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Improvement of outdoor thermal comfort for a residential development in Singapore

Souradeep Gupta, Prashant Anand, Shashwat

Department of Building, National University of Singapore, Singapore.

Abstract
With more urbanization in an island country of limited land area like Singapore, Urban heat island (UHI) is becoming a widely recognized phenomenon which is causing outdoor thermal discomfort to pedestrians and also causes high energy consumption by buildings. For a prospective residential development in Singapore, computational fluid dynamics simulation and temperature mapping have been conducted to highlight the urban parameters that should be considered to mitigate the adverse effects of UHI effect. Simulation shows higher day time and night time temperature at zones with exposed wall surfaces and pavements due to high sky view factor and higher storage of heat. Creation of more openness on ground and planting trees in such exposed spaces shows reduction in maximum temperature during day by about 2.2 ºC with increase in wind velocity as well. Improvement of outdoor thermal comfort from warm to neutral has been obtained with improved orientation of buildings and introduction of urban greenery.
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Keywords: Urban heat island; Outdoor thermal comfort; Shading, Greenery; Sky view factor; Green plot ratio (GnPR).

1. Introduction

Singapore is striving to realize its vision to be a 'city in a garden' from 'garden city' and thus extensive greening of the island city is being undertaken with support from the government. However, due to sprawling urbanization to meet the population growth several primary forest areas are being converted into built up urban localities. Greening of the island is a much appreciated initiative because trees provide shading and render cooling effect besides enhancing the aesthetics but it must also be considered that new plantations would not replace the primary forest lands. Disappearance of such forests and having new constructions instead can alter the local climatic condition and one of the widely recognized effects is urban heat island (UHI). It is a phenomenon that air temperature in urban areas is higher than the surrounding rural environment [1]. A study carried out in Singapore reveals a maximum temperature difference of 4.01 ºC between the central business district and an intensively planted area in the island [1]. Such change in urban climate has serious implications on use of outdoor spaces and various activities associated that contribute to urban livability and vitality. Pedestrians are more affected by change in urban microclimate as they are directly exposed to the environment as opposed to car users. Therefore thermal sensation or outdoor thermal comfort is affected by the microclimate and unfavorable condition outdoors such as high temperature, low wind velocity would deter people from using urban outdoor spaces. Several researches [2, 3] suggest that encouraging more people outdoors benefit cities in social, environmental, physical and economic aspects. These are key attributes in making a city more sustainable.

As a part of sustainable urban planning it is imperative to understand and consider the effects of urban developments on local climate and how it influences the outdoor thermal comfort. Implementation of sustainable urban planning for existing or future development can thus be considered a three step process - assessment of outdoor thermal comfort, identification of the factors influencing it followed by measures to improve outdoor thermal comfort. Considerable number of researches [4-7] in past decade has been conducted on the outdoor thermal comfort and thermal sensation in different climatic conditions. Lin [7] used PET as the comfort assessment index to study thermal comfort in Taiwan which has subtropical climate. The finding of the study was that cool temperature and weak sunlight are more comfortable to people in subtropical climate. Moreover, it was found that 90% of people in outdoor spaces during summer tend to choose shaded places like areas shaded by trees or building shelter. This hints at importance of shading because temperature and solar radiation are key factors determining comfort as found in [7]. Eliasson et al. [6] found that three climatic factors - air temperature, wind speed and clearness index have significant effect on thermal comfort outdoors. The study also stressed the importance of climate sensitive urban design and planning. Katzschner [5] conducted thermal comfort study in Kassel, Germany and found that people's behavior is influenced by thermal condition outdoors and their expectation. Wei et al. [4] conducted thermal comfort study in outdoor urban spaces Singapore to investigate thermal comfort perceptions and preferences and impact of thermal adaptation on human sensation. The study suggested confirmed that solar radiation or sun sensation of people most significantly effects thermal comfort in outdoor spaces. People tend to adapt by moving to shaded areas or wearing hats. To summarize the findings on outdoor thermal comfort and thermal sensation, it may be inferred that people in tropical or subtropical climate prefer lower air temperature outdoors and less exposure to solar radiation. Wind velocity can also play an important part because people in tropics feel cooling sensation in conditions of higher wind velocity as opposed to people from temperate climate. Wei [8] based on his PhD work developed a thermal comfort equation as function of wind velocity and air temperature (eqn 1) which would be used in this study.

As mentioned before due to rapid urbanization new areas including catchment areas and forest lands are being built up in Singapore. One such location is Mcritchie reservoir surrounding area (as shown in Google earth image Figure 1 (a)). The area under study is highlighted in Figure 1 (a). Mcritchie reservoir situated in northern part of the island is primarily a catchment area surrounded by forest land. New mass rapid transit line construction is proposed which would cut across the catchment area and along with a proposal for new developments is put forward in an area which was primarily a part of the forest land surrounding the reservoir (shown in Figure 1 (b)). The area under study can therefore be seen as two areas - one with existing development and another for proposed development bisected by Pan Island Expressway (PIE). Due to clearing of forest land and upcoming construction proximity to the Mac Ritchie reservoir may lead to a change in the intensity of urban heat island effect in the locality. Therefore, before the layout is prepared it is crucial to assess the outdoor thermal comfort and the different factors such as urban morphological factors and building materials which would influence outdoor comfort in the locality. This paper is aimed at discussing all such factors after simulation and thereafter proposing UHI mitigation and adaptation measures that can be taken to mitigate heat island effect in the area under study. Wind velocity and temperature have been used as climatic parameters. Temperature mapping is done with the help of STEVE tool which is developed at National University of Singapore and can predict average, minimum and maximum temperature of an estate from historical climatic data and albedo of a place [9]. Temperature values at a radius of 50m from a selected point can be obtained with the tool. Wind velocity is obtained by means of computational fluid dynamics simulation on ANSYS. The objectives of the paper can be summarized as

a) Assessing thermal comfort of the existing development and finding out of urban morphological and building material parameters that affect comfort.

b) Proposal of measures to improve thermal comfort of the upcoming development.

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(a) (b)

Figure 1. Site under study

2. Methodology

The existing development was modeled to scale on sketch up. The model was used to generate temperature map using Steve tool. As discussed earlier Steve tool forecasts the average, maximum and minimum temperature of an area as a function of reference climate predictors and urban morphology predictors at a 50m radius of the measurement point.

a) Climatic predictors - Daily minimum temperature (*Ref* T_{min}), Daily maximum temperature (*Ref* T_{max}), average temperature (*Ref* T_{avg}), daytime average temperature (*Ref* $T_{avg\text{-}day}$), nighttime average temperature (*Ref* $T_{avg\text{-}night}$), maximum solar radiation ($SOLAR_{max}$) and total solar radiation ($SOLAR_{total}$) were obtained from Tengah weather station which is closest to the site. The climate predictors are shown in Table 1. Hourly temperature values were obtained from weather station. Average of temperature values from 6 AM to 6 PM was used to calculate reference average day time temperature (*Ref* $T_{avg\text{-}day}$) while average of the rest temperature values were used to obtain reference average nighttime temperature (*Ref* $T_{avg\text{-}day}$).

b) Urban morphology predictors - percentage of pavement area over R 50m surface area (PAVE), average height to building area ratio (HBDG), total wall surface area(WALL), Green Plot Ratio(GnPR), sky view factor(SVF) were automatically calculated by Steve tool for each point from the imported model.

Average surface albedo is also required as input in Steve tool. The average albedo of a city or a district (scale more pertinent at design process) depends on the surface arrangements (e.g. density, orientation, homogeneity, etc.), on the materials used for roofs, paving, coatings, etc., and on the solar position (e.g. site latitude, date and hour) [10]. As per this, average albedo in this case was defined as a single number for the zone taking into consideration the distribution ratio of green area and built area in the zone and was taken as 0.15.

Table 1. Background climatic data for Steve tool temperature mapping

Weather station	Date	Reference Climatic variables	
Tengah (distance from site = 13.8 km)	22nd March,2015	T_{min}	22 ºC
		T_{avg}	27.33 ºC
		$T_{avg\text{-}day}$	29.66 ºC
		$T_{avg\text{-}night}$	25 ºC
		T_{max}	33 ºC
		$SOLAR_{max}$	1058.13 W/m^2
		$SOLAR_{total}$	6000 W/m^2

Measurement of outdoor thermal comfort perception is instrumental in understanding the effect of outdoor environment on human sensation. For Singapore outdoor spaces, Wei [8] in his PhD work developed a thermal comfort equation (eqn 1) which measures outdoor comfort in terms of thermal sensation vote (TSV) as a function of air temperature and wind velocity. Table 2 shows the acceptable TSV ranges for Singapore climate condition [8].

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$$TSV = 0.315T_a + 0.078V - 8.825 \quad (1)$$

where, T_a is the air temperature (ºC) and V is the wind velocity (m/s)
Concurrently, CFD simulation has been carried out on ANSYS to determine wind velocities at different locations. The use of ANSYS software is akin to wind tunnel experiment where one places 3D model of building inside tunnel and studying air stream with certain speed from inlet and analyzing air pattern around 3D block. This software performs a combination of the three types of operation which works step by step for getting the concerned output. The three types of operational engines are – a) Pre-processor:- used for creating the model and for input of the conditional data, b) Solver: - It is used for the execution of simulation. This engine is used only for calculating the part between Pre & Post solvers and does not require any input from user, and c) Post-processor:- It is used for visualizing and analyzing the obtained result.

