Street tree planting patterns to modify the sky view factor for outdoor thermal comfort enhancement

Ratnayake, C.W.; Perera, N.G.R.; Emmanuel, R.

Published in:
FARU Journal

DOI:
10.4038/faruj.v9i2.167

Publication date:
2022

Document Version
Author accepted manuscript

Citation for published version (Harvard):
Ratnayake, CW, Perera, NGR & Emmanuel, R 2022, 'Street tree planting patterns to modify the sky view factor for outdoor thermal comfort enhancement', *FARU Journal*, vol. 9, no. 2, pp. 1-11. https://doi.org/10.4038/faruj.v9i2.167

STREET TREE PLANTING PATTERNS TO MODIFY THE SKY VIEW FACTOR FOR OUTDOOR THERMAL COMFORT ENHANCEMENT

RATNAYAKE. C. W[1], PERERA. N. G. R[2] and EMMANUEL R[3]
[1, 2]*Department of Architecture, University of Moratuwa, Moratuwa, Sri Lanka*
[1]*chanodi.r@gmail.com* ; [2]*nareinperera@uom.lk*
[3]*Glasgow Caledonian University, Glasgow, United Kingdom*
Rohinton.Emmanuel@gcu.ac.uk

Abstract. Outdoor thermal conditions influence the quality of life in the urban commons. Urban vegetation is an effective way to improve pedestrian thermal comfort in the tropics as it provides shade, reduces urban surface heating, improves air quality, and human health. The primary objective of this study is to understand the correlation between the Sky View Factor (SVF) modifications and Outdoor Thermal Comfort (OTC) that could inform optimum street tree planting strategies in the warm, humid, context of Colombo, Sri Lanka. Common street tree planting patterns are identified and simulated, utilising the RayMan software. Results showed that there is a distinct advantage in utilising trees for SVF modifications and thereby increasing OTC. Tree planting patterns with less SVF yielded better results during the day, yet, showed little or no impact during the night. Conclusions discuss SVF-based design implications for the different urban canyon geometries, and orientations explored in the study.

Keywords. *Sky View Factor; Street Trees; Outdoor thermal comfort; Physiological Equivalent Temperature; RayMan*

1. Introduction

Global climate change and rising air temperature is a crisis faced by today's world, due to human activities, and is intensified within urban areas. Rapid urbanisation creates dense developments and pollution which applies significant pressure on cities and their microclimate. This eventually alters the urban energy balance and influences OTC.

Colombo's morphology is rapidly changing. For the last few decades average air temperature of Colombo has been around 27^{o}C (Ukwattage and Dayawansa 2012), but as the current conditions worsen, an increase of approximately 0.16^{o}C per decade is expected. (Department of Meteorology, Sri Lanka). This expected increase was initially limited to the North-Western region of the city, but today it is expanding towards the South (Ukwattage and Dayawansa 2012). Such irregular distribution of heat and heat waves within a city can cause thermal stress and affect human health and well-being. To improve the existing street conditions and thermal comfort in Colombo, research needs to focus on how best to positively influence urban planning, design policy, and practice. With today's climatic crisis, cities that provide pleasurable thermal experiences for pedestrians reflect a high quality of urban living, and most of these cities are seen to utilise vegetation in their adaptation and mitigation.

The primary objective of this research is to analyse the contribution of street trees in the warm, humid, context of Colombo to improve pedestrian thermal comfort. The core focus is to understand the correlation between the sky view factor and OTC – communicated using the thermal comfort index Physiological Equivalent Temperature (PET) – at both daytime and night-time, to analyse the optimum street tree planting strategies.

The study investigates two representative streets oriented in the North-South and East-West direction in Colombo, Sri Lanka, namely, Elvitigala Mawatha and Ananda Coomaraswamy Mawatha. (see Figure 2) The streets have different aspect ratios and urban densities. An area of 200x200 m^2 was modelled in RayMan Pro (Matzarakis et al. 2007) to calculate the SVF and PET of each selected tree planting pattern. An existing (base) case and nine tree planting pattern cases were identified. For each of the selected streets, an existing and potential scenario was developed. Thereby generating a case study matrix of forty cases, for simulation, data collection and evaluation.

The analysis protocol is focussed on the SVF to PET correlation, throughout and at different times of the day, and at different positions in the street canyon (receptor points). The objective is to ascertain the most effective planting strategy to modify SVF and thereby enhance OTC.

2. Literature Review

2.1. ASPECT RATIO AND SKY VIEW FACTOR (SVF)

Canyon geometry is a fundamental element of a street canyon that requires proper understanding, to improve pedestrian thermal comfort and mitigate the impact of microclimates. The parameters of street canyons can influence the surface and air temperatures, and contribute to microclimate changes. This in return decides the thermal comfort of outdoor spaces and their activity intensity. (Salleh 1994). The geometry of a street canyon can be described by three principal parameters – height-to-width ratio or aspect ratio (H/W), length-to-width ratio (L/W), and sky view factor. (SVF)

The reasons behind the urban climate anomaly – UHI - have been thoroughly examined in the last decades. The main reasons are urban geometry, as well as surface material properties. The nocturnal heat island increases with an increased H/W ratio because night-time cooling is hindered. (Johansson, Emmanuel, and Rosenlund 2004)

The Sky View Factor (SVF) was first introduced by Nusselt in 1928 as a heat transfer theory to model radiant exchange between diffused surfaces. Oke in 1981, explored SVF in Urban Climatology to evaluate the UHI phenomenon. Today, it is widely used to study urban climate, energy exchange, and thermal comfort conditions (Qaid et al. 2016). According to Oke, SVF is the proportion of the hemisphere visible from a certain location. It is a typical measurement used to evaluate the spaciousness of open air from a point in a street (Roger et al. 2016). It is graded between zero and one.

- SVF = 1, completely open area without any high objects to obstruct the view
- SVF = 0, completely enclosed environment (Bourbia and Boucheriba, 2010).

