Role of urban morphology in enhancing outdoor thermal comfort: A case of Mumbai

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Abstract

In recent years, the city of Mumbai has been experiencing the pressing challenge of urban heat islands, affecting the thermal comfort of its high-density urban environment, impacting both air and surface temperatures. The Intergovernmental Panel on Climate Change (IPCC) projected that climate change would adversely affect 27 million people in Mumbai. Understanding the intricate relationship between the built environment and its influence on microclimates and thermal comfort was imperative for creating climate-sensitive designs. This paper investigated the role of urban morphology in improving the thermal comfort of a typical neighborhood in Mumbai. The analysis was based on simulations conducted using ENVI-met, a 3D urban climate modeling tool.

The research aimed to comprehend how open spaces, aspect ratio, setbacks, and plot boundary conditions within the neighborhood affected outdoor thermal comfort. The objective was to underscore the significance of urban designers and planners in assessing the impact of built environments on microclimates and leveraging microclimatic insights for the design of public spaces. Air temperature, relative humidity, wind speed, and mean radiant temperature were measured at 15 locations within the neighborhood, Matunga east, and its primary street in February 2023. The recorded data were used to validate the Envi-Met model . Two distinct scales were analyzed: neighborhood-level and plot-level iterations. Neighborhood-level iterations focused on block-level modifications, while plot-level iterations examined street and boundary conditions. Each iteration was evaluated using EnviMet to assess changes in thermal conditions relative to the current site conditions (Base case). The analyses were conducted for the critical summer month (May). The study ultimately revealed that the introduction of road networks in prevailing wind directions and the incorporation of green open spaces within the urban fabric could reduce overall heat stress duration from 12 hours to 6 hours. Smaller-scale interventions, such as 50% porous pavements and strategically placed trees, also yielded positive outcomes. This research aspired to provide urban planners with a comprehensive framework that integrated outdoor thermal comfort as a pivotal aspect in the design of future urban landscapes.

Keywords - Outdoor thermal comfort, Climate resilience, Urban morphology,

1. Introduction

In the realm of urban design and planning, the intricate relationship between built environments and their impact on microclimate plays a pivotal role in shaping the quality of life within cities. The configuration of urban neighborhoods, with their diverse geometries and spatial arrangements, exhibit a profound influence on the local thermal environment. Densely packed urban fabrics can induce heat islands by obstructing solar radiation and diminishing wind speeds. These urban geometries, characterized by parameters like the sky view factor and height-to-width ratio, dictate the openness of street canyons and define the heat exchange dynamics in open spaces. (Dayi Lai). The implications of built geometry on air temperature are starkly evident in studies conducted in various cities worldwide. In Fez, Morocco, a deep canyon with a high aspect ratio of 9.7 was found to have 6 K lower daytime air temperatures than a shallow canyon with an aspect ratio of 0.6 (Johansson, 2006). Similarly, in Dhaka, Bangladesh, a study demonstrated a maximum temperature difference of 6.6 K when comparing shallow and deep canyons with sky view factors (SVF) of 0.51 and 0.13, respectively (Kakon et al.,2009). This underscores the intricate correlation between urban

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geometry and microclimates. Wind patterns, a vital aspect of urban microclimates, are also linked to the built environment. The configuration of buildings exerts a significant decelerating effect on wind speed in urban areas. This can be seen in the case of Shanghai, with a 10% increase in SVF, the pedestrian-level wind speed increased by 8% (Yang et al.,2013). The direction of wind flow also affects the ventilation of urban canyons, with perpendicular flow creating vortices that limit wind speed. In contrast, oblique flow generates a helical vortex that funnels the wind along the street. To optimize ventilation in high-density cities Ng (2009) recommends keeping the angle between the street and flow orientation below 30°.

Transitioning to the role of green spaces in urban planning, which hold equal significance in enhancing urban microclimates and the overall well-being of residents. Open spaces, parks, and natural features provide essential relief from the built environment and play a crucial role in creating a sustainable and livable urban ecosystem. Parameters like size, location, and vegetation abundance define the functionality and environmental benefits of these spaces. The positive impact of vegetation on air temperature is well-documented. Trees, through transpiration and shading, effectively lower air temperatures. Studies show that increasing tree coverage by 33% can lower air temperature by 1 K in Hong Kong (Ng et al.,2012). In Athens, a "green atrium" with high tree cover and porous surfaces had a Tmrt approximately 8 K lower than a building atrium, according to Charalampopoulos et al. (2013). Planting trees at 6-9m intervals on 50% of building setbacks can result in a 12°C reduction in PET and a 18°C reduction in Tmrt values, with a 3-hour decrease in extreme heat stress duration. This strategy improves thermal comfort and reduces building heat gain (Rajan and Amirtham 2021). Green roofs can also lower air temperature by 0.3 to 3 K on a city scale. However, the pedestrian-level cooling effect varies with building height (Santamouris, 2014).