Table 2. TSV ranges with perceptions [8]

TSV range	Perception
-3 to -2	Not applicable
-2 to -1	Cold to cool
-1 to 0	Cool to slightly cool
0 to 1	Slightly cool to neutral
1 to 2	Neutral to slightly warm
2 to 3	Slightly warm to warm

2.1 Pre-processor steps
A solid mass model of existing structures are created in ANSYS using preprocessor followed by the creation of an artificial domain in such a way that air is thrown with a speed of 3m/s (average annual air velocity at Singapore) from a distance of 40m from two predominant wind direction North and South individually.
Boundary Conditions Flow boundary: Inlet velocity 3m/s from (+Y) direction (means from North) and in second case from (–Y) (means from South) direction.
Details of Meshing are as following and also shown in Figure 2. The mesh comprised of just over 1 million elements. The maximum mesh size noticed was 106m and the minimum size noticed was 3m.Skewness achieved is 0.95.

Sizing	
Use Advanced Size Function	On: Proximity and Curvature
Relevance Center	Coarse
Smoothing	Low
Curvature Normal Angle	Default (18.0 °)
Num Cells Across Gap	Default (3)
Proximity Size Function Sour...	Edges
Min Size	Default (3312.50 m)
Proximity Min Size	Default (3312.50 m)
Max Size	1.06e+005 m
Growth Rate	Default (1.850)
Minimum Edge Length	2610.90 m

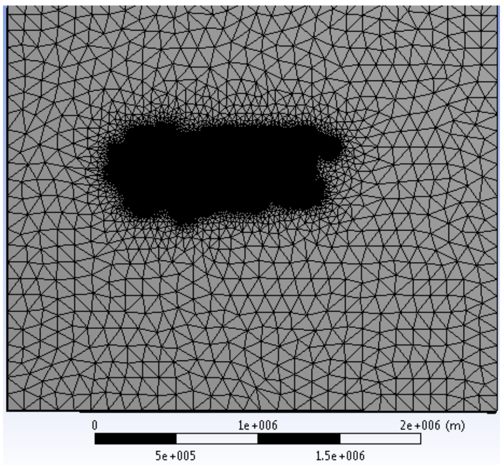

Figure 2. Mesh sizing for CFD analysis

2.2 Input for pre-processor
Analysis Type: Incompressible flow (Turbulent), Ventilation efficiency
Material Properties of Air: Fluid (Incompressible at 30ºC)
Realizable K-ε EQUATION model selected for analysis and analysis done for building massing. Effect of terrain and vegetation not included.

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From wind velocity values and temperature values, TSV s at different locations was calculated. Based on Wei's work, TSV values and corresponding thermal sensations are presented in Table 2. Hotspots are those zones having worst thermal sensations. Thus, some zones were identified for each case depending on the TSV values). For obtaining temperature profile a section is cut across each zone using in-built 'Temperature profile' function on Steve tool, the temperature distribution across a zone is obtained. Steve tool measures the temperature within a 50m radius (area of influence) and ignores the temperature of a point if it is inside a building. Thus the temperature values obtained are entirely the predicted outdoor air temperature values at only pedestrian height.

In the study, zones registering higher air temperature turned out to be hotspots. It is supported in the study by Wei et al. [8] that in Singapore condition outdoor thermal comfort is mostly influenced by sun sensation or solar radiation as obtained by correlation analysis.

TSV has been calculated for daytime and nighttime using the highest of average day time temperature ($T_{avg\text{-}day}$) and highest of average nighttime temperature ($T_{avg\text{-}night}$) respectively. Night time outdoor thermal comfort is important in case of residential development because working people usually get back home in late afternoon or evening. Air temperature rises due to reradiation from building surfaces at night. Warmer air temperature influence nighttime thermal comfort in outdoor spaces surrounded by buildings. Such effect is more prominent when wind velocity is low and thus there is lack of heat extraction from the urban environment.

Upon analysis, several factors contribute to urban heat island in an urban residential development like the cases under study have been discussed. Mitigation measures have been proposed for both existing and proposed developments that would help to ameliorate UHI. With Steve tool and CFD simulation, effect of measures such as urban greenery and modified urban layout are assessed to realize the improvement in outdoor thermal comfort.

3. Simulation results and analysis

Steve tool simulation for air temperature and CFD simulation to obtain wind velocities have been carried out for the case which is also referred to as baseline scenario. Therefore, in the first stage baseline model has been analyzed to understand the temperature and wind velocity pattern in the current settings and the associated outdoor thermal comfort. The different urban morphological factors causing outdoor thermal discomfort have been figured out and analyzed. An urban model (for the upcoming development) has been developed taking into consideration the factors from baseline case and introducing measures that would ameliorate UHI and improve outdoor thermal comfort.

CFD simulation images for wind from north and south direction at occupant height is shown in Figures 3 and 4 respectively. Comparing the results obtained, for North and South, for the four zones identified also marked in Figures 3 and 4.

Zone 1 - In both cases has highest wind velocity as it is an open area. Wind flow is not restricted by the building massing. The average wind speed observed in this zone is about 1.55 m/s.

Zone 2 - The buildings are well scattered but due to a larger footprint along the prevailing wind direction create obstruction for wind to flow into the space. In this zone, funnel effect is very clearly visible in case of North wind, channeling wind into the zone. However in case of South wind, low rise blocks create obstruction, thus poor air movement.

Zone 3 – Low rise well scattered buildings with wide openings enhance the wind movement and good air circulation for both North and South wind. Wind velocity of 1.1m/s has been observed in this zone.

Zone 4 – Dense massing with narrow pavements and no height variations leads to least wind penetration in the canyon. This is the worst situation and unfortunately depicts condition of major cities in the world. Air stagnation in such zones could have a positive feedback to pollution problems leading to adverse effect on air quality, thus respiratory ailments.

3.1 Baseline scenario

3.1.1 CFD simulation results

As shown in Figure 5, the section cut through zone 2 clearly indicates that the surface of the building overlaps with a wind speed ranging from 0.6 to 2m/s which provides a reasonable amount of surface is cooling. Whereas, the building surface on the leeward side have less but enough amount of surface overlap for necessary cooling.

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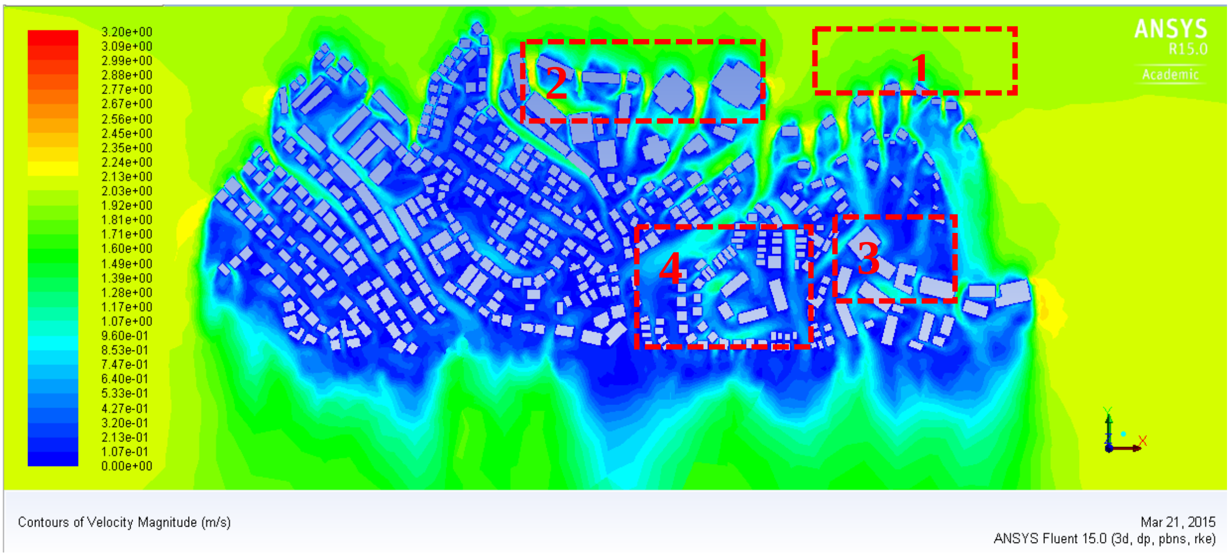