SVF can control;

- The amount of short-wave radiation gains during the day (also determines daylight possibilities)
- The amount of long-wave radiation loss from city to sky (cools down urban surfaces at night)

Usually, the SVF is measured at a height between the ground level and 2m above the ground. Most researchers measure it at eye level, but according to Svensson (2004), the best level to measure the SVF is at ground level (Qaid et al. 2016).

Further, studies done by Hu et al. (2016), discuss the strong correlation between UHI and SVF, which illustrates a potential linkage between UHI and urban form. The results concluded that high building densities cause high UHI intensities due to low SVF. (Hu et al. 2016)

2.2 ROLE OF URBAN VEGETATION

Vegetation significantly influences the outdoor temperature, urban microclimate, and urban heat balance by providing shade, evapotranspiration, and directing wind either as a windbreak or as a wind funnel. Research shows that the shading properties of trees have a major influence on local cooling rather than evapotranspiration, and also that large, vegetated areas such as parks in the middle of a city can affect the surrounding built-up areas in an effective manner (Shashua-Bar and Hoffman 2000).

The main influencing parameter in the microclimate and urban environment is mostly driven and controlled by changes in the mean radiant temperature (MRT) and wind speed, especially in tropical cities. (De Abreu-Harbich et al. 2015). Shade provided by trees becomes a significant factor since it reduces the amount of heat absorbed by surface materials. As a result, it reduces the MRT and improves thermal comfort. Research done on deep and shallow street canyons, with two levels of tree canopy covers (high and low) concluded that the cooling benefit of street tree canopies increases as street canyon geometry shallows and broadens (Coutts et al. 2016).

A study conducted on the role of vegetation to mitigate the urban heat island (UHI) effects and global warming concluded that evergreen and deciduous trees were the best solutions to mitigate the UHI effect, while grasslands were the worst (Satir 2016).

3. Method

The primary objective of the study is to understand the correlation between the SVF modifications that trees create, and the OTC throughout the day. Thus, generate patterns that could lead to optimum street tree planting strategies.

3.1. SITE SELECTION

Colombo is the commercial capital of Sri Lanka and is located on its western coastline (6.920N, 79.860E). Today, it is the country's largest and most developed city. It has a climate that experiences high air temperature and high humidity throughout the year. Since Colombo is located closer to the equator, solar elevation is high, and the period between March to May is usually the hottest (temperature rises to 32°C). October to December is the least uncomfortable period (temperature decreases up to 23°C). Colombo has an annual rainfall of 2300 mm. (Department of Census and Statistics).

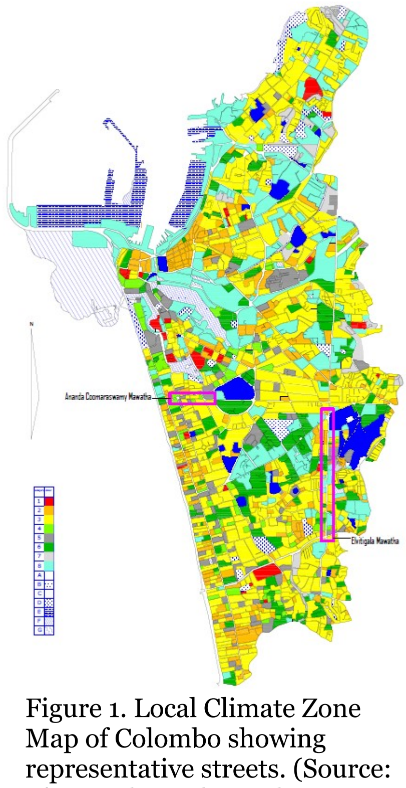


Figure 1. Local Climate Zone Map of Colombo showing representative streets. (Source: after Rathnayake et al. 2020)

3.1.1 Selection of representative streets in Colombo

The research design limits its scope to selected representative streets in Colombo for simulation, analyses, and discussion.

According to Orientation - To represent the general layout of streets in Colombo, two urban canyons, oriented North-South and the other East-West were selected. As shown in Figure 1, the selected streets, and their extended trace, form two major vehicular arteries of the city.

According to the Aspect Ratio - The building skyline of Colombo is generally low. Most of the high-rise buildings are scattered around the city centre. Therefore, in most parts of the city, the aspect ratio rarely exceeds 1. Based on the local building density, two categories of aspect ratios were identified.

Category 01: Includes a street area with an aspect ratio below 0.5

Category 02: Includes a street area with an aspect ratio between 0.5 and 1

Street 01 - Elvitigala Mawatha - Elvitigala Mawatha is oriented in the North-South direction and

Figure 2. Street 01 - Elvitigala Mawatha, Site and Receptors

Figure 3. Street 02 - Ananda Coomaraswamy Mawatha, Site and Receptors.

stretches from Kirulapone to Borella and is a part of and an extension of the Baseline Road. Baseline road is so termed, because of its original use to establish a base axis for land survey purposes. (See Figure 1 and 2)

Street 02 - Ananda Coomaraswamy Mawatha - Ananda Coomaraswamy Mawatha is oriented in the East-West direction and stretches from Borella to Colpetty. Its extended trace spans from the western coast to the interior of the city. As seen in Figure 1, Ananda Coomaraswamy Mawatha intersects the Elvitigala Mawatha extended trace perpendicularly. (See Figure 1 and 3)

3.2 STREET TREE CATEGORISATION

The term 'tree type' usually categorises characteristics of trees based on the mature size (crown shape and width, tree height, growth rate) and foliage period (evergreen or deciduous) of a species. Understanding the ideal tree type and its position within an urban canyon helps to improve thermal comfort. Due to the location of Colombo and its relatively high solar elevation, evergreen trees with relatively wide crown canopies are ideal to create shade. However, the selection of street trees gets limited due to particular street canyon geometry. To analyse the suitable tree height and position in the street geometry, the following factors are considered. (As defined in Rantzoudi et al. 2017).

- Minimum allowable tree height (to not disturb pedestrian and vehicular movement)
- Minimum required distance from buildings.

Based on the considerations stated above, the trees were categorised based on the tree size, distance from the building and their orientation in the urban canyon.

