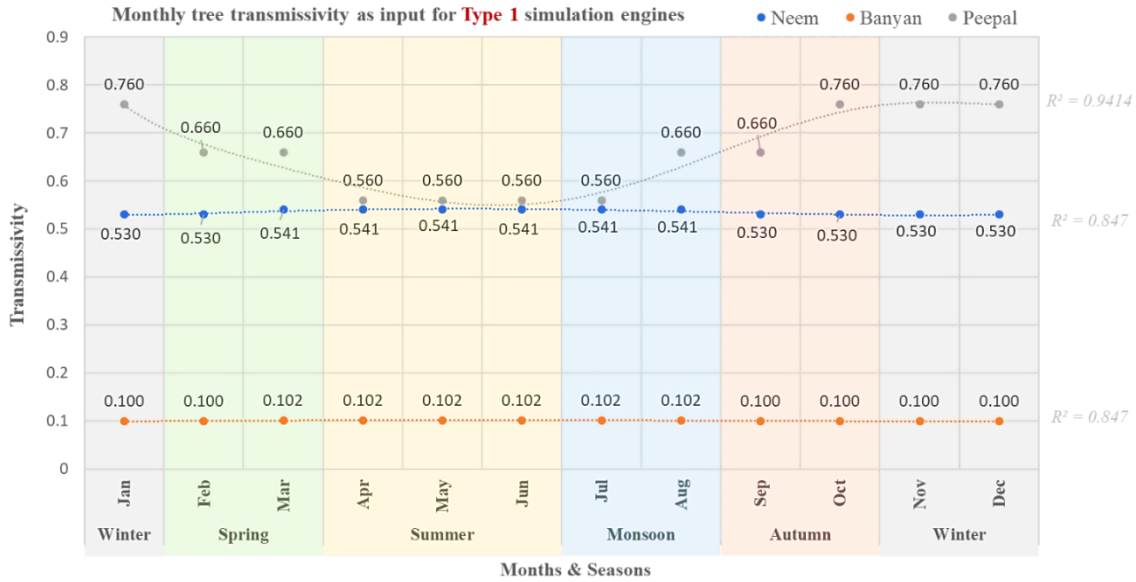


Figure 7: Transmissivity schedule for TYPE 1 simulation engines - Energy plus (DB and OS), eQUEST, IESVE.

and genetics, among others. Therefore, it is understood that summer SHF is high for deciduous as well as evergreen trees. This study derives a methodology to incorporate a tree's shading effect into a simulation engine, by jointly using measured data (through hemispherical photography) and parameters identified from simulations (from honeybee/grasshopper) as inputs. The simulations are conducted in DIVA, a user-friendly tool that supports simulation-based decisions in early design stages.

As contribution to the domain, this study reports methodology and limited results for tree transmissivity schedule, as resultant inputs to simulation engines that require geometrical input: like Energy Plus, eQUEST and IESVE. Also, shading factor schedule is obtained as input for simulation engine that do not require geometrical input: like EDSL Tas.

Exceptions and assumptions include Neem's ability to adopt deciduous tree traits and change its transmissivity under extremely harsh conditions as confirmed by various studies. Yet for this study, the selected standalone Neem tree is considered as an evergreen tree, since the above hypothesis could not be confirmed in the timeframe of this research. Since data was collected solely for the winter period, the results represent a worst-case scenario for both evergreen and deciduous trees.

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