Figure 3. North wind @2m\s and Section cut at 1.2m height

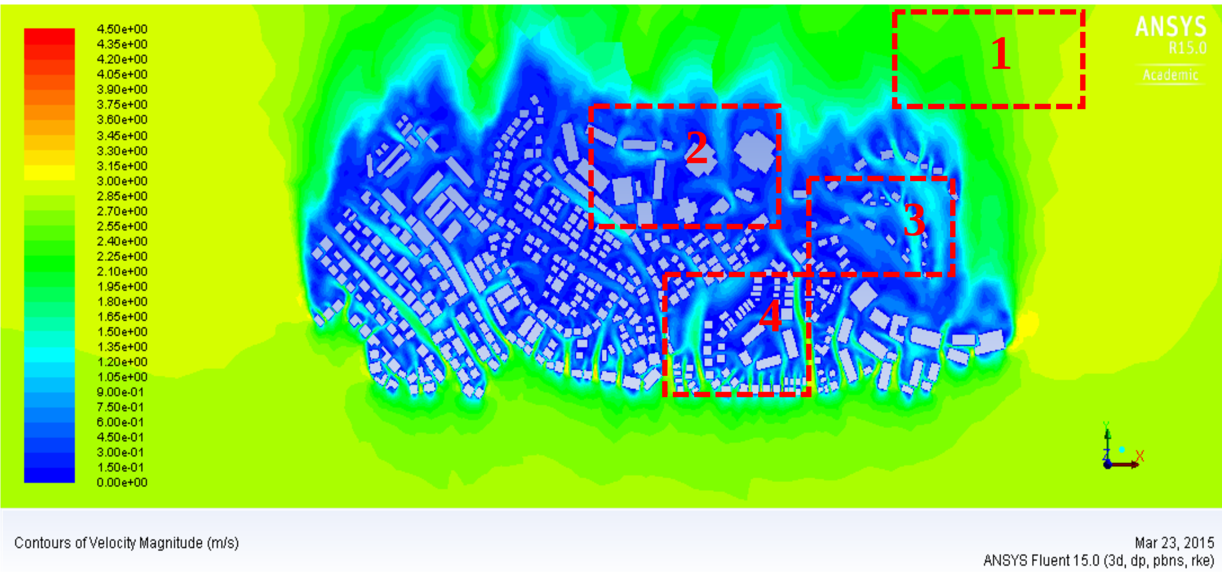

Figure 4. South Wind @2.8m/s and Section cut at 1.2m height

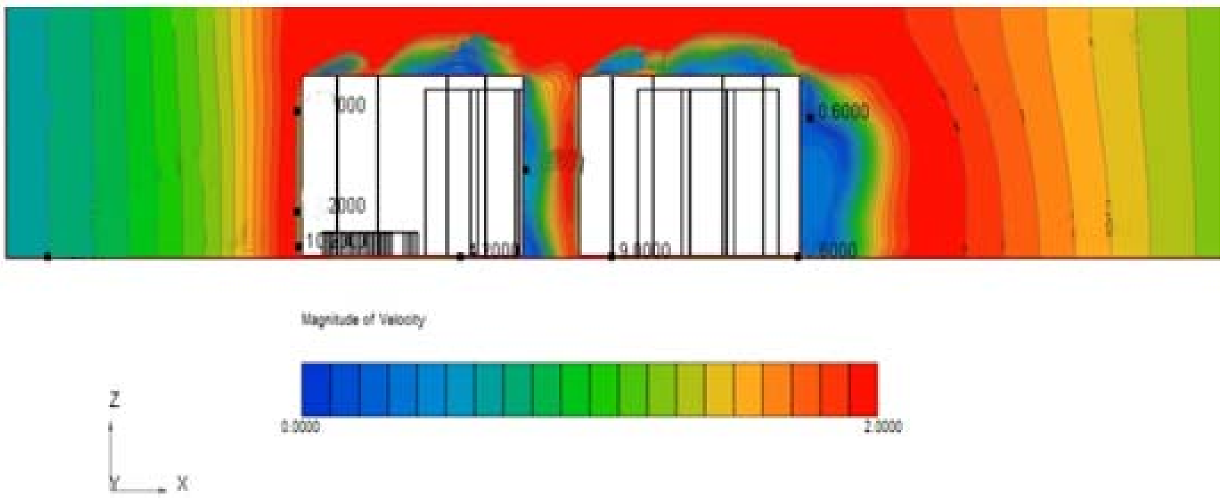

Figure 5. Wind speed around a building in zone 2

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3.1.2 Temperature mapping (Steve tool) and calculation of outdoor thermal comfort

Same zones as considered in CFD analysis are also considered for analysis of temperature distribution. All the zones have different urban features and landscapes. In Figure 6, Zone 1 is marked by 1, Zone 2 marked by 2 and so on. Zone 1 is this case is the zone having highest percentage of greenery because of the presence of primary forest land and no built area in the zone. Zone 2 is the area having higher rise buildings with some greenery in between buildings. Zone 3 has lower storey buildings but still sky view factor is not very high due to presence of greenery in the zone. Zone 4 is characterized by lower storey buildings and lesser greenery compared to zone 3 and therefore higher SVF and more exposure to solar radiation. Most hotspots are developed in zone 4.

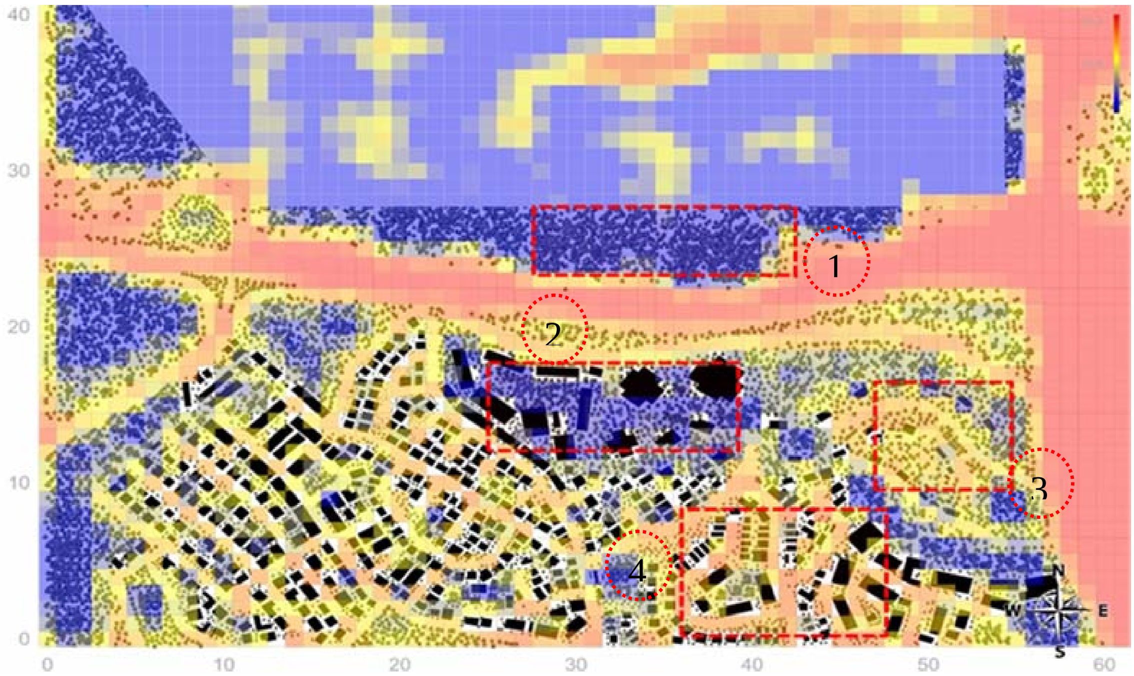

Figure 6. Maximum temperature distribution map and zoning

The daytime and nighttime thermal comfort indices for different zones are shown in Table 3 and Table 4 respectively. It can be observed Zone 1 is the only thermally comfortable zone while Zone 2, Zone 3 and Zone 4 display thermally uncomfortable outdoor environment (sensation on warmer side). As expected Zone 4 display worst outdoor thermal comfort among all four zones.

Nighttime indices can be interpreted as all zones to be in the thermally comfortable range. Zone 1 has the widest extent of greenery and thus displays lowest nighttime temperature due to reduced absorption of radiation during daytime because of shading by trees. Many factors such as SVF, greenery and so on could be attributed for other zones showing outdoor thermal comfort during nighttime. The next section analyses the thermal comfort and formation of hotspots at different zones.

For Case 1 it is observed that all the zones have some amount of greenery and therefore the analysis graphs are made with GnPR as the parameter on x-axes and the variation in temperature is studied. Zone 1 is perhaps the best case scenario in terms of thermal comfort and therefore analyzed to understand the variation of temperature with green plot ratio and sky view factor. Zone 1 does not have any building and thus no building parameter (e.g., wall area, height of building etc) has been analyzed with respect to temperature profiling.

Table 3. Daytime outdoor thermal comfort indices

Zones	Temperature (^oC)	Wind speed (m/s)	TSV	Remarks
Zone 1	29.65	1.55	0.39	Slightly cool to neutral
Zone 2	32.5	0.75	1.35	Neutral to slightly warm
Zone 3	32.83	1.1	1.43	Neutral to slightly warm
Zone 4	32.95	0.67	1.50	Neutral to slightly warm

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Table 4. Nighttime thermal comfort index for different zones

Zones	Temperature (^{o}C)	Wind speed (m/s)	TSV	Remarks
Zone 1	24.96	1.55	-1.08	Cold to cool
Zone 2	25.47	0.75	-0.86	Cool to slightly cool
Zone 3	25.56	1.1	-0.86	Cool to slightly cool
Zone 4	25.66	0.67	-0.18	Cool to slightly cool

3.1.3 Steve tool simulation results and analysis

Zone 1

Temperature profile for zone 1 - minimum temperature (Tmin), average temperature (Tavg), maximum temperature (Tmax) and SVF are shown in Figure 7.