According to Tree Size - According to Russ (2009) the minimum acceptable distance to locate a tree from the building is 1/4 to 1/3 of the tree's mature height. The minimum acceptable tree height recommended is 2.4m, although it is further stated that for an urban street it should be more than 5m. (Figure 4)

According to Street Canyon Shape - Generally, trees are planted on the sidewalks and median strips of a vehicular street. Based on the available planting positions five patterns were identified. (Figure 5)

	Tree Height	Canopy Diameter (1/2 of tree's mature height)	Distance (1/4 of tree's mature height)
Class 1	Equal or less than 10 m: (10 m)	5 m	2.5 m
Class 2	Between 10 m and 20 m: (15 m)	7.5 m	3.75 m
Class 3	Equal or more than 20 m: (20 m)	10 m	5 m

Figure 4. Classification of trees according to height, diameter, and distance.

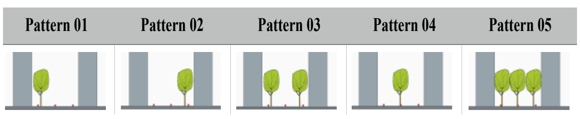
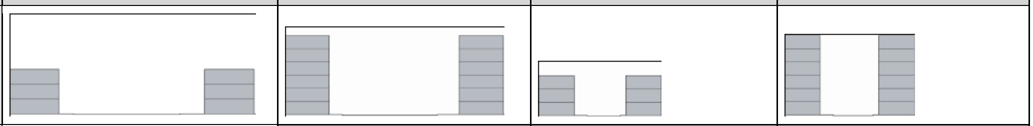
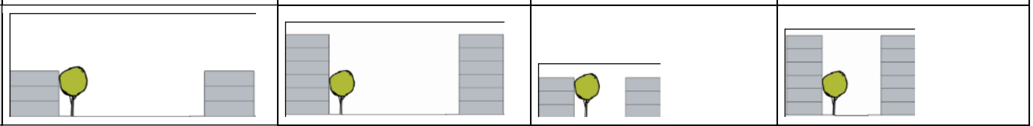
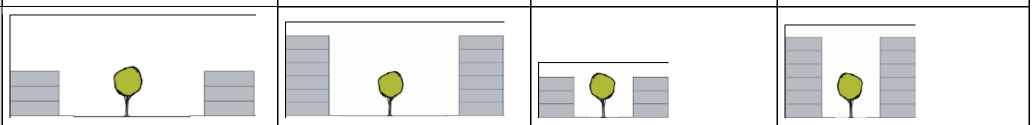
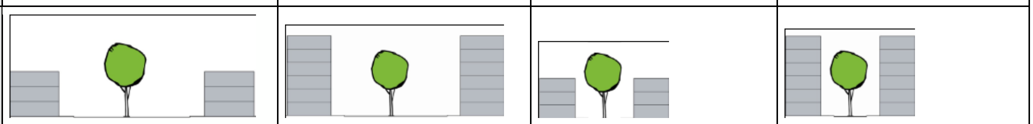
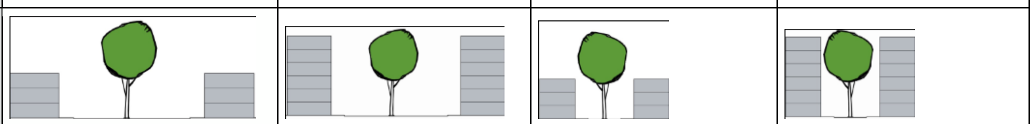
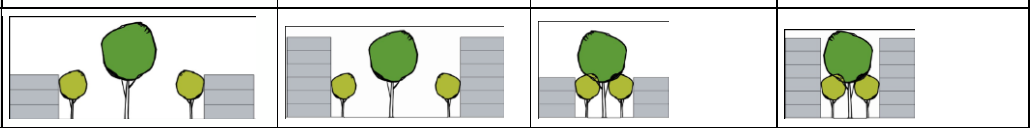


Figure 5. Street tree planting patterns.

3.3 CASE STUDY MATRIX

Incorporating both the tree size and the placement within the street canyon defined above, the following cases were generated and formed the basis for simulations as case studies. (Table 1)

	Table 1. Case Study Matrix			
	Street 01		Street 02	
	Scenario X (Existing Scenario)	Scenario Y (Potential Scenario)	Scenario X (Existing Scenario)	Scenario Y (Potential Scenario)
Base Pattern				
Case 01 (C1)				
Case 02 (C2)				
Case 03 (C3)				
Case04 (C4)				
Case 05 (C5)				
Case 06 (C6)				
Case 07 (C7)				
Case 08 (C8)				
Case 09 (C9)				

The cases encompass both the existing scenario and a potential scenario (a maximum possible increase of building height) that draws on the development possibilities defined by the 'Colombo Core Area Development Plan', under the larger umbrella of the Western Region Megapolis Planning Project, of the Ministry of Megapolis and Western Development, Sri Lanka. (see www.megapolismin.gov.lk).

Each case defined incorporates a unique SVF value in its combination of buildings and trees, as seen in Table 2 and Table 3 in this paper.

3.4 SIMULATION PROCESS AND DATA ANALYSIS PROTOCOL

Simulation Process - The comparative simulation study utilises the simulation software RayMan - "radiation on the human body", developed by Matzarakis et al. (2007). It has been used around the world to calculate short and long-wave radiation flux that affects the human body. Various planning and designing scenarios from the micro to the regional scale can be analysed using this software. Data on OTC indices such as PET, PMV, MRT, SET, UTCI, SVF, sunshine hours, global radiation, and shadows, among others, can be generated utilising RayMan. (urbanclimate.net/RayMan)

For this study, an area of 200x200m² was modelled in RayMan Pro to calculate the SVF and PET of each selected tree planting pattern. (see Table 1). The building outlines were obtained from digital maps and were verified by field studies and observational data on Google Earth to define the model. Building heights were defined by the number of floors, considering one floor is equal to 3m. Climatic data for the study were collected from the Department of Meteorology, Sri Lanka.