- The temperature in this zone is entirely dependent on shading created by greenery. With increase of GnPR, there is a reduction in average and minimum air temperature. Higher GnPR means reduction in exposure to radiation (SVF) and thus higher shading. There are fluctuations in average temperature (Tavg) due to fluctuation in GnPR. However, once complete shading is provided, the fluctuation is less. Highest recorded peak has been observed when there is some exposure at highest SVF (plotted on secondary y-axis) of 0.11.
- Increase of GnPR most prominently affects minimum air temperature (Tmin). Minimum temperature is recorded usually during night hours and thus Tmin is much dependent on GnPR because the heat released from the surface depends on the amount of shading provided. Higher shading translates into reduced absorption of radiation and thus reduced reradiation from the surface.

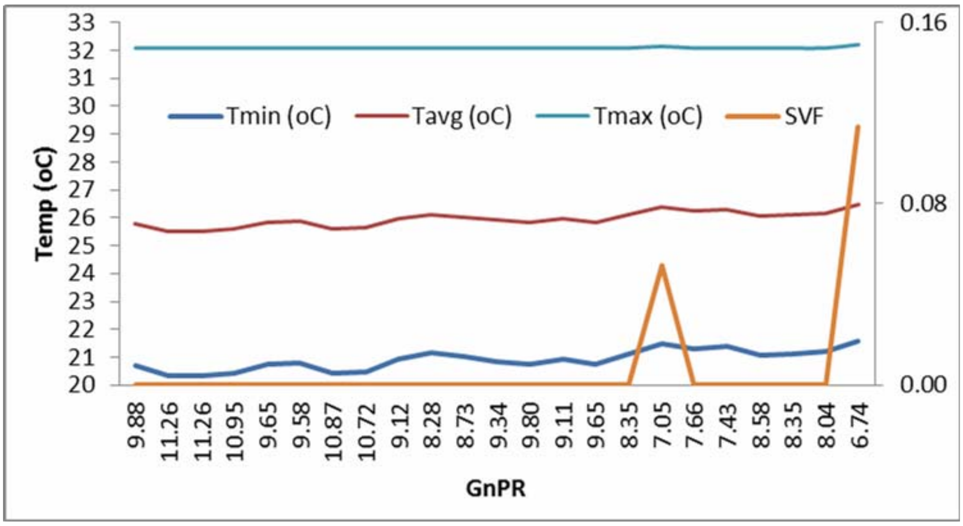

Figure 7. Temperature profile for Zone 1

- Once the greenery completely covers up the sky (SVF = 0), only greenery density reduces Tavg. Complete shading has been provided at GnPR of 8.35. As per [9], reduction in average temperature is more prominent when GnPR increase in the range of 0 to 4. In this zone, the lowest GnPR recorded was 6.74 and thus any increase from this figure does not reduce average temperature by significant extent.
- Maximum temperature (Tmax) is fairly constant in this zone (very minimal reduction). It is supported by Jusuf and Wong (2009) that once complete shading (SVF = 0) is provided, further increase in greenery (GnPR) do not significantly impact maximum temperature.

Zone 2

Temperature profile for zone 1 - minimum temperature (Tmin), average temperature (Tavg), and maximum temperature (Tmax) is shown in Figure 8. Wall area (scaled down) and average height are also plotted on secondary y-axis.

- Maximum temperature appears to be influenced by pavement area and exposure to sky. At low GnPRof 1.93 and 1.46, maximum pavement area and high sky view factor were encountered and thus

Tmax was high at these two points. Due to dense greenery in the region, the maximum temperature remains fairly constant at other points across the zone.

- Complete shading has been provided at GnPR of 3.63 which is the green area between buildings. Closer to the buildings Tavg appear to increase due to high wall surface area. Although tall buildings are supposed to provide shading, the building footprint in this case is high and thus with high wall area, Tavg is affected by long wave radiation from walls.

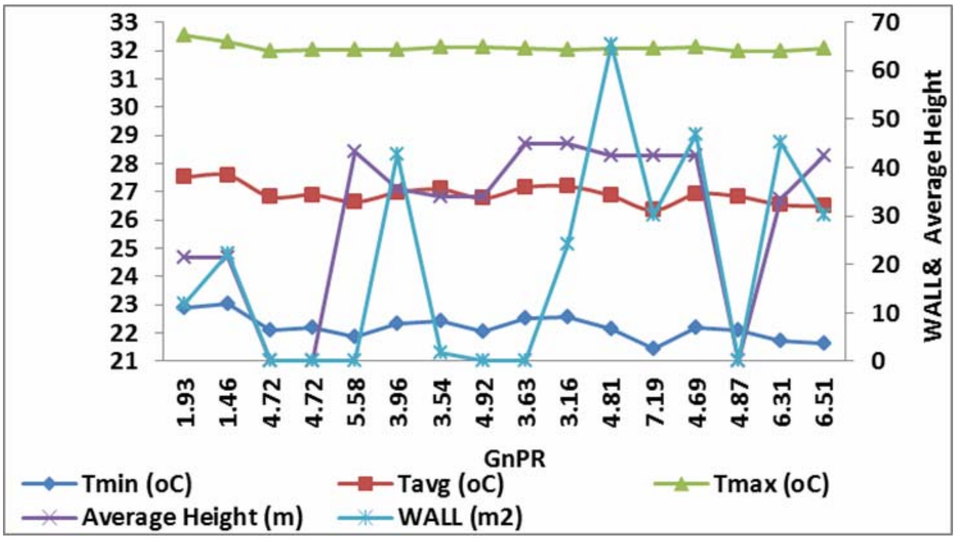

Figure 8. Temperature profile for zone 2

- This zone is characterized by high extent of greenery and tall buildings and therefore it is difficult to single out the affect of shading by building or by trees. This is more of a combined effect of both. In Figure 8 when GnPR decrease from 3.63 to 3.16, there is no change in Tavg (although very little change in Tmin) possibly because of the shading by tall buildings as the zone is between two high rise buildings (shown by border in Figure 10).
- Also, as shown in Figure 9, when GnPR decrease from 4.92 to 3.63 and further to 3.16, SVF also decreases which is due to high rise buildings in the zone. With increase in height of the building (as highlighted by dotted box in Figure 9), more shading is provided and hence even after decrease in GnPR, SVF is reduced in this location.
- Tmin although mimics the trend of Tavg is more influenced by GnPR and thus decrease more sharply with increase in GnPR.

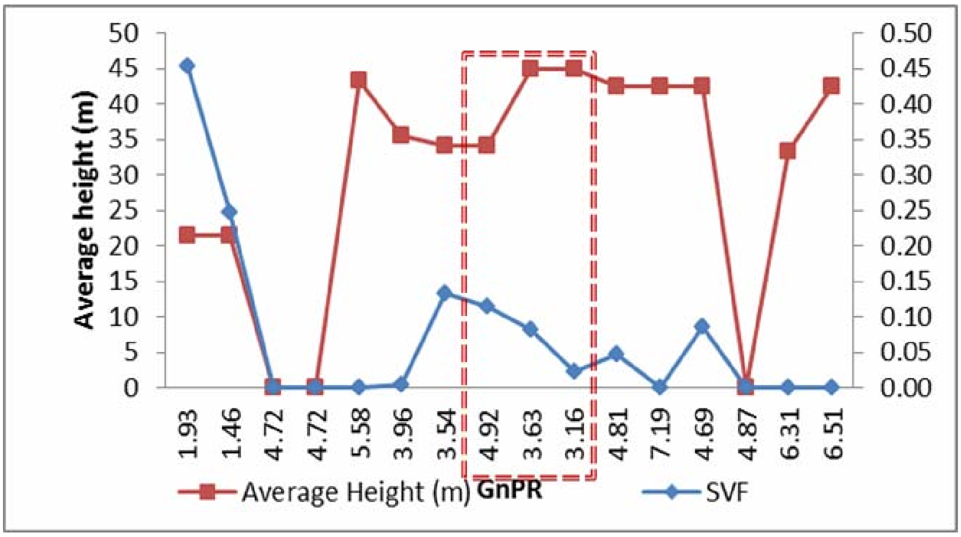

Figure 9. Average height and SVF across Zone 2

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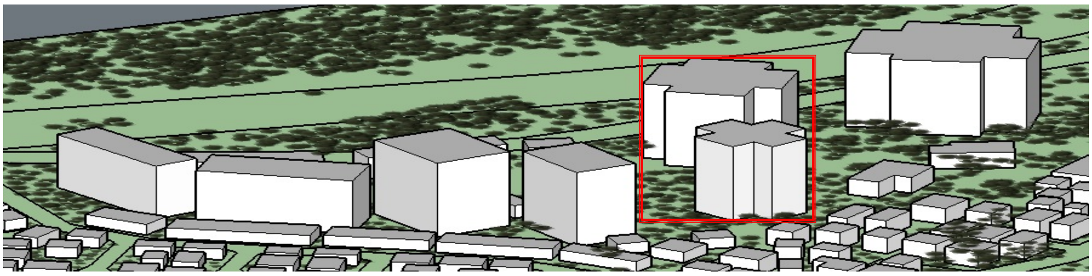

Figure 10. Layout of Zone 2

Zone 3

Temperature profile for zone 1 - minimum temperature (Tmin), average temperature (Tavg), maximum temperature (Tmax) is shown in Figure 11. Wall area (scaled down) and average height are also plotted. SVF is plotted on secondary y-axis.

■ Zone 3 has higher openness (average SVF = 0.60) compared to zone 1 and zone 2 and comparatively lower GnPR as well ; wind velocity is low because of obstructions on north and south side and therefore some hotspots are formed.

■ More lower storey buildings (2-3 storeys) in the area and thus less shading by buildings. Average temperature show a fairly constant profile due to less variation in GnPR . Although building height is fixed in this zone, little increase in Tavg has been observed nearer to wall surface with GnPR reduction from 5.03 to 3.47.

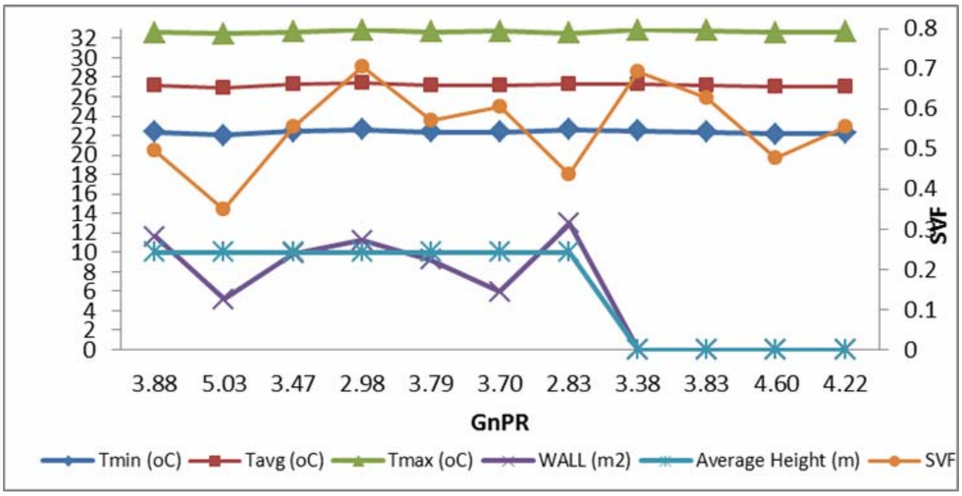

Figure 11. Temperature profile for Zone 3

■ Higher Tmin recorded near the wall surfaces. Minimum temperature of a certain day happen during late evening to night when building surfaces release absorbed heat by long wave radiation. Therefore, near wall surfaces especially near unshaded surfaces higher minimum temperature is recorded.

Even with relatively small sample size, the correlation between Tmin and wall area (scaled down) was found to be strong as shown in Figure 12.

Zone 4

Temperature profile for zone 1 - minimum temperature (Tmin), average temperature (Tavg) and maximum temperature (Tmax) is shown in Figure 13 with variation in GnPR. Wall area (scaled down) and average height are also plotted. on secondary y-axis.

■ Maximum number of hotspots could be seen in Zone 4. Complex geometry of the zone (wind speed of 0.62 m/s) with high building density and higher openness (SVF = 0.77) results in worse outdoor thermal comfort.

Figure 14 shows the variation in average height and SVF with different GnPR s across the zone. In this location, SVF is more influenced by localized greenery and wall spans than building height, which is constant in this zone.

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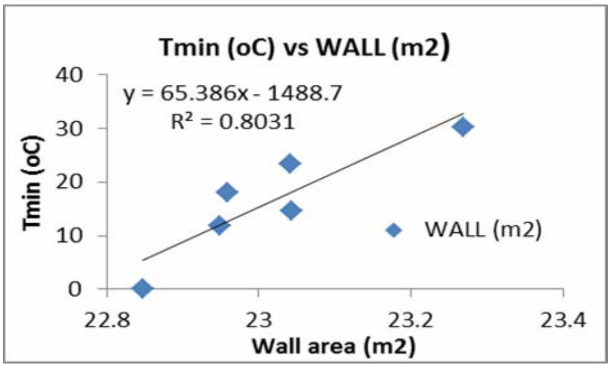

Figure 12. Correlation between Tmin and Wall area (scaled down)

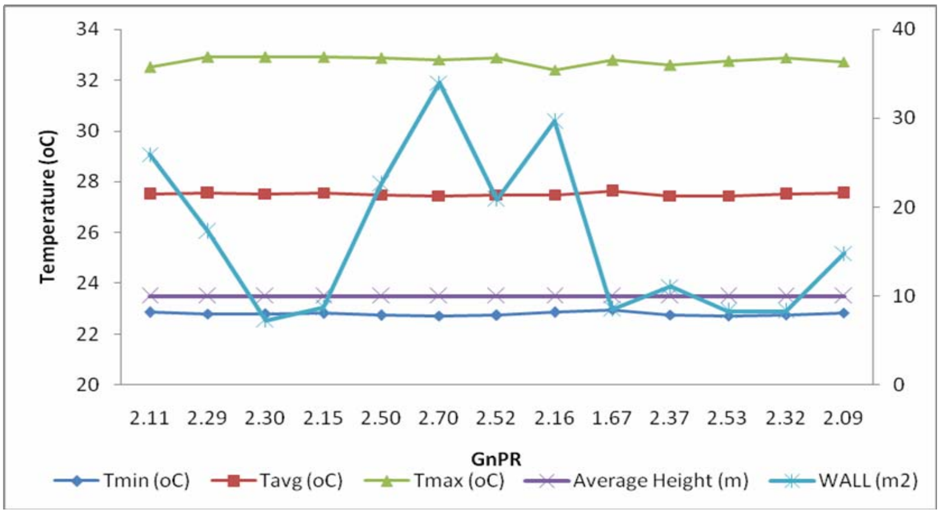

Figure 13. Temperature profile for Zone 4

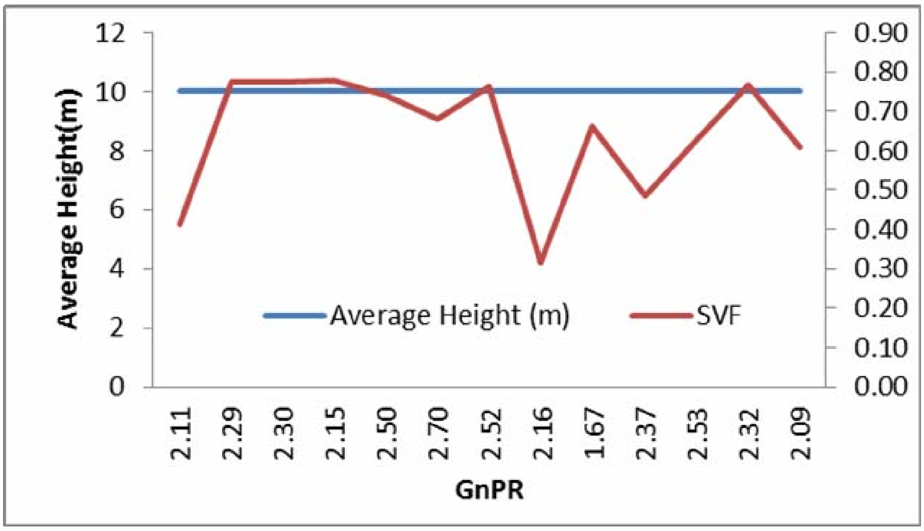

Figure 14. Average height and SVF across Zone 4 (SVF plotted on secondary y-axes)

- Maximum temperature is fairly constant except a decrease is observed from the zone with GnPR = 2.52 to 2.16 coupled with increase in Wall area. This is evident of shading by long walls facing the measurement point.
- Average air temperature in this zone is fairly constant except a little increase with decrease in GnPR from 2.16 to 1.67 and simultaneous decrease in wall area. This is a situation of higher degree of openness to radiation.

■ Higher minimum air temperature is observed near wall surfaces which have been discussed earlier under analysis of Zone 3.

3.2 Analysis- day and night time temperature profile

It is important to analyze the average day time and average night time temperature across four zones since all the zones are different in types of the parameters that govern the temperature of the area like wall area, building height, GnPR, SVF and so on. Average day and average nighttime temperatures are plotted across four zones in Figure 15.