PET values were obtained from three receptors (measurement points) in each street. One on each side of the canyon (A and C) adjacent to the built edge and one on the centre median of the street canyon (B). (See Figure 2 and 3).

Data for each case, at each receptor, obtained from RayMan is communicated as PET and is based on Thermal Perception and Physiological Stress Level (Matzarakis and Mayer, 1996; Lin and Matzarakis, 2008 as cited in Koerniawan et al. 2015) (Figure 6).

PET[a] moderate region (°C)	PET[b] (Sub) Tropical region (°C)	Thermal perception	Grade of physiological stress
		Very Cold	Extreme Cold Stress
4	14		
		Cold	Strong Cold Stress
8	18		
		Cool	Moderate Cold Stress
13	22		
		Slightly Cool	Slight Cold Stress
18	26		
		Comfortable	No Thermal Stress
23	30		
		Slightly Warm	Slight Heat Stress
29	34		
		Warm	Moderate Heat Stress
35	38		
		Hot	Strong Heat Stress
41	42	Very Hot	Extreme Heat Stress

Source: [a]Matzarakis and Mayer (1996), [b]Lin and Matzarakis (2008)

Figure 6. Comparison of PET Index between the moderate region and (sub) tropical region. Source: Koerniawan et al., 2015

The 'Comfortable' range is stated as between 26°C and 30°C, therefore, all PET plots in the analyses identify the range and 28°C line for easy reference. (see Figure 7 and Figure 9)

Data Analysis Protocol - The analyses are discussed separately for each street orientation. (E-W and N-S). Further, for each street orientation, the graphs are separated as corresponding to the morphology scenario. (Existing and Potential).

The analyses utilise two major steps. The first plots PET against time, for each case study. This focuses on ascertaining how each pattern behaves throughout the day and in comparison, to each other. The graphs are generated for each receptor point (A, B, and C) separately.

Secondly, the analyses correlate SVF and PET, to ascertain the feasibility of the utilisation of tree cover to modify the SVF, at the different receptor points. The analysis utilises PET data from all case studies for correlation.

Assumptions, scope, and limitations - In the simulation process following factors were taken into consideration to simplify the simulation process;

- The scope of the research is limited to two representative streets in Colombo, Sri Lanka, with perpendicular orientations.

- The canyon geometry draws from the existing building fabric and the planting patterns are based on three types of typical tree sizes and configurations.
- Utilising RayMan, the simulations are carried out for a single day of the year – 15th April – deemed on average, one of the hottest, in warm, humid Colombo.
- Output of RayMan estimates PET from 07:00 h till 18:00 h and gives a single PET value for after sunset. However, PET at 18:00 h is not taken into evaluation.

4. Results and Discussion

The analyses comprise a series of scenarios that have been developed to identify the most effective street tree planting pattern to modify SVF and thereby, enhance the OTC in two representative streets of specific orientation, in Colombo.

4.1 ELVITIGALA MAWATHA – STREET 01

4.1.1 Physiologically Equivalent Temperature Analysis

Elvitigala Mawatha is oriented in the North-South direction, and the amount of solar radiation received by surfaces varies throughout the day. In this circumstance shading requirements of the sidewalks differ. Of the two selected canyon geometries, the deeper canyon (Scenario Y) has a better outdoor thermal condition than the shallow canyon (Scenario X) during the day. However, during the night, both canyon geometries (existing and potential) have little variation. (Figure 7)

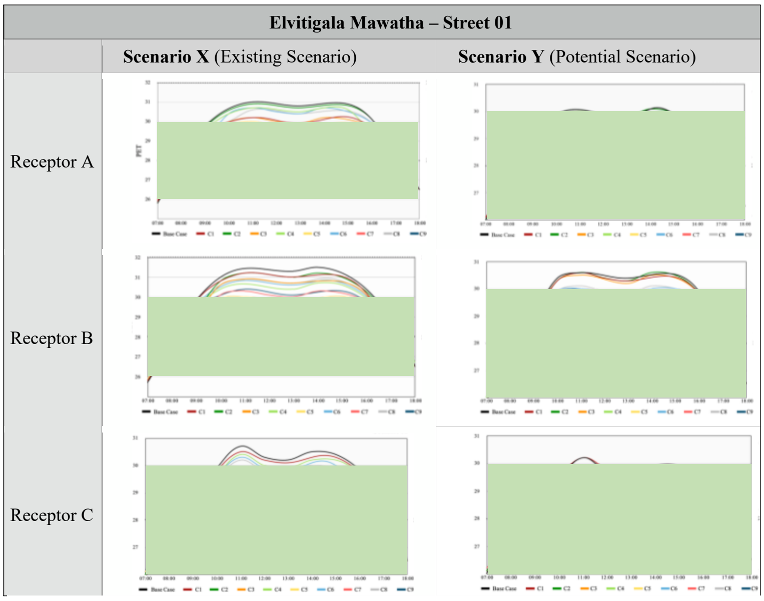


Figure 7. Elvitigala Mawatha – Street 01 – PET analysis

In both scenarios, there is a clear difference in PET values between shaded and unshaded cases. However, while scenario X show PET values within the 'slightly warm' condition during the day, especially for the centre median (Receptor B), in scenario Y, the street is in comfort for most of the day, and also the night.

Most tree-lined street patterns show an increase in comfort towards the middle part of the day. Yet, patterns that include trees at all three receptor points show a more uniform pattern,

Considering the PET outputs, the best OTC for the sidewalks were seen from the case that had a row of Class 3 trees on the median strip and a row of Class 1 trees on both sidewalks (C9) at receptor point C (scenario Y). The pattern has the lowest SVF of 0.274 among all cases considered. The row of Class 3 trees at the canyon centre provides shade in the afternoon hours, as opposed to a similar pattern that adopted Class 1 trees on the centre median (C5, Receptor C, SVF 0.230). However, this was not beneficial for the comfort at Receptor B (C9, SVF 0.450) on the centre median, where C5 with Class 1 trees (SVF 0.429) was a better option.