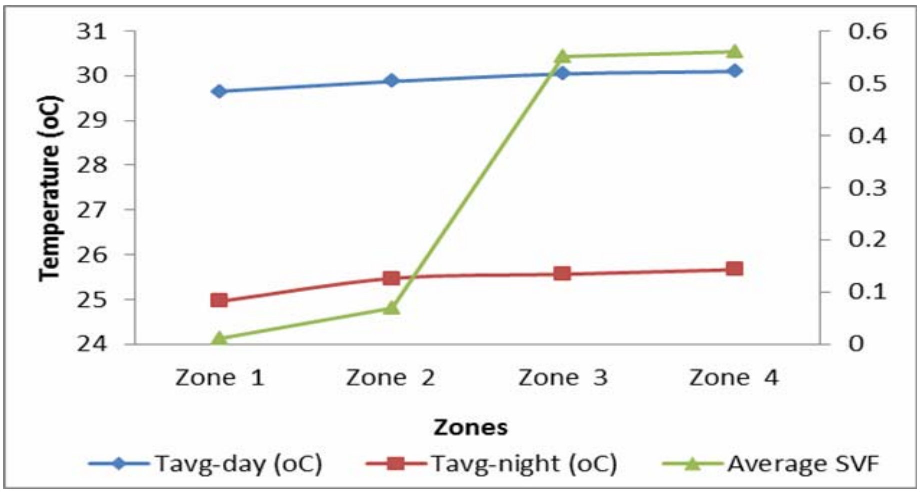

Figure 15. Variation in day and nighttime temperature in different zones

3.2.1 Day profile

■ Zone 4 is characterized by high small building density and high average SVF which indicates higher exposure to solar radiation during day time. Thus the highest average day time temperature is recorded for zone 4.

■ Zone 3 has comparable SVF as zone 4 and therefore display almost same temperature during daytime. However, very small difference is observed which may be due to higher GnPR in zone 3.

■ Much lower SVF is experienced in Zone 1 and Zone 2. Zone 1 is covered with greenery with no buildings and therefore the shading is entirely due to trees in the area while Zone 2 experience shading due to both greenery and buildings. However, during day time shading by any means reduce temperature and therefore Zones 1 and 2 experience lower average day time air temperatures.

3.2.2 Night profile

The role of SVF is more prominently understood in the analysis of average nighttime temperature when studied together with building/ pavement parameters. In urban environment building surfaces such as walls and pavements absorb radiation and store it only to release by long wave radiation during night. Therefore, let us take wall area (WALL) as the parameter to better analyze the night time profile.

■ Zone 4 has higher building density and therefore higher wall area and comprises mainly of low rise buildings. Due to high degree of openness and therefore high SVF, more wall area means more absorbance of radiation and more resultant long wave radiation from wall surfaces especially at night. Average day and night time temperature profile for different zones are shown in Figure 16. Table 5 lists the average wall areas at four zones.

■ Zone 3 has denser greenery and lower wall area compared to zone 4 and therefore experience lower temperature than Zone 4. Radiation at night expected mostly from wall and exposed pavement surfaces.

■ In the night time case, higher difference in air temperature between Zone 1 and Zone 2 could be observed from the graph. Previously it was mentioned that the amount of shading in both the zones are high but this temperature difference is created by the difference in shading means. In Zone 2, some shading is also provided by high rise buildings along with greenery and therefore absorbed radiation during day is released in the night resulting in higher temperature in Zone 2. The slope of average SVF from Zone 1 and Zone 2 is very identical to the slope of average night time temperature from Zone 1 to Zone 2.

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The analysis of the baseline model reveals several urban morphological factors that influence outdoor thermal comfort. A summary of baseline model analyses listing all the factors is presented in Table 6.

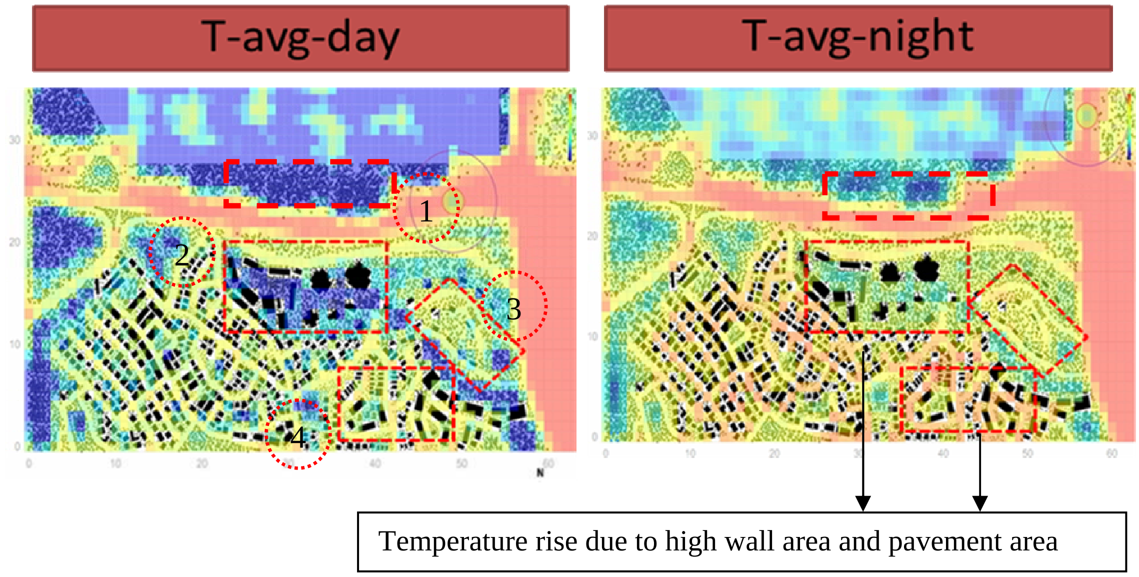

Figure 16. Average day and night time temperature profile for different zones

Table 5. Average wall area across zones

Zones	Wall area (m^2)
Zone 1	0
Zone 2	2004
Zone 3	944
Zone 4	1620

Table 6. Summary of factors influencing outdoor air temperature as analyzed in case 1 and case 2

Factors	Effect
Sky view factor (SVF)	High sky view factor means more exposure to direct solar radiation and higher absorption by buildings in urban environment. Contribute to urban heat island due to build up of sensible heat because of warm building surfaces.
Complex urban geometry	Complex urban geometry is one of the reasons of heat buildup in urban canyons or highly built-up areas like the case under study. As observed from CFD analysis, there is very low wind velocity at locations of complex building orientation. This is associated with reduced heat extraction and consequential heat build up by multiple long wave radiation between building surfaces.
Green plot ratio (GnPR)	Higher green plot ratio means more trees and thus higher extent of shading. Shaded pavements and buildings means reduced absorption of solar radiation and thus reduced buildup of sensible heat. Nevertheless, higher GnPR means cooling of urban air by evapotranspiration as well.
(Unshaded) Wall and pavement area	High wall and pavement area if unshaded would cause air temperature to rise, especially during nighttime. Heat absorbed during day time is stored and released as long wave radiation during night and cause warm air temperature. In other words, unshaded walls and pavements may be responsible for causing nighttime UHI.
Building height	High rise buildings may provide shading by reducing sky view factor. However, once complete shading is provided, increase in building height may be associated with temperature rise due to high wall area (Jusuf and Wong, 2009). This would also depend on the shape (e.g. aspect ratio of building) and orientation of building.

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4. Mitigation strategies

4.1 Proposed mitigation strategies

Mitigation of UHI is a very complex process and not one method would be sufficient to address it. This is even more difficult for already developed area. However, the land area which is yet to be developed can be designed such that it can be minimized. There are many ways of doing so- from building form to areas urban design, from choice of material application to introduction of vertical greenery, from land use to behavior of people residing or using the area. By our study we have found that following which can be considered while designing new place for less UHI impact. Table 7 lists the mitigation measures at urban level and building level that may be implemented to mitigate UHI in the proposed development.

Table 7. Proposed Mitigation measures

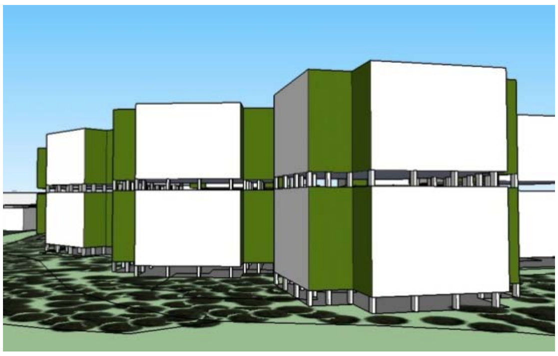
Scale	Mitigation measures	Mechanism	Scheming
Building	Use of high albedo coatings on roofs and walls	Sensible heat gain may be reduced by application of high albedo coatings like cool paints on roofs and walls. High albedo paints are proposed on roofs and walls of high rise buildings. Application of cool coatings on roofs of only high rise buildings would mitigate glare and effect of reflected radiation experienced by lower storey buildings.	
	Green roofs and green walls	Green roofs and green walls may be explored to reduce heat gain by building walls and roofs. Due to high wall area green walls would be an excellent means to shade the walls and mitigate storage of heat in such building elements of high thermal mass. Green roofs may be widely implemented for lower rise buildings or as sky gardens in case of high rise as well.	
	Creation of void decks	Enhancing wind flow in urban canyon would create better urban ventilation. Creation of void decks is proposed at ground level and/ or at mid height of high rise buildings to provide unhindered movement of wind through buildings and urban canyon. Such alteration in building design can also help in effective increase of wind speed through the canyon.	

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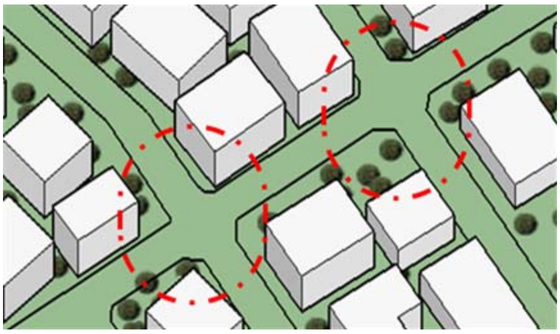
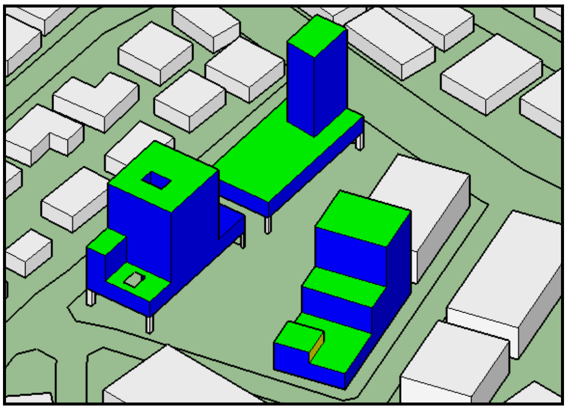
Table 7. Continued

Urban	Urban greenery	Introducing urban greenery in the form of parks or planting trees along the roadside or near buildings can provide excellent shading and reduce heat gain by the building fabric. Outdoor thermal comfort may be significantly improved by introduction of greenery because people in tropics tend to be sensitive to direct solar radiation which would be minimized by shading.	
	High albedo pavements	Dark and rough materials are warm materials and therefore trap heat [11]. High albedo pavements (for example, white concrete pavements) can be implemented which would mitigate high sensible heat buildup in case of otherwise dark asphalt pavements. Permeable pavements can also be implemented in case of internal roads. They have higher effective albedo and are able to convert some sensible heat into latent heat.	
	Orientation, shape of building for effective wind paths	Making building design and urban form which has • Stepped structures with lower height in the direction of prevailing wind for better ventilation performance • Buildings at different height in the region to promote the effective ventilation and voids for cross ventilation • Minimum footprint on ground level thus minimizing the amount of heat stored within the structures. • Vertical Shafts or central open area can help in maintaining the wind flow. They provide permeability along the prevailing wind conditions and hence the orientation can be fixed on the basis of the prevailing wind conditions.	

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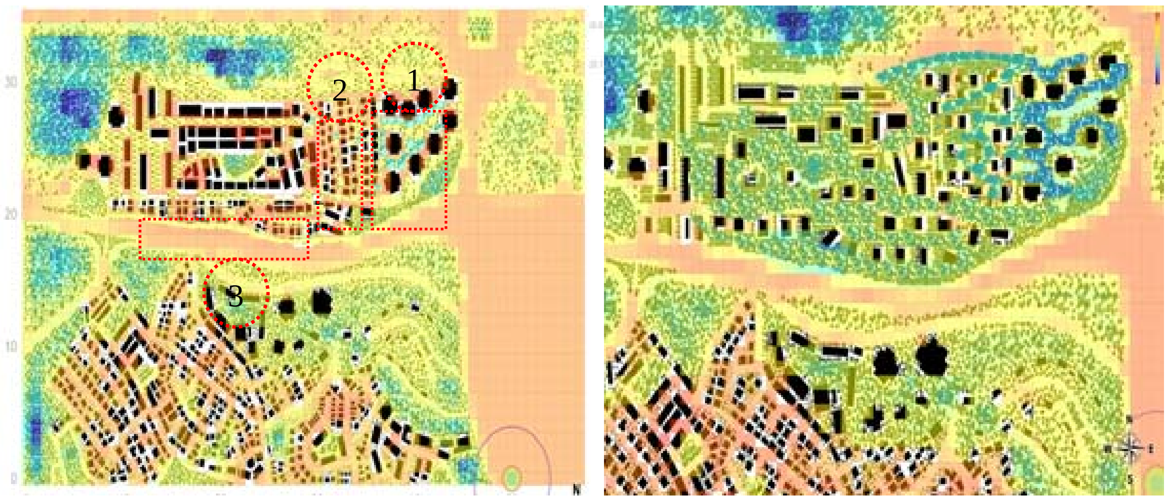
4.2 Improvement of thermal comfort by urban greenery and changing building morphologies

To study the effect of mitigation strategies in improving thermal comfort for the proposed development, two cases are developed. First case is developed with GnPR equal to average GnPR of Zones 2, 3 and 4 in baseline case (GnPR = 3.52). In this case the height distribution of buildings is kept same as baseline case but the orientation is done to maximize the number of housing in the proposed development at the mentioned GnPR. The second case is modeled considering the mitigation strategies already discussed in section 4.1. For example, for high-rise buildings void deck and a void between floors have been provided, lower rise buildings have been oriented on the street to provide space for greenery and so on. Such change in urban morphology influence thermal comfort by providing better urban ventilation and thus higher wind speed through the urban canyon. Such modified layouts also influence the temperature distribution by providing more shaded spaces owing to introduction of more greenery.

Wind velocities have been obtained from CFD simulation conducted for both the cases following the same methodology for baseline case. Similarly, Steve tool has been used to obtain the temperature distribution. The effect of urban greenery was studied by means of Steve tool. The cooling effect due to greenery is manifested by shading it provides to otherwise exposed buildings and pavements. Three sample zones - zone 1, zone 2 and zone 3 are chosen to study the effect on improvement of thermal comfort by introducing the mitigation measures. Selection of zones was based on the characteristics of each zone before mitigation measures were adopted. Zone 1 is characterized by high-rise buildings while zone 2 is mostly occupied by low rise structures with high SVF. Zone 3 has been chosen for two reasons – firstly, the same zone in first case was occupied by dense greenery and thus a comparison may be valuable; secondly, this zone has rather complex layout. Such layout may have important implications on heat buildup and rise in air temperature.

The Steve tool average temperature distribution is shown in Figure 17 (a) and (b) for the cases before mitigation and after adopting mitigation measures respectively. As could be seen from temperature map, there is difference in average air temperature of the zone after introduction of such measures. The previously red zones depicting higher temperature are mostly green now meaning lowering of ambient temperature.



(a) (b)

Figure 17. (a) Average temperature map for Unmitigated case (b) Proposed case by introducing mitigation measures

Average temperature is reduced by introduction of greenery because SVF of previously exposed zones were reduced by shading by trees. Reduction upto 0.5 degrees during day and upto 1 degree during night have been observed as shown in Figure 18. For zones 1 and zone 3, reduction during nighttime is more prominent than during daytime. Night time reduction may be expected to be more in these zones because due to low SVF, walls and pavements absorb less radiation during day and thus nighttime radiation from those elements decrease significantly. Shading in Zone 1 is provided by tall buildings which absorb radiation during daytime; therefore due to shading in this zone, more prominent reduction is observed during nighttime. In case of Zone 3, wall area is substantially high with exposed pavement area due to low SVF and therefore, more reduction in temperature observed during night.

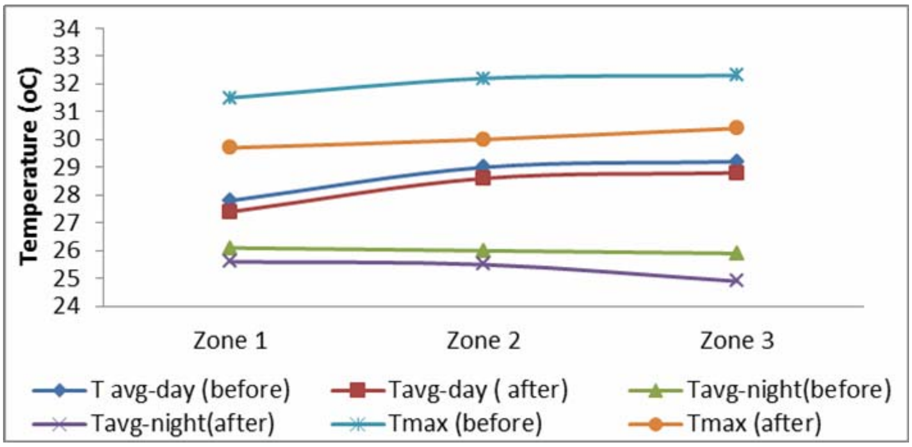


Figure 18. Maximum and Average night and day time temperature before and after mitigation

Paired t-test was conducted to test the effect of introducing mitigation solutions on air temperature - average, average daytime and average nighttime temperature. Under the null hypothesis that there was no effect due to greenery, for all three cases $t_{critical} > t_{tabulated}$ at 95 % confidence interval (average temperature, $t_{critical}$ = 8.97 > $t_{tabulated}$= 2.06;average day temperature,$t_{critical}$ = 13.70 > $t_{tabulated}$= 2.06; average night temperature, $t_{critical}$ = 12.07 > $t_{tabulated}$= 2.06). Statistically, there was significant reduction in air temperature obtained dueto introduction of greenery.