The impact of the North-South orientation is evident in the warming and cooling patterns during the day, for both scenarios X and Y, where they show a symmetricity before and after midday.

The patterns that incorporate tree cover at the street centre (Receptor B), are cooler than the patterns with trees only on the sidewalks (C1, C2, C3). The aspect ratio of the canyon, in both scenarios, is inadequate to provide shade on the opposing sidewalks and at the centre, but with trees on the centre median, this disadvantage is overcome to a certain degree.

The centre median receptor (Receptor B) is warmest for all tree-lined streets when trees on one or both sides of the canyon were incorporated (C1, C2, C3). The orientation of the street ensured one side of the canyon was in shade, therefore the PET values on the sidewalks were lower. Further, the PET drop pattern at midday, in comparison to the other receptors, is distinctively lower.

4.1.2 Sky View Factor Analysis

Table 2 below shows the highest and lowest SVF values at each receptor.

Table 2. Elvitigala Mawatha (N-S) – Street 01 - SVF at all three Receptors

		BC	C1	C2	C3	C4	C5	C6	C7	C8	C9
Receptor A	Scenario X	0.681	0.507	0.667	0.502	0.620	0.444	0.606	0.427	0.601	0.407
	Scenario Y	0.483	0.314	0.488	0.309	0.455	0.288	0.413	0.248	0.390	0.229
Receptor B	Scenario X	0.784	0.718	0.729	0.661	0.612	0.460	0.646	0.524	0.666	0.540
	Scenario Y	0.600	0.583	0.589	0.575	0.430	0.429	0.465	0.439	0.482	0.450
Receptor C	Scenario X	0.567	0.540	0.405	0.369	0.504	0.310	0.480	0.295	0.460	0.274
	Scenario Y	0.451	0.454	0.281	0.280	0.396	0.230	0.365	0.201	0.356	0.194

The Base Case (BC) with no trees in the street canyons show the highest SVF values. Among the case studies, C1 (Class 1 tree on one side of the street canyon) has the highest SVF at Receptor A and B, while Receptor C has the highest SVF for C1. C9 (Class1 trees on the sidewalks and Class3 tree at the median) has the lowest SVF at Receptor A and C, and C5 (Class1 trees on the sidewalks and centre median) show the lowest at Receptor B. The SVF values generated by RayMan show slight variations even in cases that are similar and symmetrical across the centre median of the canyon. This is due to the adoption of the existing morphology (non-uniform) of the built fabric as opposed to a simplified urban canyon (uniform).

4.1.3 Correlation between SVF and PET

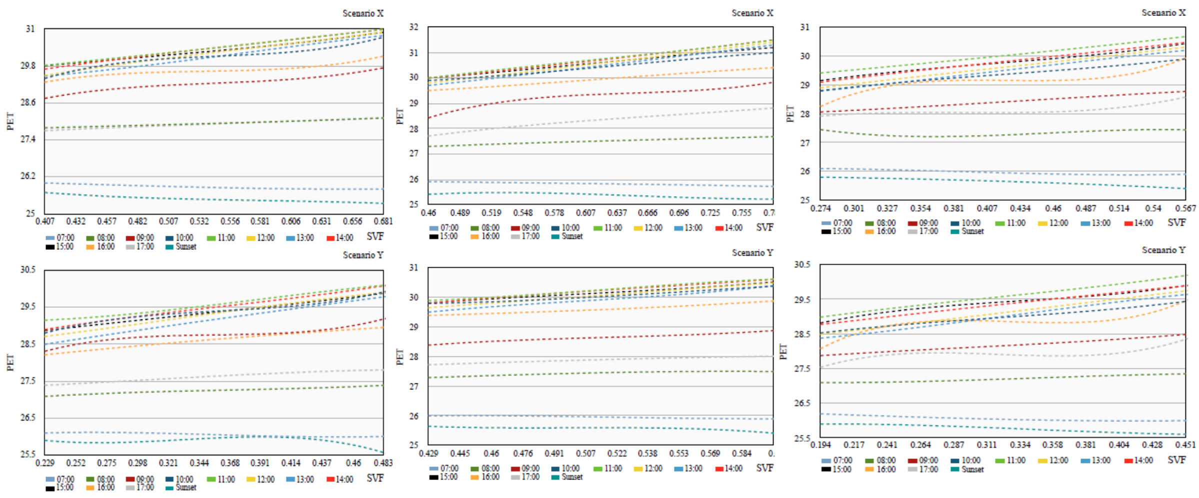


Figure 8. PET and SVF Correlation – Street 01 – Receptor A, Receptor B and Receptor C – Scenario X and Y

To ascertain the impact of SVF on PET, for each receptor point, the data generated for each parameter is correlated. (As detailed in the analysis protocol in Section 3.4 of this paper) (Figure 8)

For all receptor points, Receptor A, Receptor B, and Receptor C, the correlation between PET and SVF show a strong positive correlation. This is found true for both Scenario X and Scenario Y. However, after sunset, both scenarios have a negative correlation between the variables. This indicates that low tree cover improves OTC during the night.

At 07:00 h PET and SVF show a strong negative correlation at all receptor points. Similarly, the correlation becomes weak after 16.00h. In a comparison of the two scenarios, the correlation is stronger during the daytime hours for the potential scenario. (Y).

4.2 ANANDA COOMARASWAMY MAWATHA – STREET 02

4.2.1 Physiologically Equivalent Temperature Analysis

Ananda Coomaraswamy Mawatha – Street 02 is oriented in the East-West direction. Therefore, it is exposed to direct solar radiation throughout the day and requires shade for pedestrians to move around without thermal discomfort.

Overall, in comparison of the two scenarios, the deeper canyon (Scenario Y) is in a better range of OTC conditions than the shallow (Scenario X) during the day. However, during the night, both canyon geometries (existing and potential) have little variation. (Figure 9)

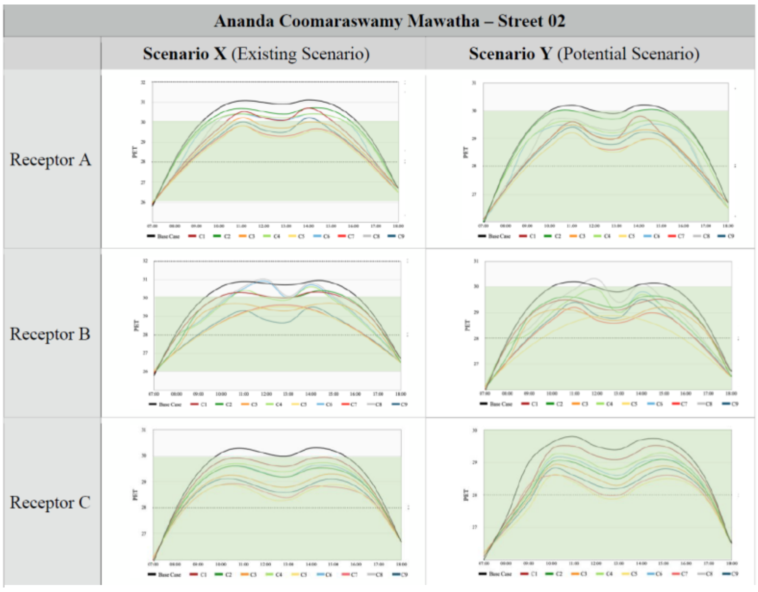


Figure 9. Ananda Coomaraswamy Mawatha – Street 02 – PET analysis

Considering the PET outputs, in Scenario X, orienting rows of Class 1 trees on each sidewalk and the median strip (C5) creates the best thermal sensation during the day. In this case, the trees cover a larger part of the street at a lower height and provide shade for a longer duration.

The PET difference between the Base Cases (BC) and the tree-covered options are clear. Where the PET values generated are the highest during the daytime hours. Yet at night-time, the difference is not as significant and shows lower PET values.

On average, it is seen that when the tree size increases, the thermal comfort level reduces. However, when the aspect ratio is increased, the thermal comfort created by Class 3 trees gets better or almost equal to Class 1 trees. This indicates a connection between tree height and building height. Deeper canyons gain a better comfort level under Class 3 trees as they cover a large surface area and reduce the heat absorption of shaded surfaces. However, this happens only during mid-day, based on the solar orientation, shadow angle and time duration.

Most tree-lined street patterns show an increase in comfort towards the middle part of the day. Yet, patterns that include trees at all three receptor points show a more uniform pattern, Patterns with trees on both sidewalks (C3) create better comfort in the street centre (Receptor B) than the patterns that only cover the street centre (C4, C6 and C8).

C8 (Class 3 tree at the centre median only) for scenario X, at receptor point B, projects the worst-case scenario for all tree-included patterns. The values, although less than the base cases for most of the day exceeds the base case at noon, with a PET value of 31°C.

During the night-time, increased crown cover can be considered the least suitable method to maintain a neutral thermal condition, because such patterns break the connection between the street and the sky, and thus impede radiation loss. When the heat absorbed by surfaces during the day is discharged back to the atmosphere at night, a high crown cover is deemed to trap the heat within the canyon and increases the PET. In addition, cases with Class 3 trees have a better thermal comfort level than Class 1 trees. However, the PET of all the cases in both scenarios is within the comfort conditions during the night.

From all three receptors (A.B, and C), cases that covered the opposite sidewalk of the respective receptor (C1 and C2) or only the median strip (C4, C6 and C8) had a higher PET, since these cases do not provide adequate shade. However, based on the simulation results, shielding the middle of the street from solar radiation using trees only on the median strip, can provide enough shade and improve OTC in this context of an East-West-oriented street.

4.2.2 Sky View Factor Analysis

The table below shows the highest and lowest SVF values in each receptor.

Table 3. Ananda Coomaraswamy Mawatha (E-W) – Street 02 - SVF at all three Receptors

		B C	**C1**	**C2**	**C3**	**C4**	**C5**	**C6**	**C7**	**C8**	**C9**
Receptor A	Scenario X	0.696	0.532	0.611	0.458	0.557	0.366	0.54	0.38	0.544	0.419
	Scenario Y	0.502	0.326	0.464	0.331	0.37	0.232	0.336	0.232	0.379	0.28
Receptor B	Scenario X	0.666	0.525	0.529	0.381	0.505	0.232	0.527	0.237	0.540	0.261
	Scenario Y	0.489	0.340	0.375	0.258	0.323	0.107	0.327	0.235	0.339	0.275
Receptor C	Scenario X	0.524	0.436	0.354	0.276	0.395	0.181	0.366	0.206	0.367	0.236
	Scenario Y	0.398	0.339	0.231	0.185	0.279	0.096	0.245	0.115	0.274	0.150

As seen in Street 01, the Base Case (BC) with no trees in the street canyons show the highest SVF values. Among the case studies, C1 (Class 1 tree on one side of the street canyon) has the highest SVF at Receptor C, while C2 Receptor has the highest SVF for A and B. The highest SVF for Receptor B, Scenario X is seen in C8 (Class 3 tree on the centre median). This is a factor that was not evident in Street 01. C5 (Class1 trees on the sidewalks and centre median) has the lowest SVF at all Receptors, while C7(Class1 trees on the sidewalks and Class2 trees on the centre median), scenario Y, shows a similar value to C5 at the Receptor point A.

4.2.3 Correlation between SVF and PET

As seen in Street 01, (Figure 10) at 07:00 h both scenarios have a negative correlation between PET and SVF. Towards mid-day, the correlation becomes stronger and remains the same till 15:00 h. The correlation becomes moderate just before sunset. This shows that in the early hours of the day, tree cover does not have a major influence on OTC, but towards mid-day shade provided by tree cover helps to reduce PET and improves comfort levels.

After sunset, Scenario X has a weak negative correlation. This is because the available sky view is deemed sufficient to allow radiation loss, thus, better OTC. However, Scenario Y has a strong negative correlation. In this scenario with the influence of the aspect ratio, more sky view improves outdoor comfort during the night.