For first case, thermal comfort was calculated with the obtained temperature values and wind velocities. The thermal sensations for day time and night time are listed in Table 8 and 9 respectively. As could be seen from the table, the thermal sensation is outside the comfort range in all three zones during daytime. This may be due to lack of sufficient greenery and therefore shading in the zones which in turn increases the exposure of surfaces like concrete walls and asphalt pavements to solar radiation. Radiation absorbed is releases gradually over time thus making the air temperature rise and making thermal sensation move towards the warmer side.

However, nighttime thermal sensation is within the comfort range for all zones. In such urban configuration, nighttime thermal comfort also depends on SVF. More openness to sky would help release the heat absorbed faster from the urban canyon and air temperature may be thermally comfortable at night.

Table 9 presents the thermal sensation after the mitigation measures are adopted. Thermal sensation has been improved from the case before mitigation. Comparison of TSV before and after mitigation is shown in Figure 19. After introduction of measures, all the zones show thermal sensation in comfort range. Maximum temperature which occur during daytime is reduced considerably primarily due to introduction of urban greenery and consequent shading.

Table 8. Daytime thermal comfort indices for different zones before mitigation

Zones	Temperature (^oC) Tmax (before)	Wind speed (m/s)	TSV	Remarks
Zone 1	31.50	0.92	1.17	Neutral to slightly warm
Zone 2	32.20	1	1.40	Neutral to slightly warm
Zone 3	32.30	0.36	1.38	Neutral to slightly warm

Table 9. Daytime thermal comfort indices for different zones after mitigation

Zones	Temperature (^oC) T max (after)	Wind speed (m/s)	TSV	Remarks
Zone 1	29.70	1.23	0.63	Slightly cool to neutral
Zone 2	30.00	1.08	0.71	Slightly cool to neutral
Zone 3	30.40	0.50	0.79	Slightly cool to neutral

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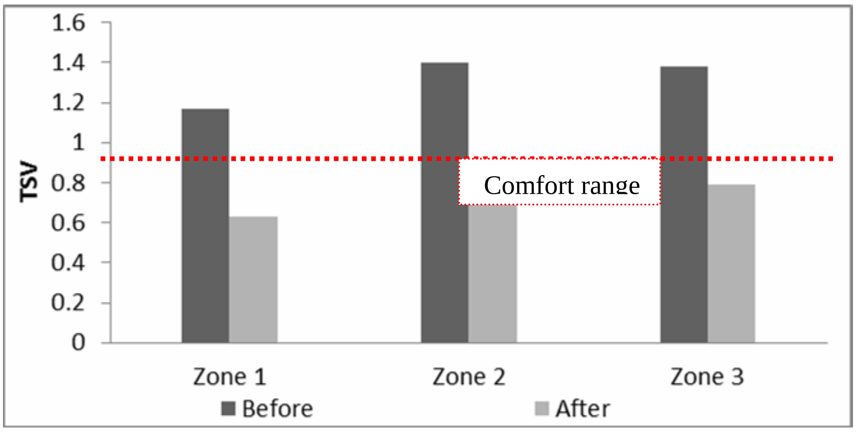

Figure 19. TSV for zones before and after mitigation

4.3Mitigation by using high albedo materials - comparison by Steve tool temperature mapping

As per report of American Pavement association , asphalt pavements are dark and new asphalt pavements generally have albedo between 0.05 and 0.10 while old ones have albedo between 0.10 -0.15. This cause them to reflect back very little radiation incident on them and absorb bulk of radiation just to release it over time. White cement concrete pavements or cool paver materials typically have albedo between 0.35-0.40.

To test the effect of higher albedo pavements albedo of pavement was changed from 0.10 to 0.30 in Steve tool. Raising albedo to 0.30 from 0.10 had insignificant impact on reduction of average and minimum temperatures as observed from the graph in Figure 20. Only maximum temperature of the zone has increased significantly when albedo was raised. This may be perhaps due to the fact that ground with high albedo tries to release radiation into the air above it, mostly at the occupant level raising the maximum air temperature although average day and night temperature values remain almost unchanged.

However, it has been studied and suggested by many researches that use of high albedo materials on roofs and walls can reduce surface temperature to a great extent and reduce the buildup of sensible heat in the urban canyon. Using high albedo materials reduces absorption of heat in building envelopes [12]. Savio et al. [13] studied the effect of using high albedo materials on ambient temperature. Using an average of solar reflectivity = 0.5, average reduction of 3 PM peak temperature was obtained to be in the range of 0.31 K to 0.62 K depending on the location characteristics. Similar finding was reported by Synnefa et al. [14] by using materials of albedo = 0.63 which reduced ambient temperature at 2 m height in the range of 0.5 K to 1.5 K. Also for walls high albedo coatings can be used but to prevent redirection of incident radiation towards pedestrian level, retroreflective coatings shall be used on external wall surfaces.

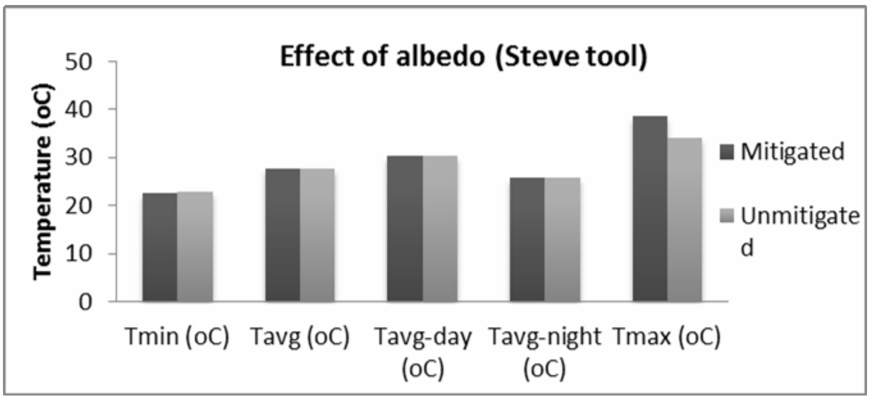

Figure 20. Effect of albedo on different temperature measures

5. Conclusion

This paper has reported some factors that must be considered for a sustainable urban planning taking into consideration thermal comfort of pedestrians. The following points could be concluded from the study:

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Highly exposed pavements and walls store heat during day time and thus more sensible heat buildup in the urban canyon causing daytime UHI and thermal discomfort to pedestrians. The same urban elements release heat during nighttime causing air temperature to rise and consequentially become reasons for nighttime UHI. Tall buildings generally provide shading to pedestrians but at the same time absorb solar radiation. Nighttime thermal comfort would then depend on the wall area at pedestrian height.
Thermal comfort in urban environment also depends on the building materials chosen. Dark and rough materials tend to absorb and store more heat energy. High albedo materials mitigate storage of heat in the urban environment.
Shading by matured trees is instrumental in reducing heat buildup and provide outdoor thermal comfort. Changing urban morphology to create low density housing and reduce SVF my planting more trees can improves thermal comfort. Wind movement would have cooling effect in urban environment and thus low density housing with trees lined along roads can create good wind paths and provide appreciable urban ventilation.
However, outdoor thermal comfort is a very complicated and dynamic quantity to measure because it is affected by many other physiological, environmental or urban factors. Some factors such as presence of water body, evapotranspiration, anthropogenic heat etc were not considered. For successful sustainable urban planning these factors should also be considered and researched precisely.

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Souradeep Gupta has received Bachelor's degree from National Institute of Technology, Jamshedpur, India and Master's from National University of Singapore. He is currently pursuing PhD at Dept. of Building, School of Design and Environment at National University of Singapore. His major field of research is smart and green materials for urban construction. Mr. Gupta is one of the Directors at Singapore concrete Institute (SCI) and also member of American Concrete Institute, Singapore chapter and student member of ASHRAE.
E-mail address: gupta.souradeep@u.nus.edu

Prashant Anand has received Bachelor's degree from National Institute of Technology, Patna, India and Master's from Indian Institute of Technology Madras, India. He is currently pursuing PhD at Dept. of Building, School of Design and Environment at National University of Singapore. His major field of research is Energy Efficient and Sustainable Buildings. Mr. Anand is a registered Architect by Council of Architecture India and also a student member of ASHRAE Singapore.
E-mail address: ar.prashantanand@gmail.com

Shashwat has received Bachelor's degree from Birla Institute of Technology, Mesra, India and Master's degree from National University of Singapore. He has worked as design architect and his area of interest lies majorly in sustainable building design, performance based simulation tools. Mr. Shashwat is a registered Architect with Council of Architecture, India.
E-mail address: sp.arch@hotmail.com

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