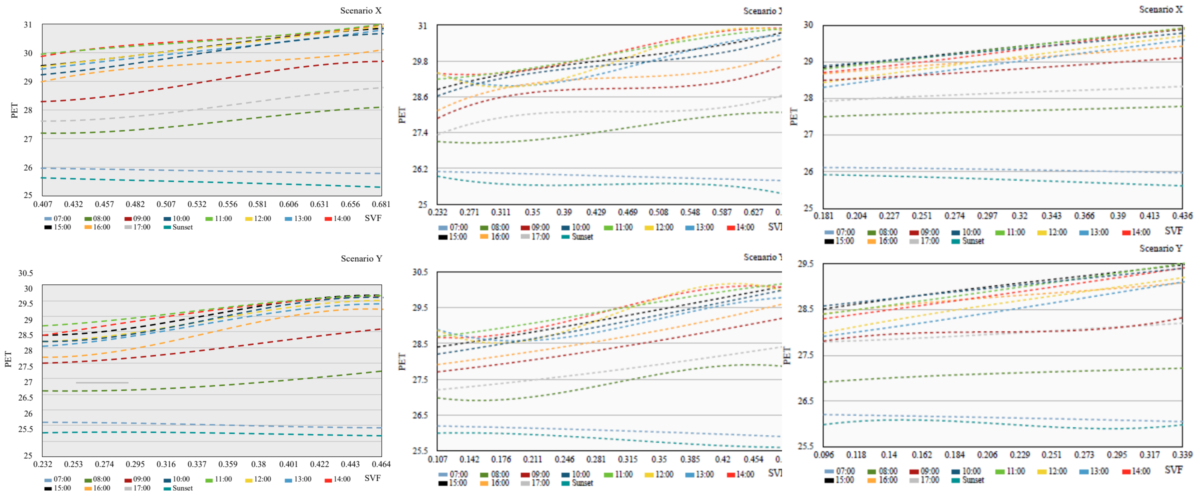


Figure 10. PET and SVF Correlation – Street 02 – Receptor A, Receptor B and Receptor C – Scenario X and Y

4.3 ORIENTATION ANALYSIS

PET values of the two streets are comparatively evaluated in terms of the SVF which includes the crown cover and aspect ratio. Figure 11 shows the PET values of two cases, from the two selected orientations, that share the same receptor point and SVF. The graphs indicate that although the SVF is the same value, the PET values differ. It is clear and known, that SVF is not the only parameter that impacts PET in the urban outdoors. Therefore, the PET variation between the two differently oriented streets cannot be generalised.

Figure 11. Orientation Analysis for similar SVFs for Street 1(N-S) and Street 2 (E-W)

5.0 Conclusions

5.1 DISCUSSION AND SVF IMPLICATIONS

Daytime and night-time thermal comfort of an urban street can be controlled by determining the amount of solar radiation and visible sky. To determine these variables, factors such as street orientation, shading conditions and street geometry should be taken into consideration. This study investigates the optimum choices of street tree planting strategies based on SVF, to improve OTC throughout the day.

The study was conducted on two streets directed to the E-W and N-S orientations in Colombo. Results show that independent of the street orientation, the unshaded and shaded, tree planting patterns had clear impacts on PET values. The impact of tree cover shade was greatest in the daytime hours, while night-time impacts were minimal.

On average C1 and C2 had the highest PET in the E-W case study. These cases have a single row of Class 1 trees on a respective sidewalk. Since the opposite sidewalk and horizontal surfaces were exposed to solar radiation PET values were high. This fact is further proven by other cases at Receptor B. For example, C3 has rows of Class 1 trees on each sidewalk and exposes the median strip, but had a lower PET compared to cases that had a tree row only on the median strip exposing the sidewalks. Therefore, it is crucial to provide shade on building facades to reduce its negative influence on the OTC, especially in an E-W-oriented street. However, this is not a major concern on N-S street.

The SVF can be determined in terms of the aspect ratio and the tree crown cover. Selected streets for the study have two different aspect ratios. As a result, the analysis was mainly focused on the SVF as a whole, and not only in terms of tree crown cover.

In both orientations, high SVFs have a higher PET during the day. On average, N-S street has a higher SVF variation than E-W street since the aspect ratio is low. When different cases that shared the same SVF, receptor and scenario from the two orientations were compared, similar PET values were shown (Figure 11). This also showed that similar SVF can show differing PET values since SVF is not the only parameter that can influence thermal comfort in the urban outdoors.

The pedestrians use sidewalks for movement. Hence, more focus should be given to tree patterns that reduce PET at Receptors A and C when improving thermal sensation for pedestrians. Since E-W street canyons continuously get affected by solar radiation, planting patterns that provide shade on a larger surface area for a longer period, are more suitable to improve the OTC. On average C5 has the best influence on the thermal comfort of Street 2 (scenario X). This case provides shade on each sidewalk, building facades and also at the street centre. Therefore, it reduces solar access and improves thermal sensation during the daytime. All the trees, in this case, are Class 1 in size and provide shade at a lower scale for a longer period.

When the aspect ratio of Street 2 was increased, C5 still had the lowest PET but was equal to the PET of C7. This shows a connection between tree heights and building heights, that is Class 3 trees function well with tall buildings as these buildings contribute to the shade.

For the N-S street, Street 1, C9 planting pattern can be recommended as it contributes more to the sidewalks. This case has a row of Class 1 trees on each sidewalk and a row of Class 3 trees on the median strip. In the morning and evening hours when solar radiation affects the respective sidewalk and facades, available Class 1 trees in these spaces provide shade and reduce heat absorption. In parallel, the row of Class 3 trees provides additional shade on the respective sidewalk and further contributes to improved thermal comfort. This is because, when the solar altitude is low, Class 3 trees on the median street cast long shadows, long enough to cover areas near the sidewalks, but if there were Class 1 trees on the median strip, it will cast less shadow for an area closer to the tree itself. This is the reason for Class 1 trees are beneficial for narrow streets such as Street 2. When the aspect ratio was increased, C9 still had the best contribution to the thermal comfort of the two sidewalks.

Even though the instinctive solution is to provide shade on surfaces to reduce PET and improve OTC during the daytime, these surfaces should also be able to discharge stored energy back into the atmosphere during the night. This improves OTC during the night as well as supports the comfort of the following day. To avoid this, implementing less or no tree cover - therefore higher SVF values - is beneficial to improve thermal comfort during the night. This is common for both orientations.

In this matter, tree patterns most suitable during the day will have a negative effect during the night. Even though SVF implications suitable for daytime and nighttime imply a contradiction, some patterns are conducive for both time durations. For example, in Street 2, C9 will have a considerably low PET during the day and adequate sky view to discharge heat.

However, all the case studies in both orientations and scenarios have PET values that are within the 'comfort' condition at night. Therefore, any planting pattern used for the study is suitable to experience OTC during the night.

In consideration, C5 and C9 can be recommended for E-W street and N-S street respectively to obtain a better OTC during both daytime and night-time.

In terms of aspect ratio, deeper canyons have a lower comfort level during the night. Yet, design strategies can be implemented to minimise the influence. Hence, OTC during the day and night can be simply controlled by the visibility of the sky. The amount of incoming solar radiation does not affect the air temperature, mean radiant temperature or PET alone. The time duration of which solar radiation is received and trapped within the urban fabric also matters. If this fact is neglected excessive solar radiation can deteriorate pedestrian thermal conditions. Avoiding such problems and providing solutions at the design stage is more effective than subsequent mitigatory processes.

5.2 DIRECTIONS FOR FUTURE RESEARCH

The research was focused on representative streets of typical orientations, to explore the relationship between SVF and PET, in the warm humid outdoors of Colombo, Sri Lanka. Future research needs to encompass patterns that extend the scope of the current study to include other orientations and street canyon geometry.

A critical parameter explored was the size and shape of street trees and the patterns in which they were incorporated into the street canyons. Research shows that trees - as living entities - behave differently from species to species. It is interesting to see which particular species works best for the warm humid streets of Colombo.

5.3 CONCLUSION

Safe walkways and driveways, comfort and shade are important aspects of an urban street. Therefore, urban planning needs to be done specifically addressing climatic conditions while improving OTC. Urban planning and design can implement such methods to select trees for different outdoor situations. Urban planners around the world need to practice proper tree planting methods addressing all requirements for overall sustainability. Some follow design guidelines and regulation which includes tree ratings to show the most suitable types of trees and vegetation. Street trees not only improve OTC at the microscale but also at a larger urban scale ensuring environmental performance and reducing the energy consumption of buildings.

6. References

Bourbia, F., Boucheriba F. (2010). Impact of street design on urban microclimate for semi-arid climate (Constantine). Renewable Energy 2010:35(2):343–347. doi:10.1016/j.renene. 2009.07.017

Coutts, A. M., White, E. C., Tapper, N. J., Beringer, J., and Livesley, S. J. (2016). Temperature and human thermal comfort effects of street trees across three contrasting street canyon environments. Theoretical and applied climatology, 124(1-2), 55-68.

De Abreu-Harbich, L. V., Labaki, L. C., and Matzarakis, A. (2015). Effect of tree planting design and tree species on human thermal comfort in the tropics. Landscape and Urban Planning, 138, 99-109.

Hu, Y., White, M., and Ding, W. (2016). Procedia Engineering. An Urban Form Experiment on Urban Heat Island Effect in High-Density Area, 167-173. doi:10.1016/j.proeng.2016.10.020

Koerniawan, M. D., and Gao, W. (2015). Thermal comfort investigation in three hot-humid climate theme parks in Jakarta. American Journal of Environmental Sciences, 11(3), 133.

Johansson, E., Emmanuel, R., and Rosenlund, H. (2004). Microclimate and thermal comfort in the warm humid city of Colombo. In 21st International Conference on Passive and Low Energy Architecture (PLEA) (pp. 329-334). PLEA Secretariat, London, UK.

Matzarakis, A., Rutz, F., and Mayer, H. (2007). Modelling radiation fluxes in simple and complex environments—application of the RayMan model. International journal of biometeorology, 51(4), 323-334.

Oke, T.R. (1981), Canyon geometry and the nocturnal urban heat island: Comparison of the scale model and field observations. J. Climatol., 1: 237-254. https://doi.org/10.1002/joc.3370010304

Qaid, A., Lamit, H. B., Ossen, D. R., and Shahminan, R. N. R. (2016). Urban heat island and thermal comfort conditions at a micro-climate scale in a tropical planned city. Energy and Buildings, 133, 577-595.

Rantzoudi, E. C., and Georgi, J. N. (2017). Correlation between the geometrical characteristics of streets and morphological features of trees for the formation of tree lines in the urban design of the city of Orestiada, Greece. Urban Ecosystems, 1-26. doi:10.1007/ s11252-017-0655-4.

Rathnayake, N. U., Perera, N. G. R., and Emmanuel, M. P. R. (2020). Anthropogenic heat implications of Colombo core area development plan. In IOP Conference Series: Earth and Environmental Science (Vol. 471, No. 1, p. 012002). IOP Publishing.

Satir, O. (2016). Defining the Plantation Role to Mitigate the Urban Heat Island Effects on Global Warming Using Thermal Satellite Sensor. Advanced Technology & Sciences, 3, 1469-1472. Retrieved June 13, 2017.

Shashua-Bar, L., and Hoffman, M. E. (2000). Vegetation as a climatic component in the design of an urban street: An empirical model for predicting the cooling effect of urban green areas with trees. Energy and Buildings, 31(3), 221-235.

Ukwattage, N. L., and Dayawansa, N. D. K. (2012). Urban heat islands and the energy demand: an analysis for Colombo City of Sri Lanka using thermal remote sensing data. International Journal of Remote Sensing and GIS, 1(2), 124-131.