Oke et al. (2017) conducted studies that showed how trees in urban areas affect airflow by increasing surface roughness and creating drag. Trees, being porous, cause minor pressure differences and create smooth changes in wind speed, unlike solid buildings. Multiple studies showcase that trees can reduce wind speed in urban areas. For instance, four sidewalk trees were found to decrease wind speed by 51%, according to measurements conducted by Park et al.,(2012) at a scale model site. Heisler, (1990) analyzed the wind speed in urban areas with and without green cover and found that 77% tree coverage increased the wind-speed reduction from 22% to 70%. The Chicago Urban Forest Climate Project, (Heisler et al.,1994) reported that trees could reduce wind speed by 90%. Vegetation improves the microclimate by reducing radiation and lowering the air temperature, despite decreasing wind speed. Trees, which can provide shading, are more impactful than grass. Dense trees and grass can reduce MRT by 7°C and PET by 4°C in Dar es Salaam, Tanzania. Additionally, (Qin et al.,2013) the study in Shanghai Botanical Garden found that people consider the color of street greenery to be an essential aspect of their overall satisfaction with the surrounding vegetation.

As the global population continues to urbanize, the importance of sustainable and adaptable urban environments becomes increasingly evident. Urban designers and planners are tasked with the critical responsibility of harmonizing built and unbuilt spaces to create resilient and livable cities. The effects of microclimates on thermal comfort and outdoor activities cannot be underestimated. In the context of climate change and evolving urban landscapes, designing for enhanced public spaces is not just a luxury but a necessity to ensure the well-being of urban dwellers. The interplay between urban geometries, green spaces, and microclimates shapes the fabric of our cities. Understanding these dynamics and leveraging them through urban design and planning strategies is essential in creating vibrant, comfortable, and sustainable urban environments. As the global population continues to surge and cities become hubs of growth. Addressing the challenges posed by climate change and ensuring the well-being of residents through thoughtful design will be central to shaping the future of urban living. The same can be seen in Mumbai, the rapid urbanization has resulted in increased temperatures.

The study conducted in Mumbai (Bhanage, 2022), indicates that the temperature would increase by 1.41°C due to future urbanization. And by 2050, the total number of hyperthermal hours will increase by 3–5 hours per day over the newly urbanized area. However, if we adopt a mitigation strategy, then this rise would be restricted to 0.90°C. In the study conducted for the urban heat island effect in Delhi and Mumbai, higher urban heat islands were measured in Mumbai. (Grover, 2015) In Mumbai, the absence of tree cover along with other factors has led to increased land surface temperatures. With urbanization , the difference between maximum and minimum land surface temperature (LST) declined in Mumbai city from 30.04°C in 1991 to 20.07°C in 2018. During the last three decades, Rahaman et al. (2020) observed a threefold increase in areas with a higher magnitude of LST in Mumbai because of persistent growth in urban areas.Therefore the present study aims to explore the role of urban parameters in enhancing the comfort conditions outdoors thus improving the standard of urban living.

2. Methodology

The present study analyzes the relationship between various urban parameters and outdoor thermal comfort. Through the literature review, urban parameters such as open spaces, aspect ratio, setbacks, and boundary conditions were identified which significantly influenced the outdoor thermal comfort. Previous research had validated the methodology employed by EnviMet, particularly in a study by Ayyad and Sharples (2019) that demonstrated a high correlation between wind speed and air temperatures.

The methodology adopted in this study comprises five steps.

1. Mapping of urban built form: The built environment characteristics of the chosen neighborhood were mapped in detail to analyze the impact of the four identified urban parameters.

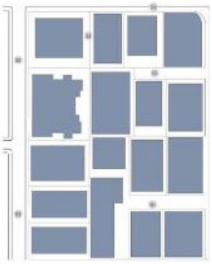
2. Field measurements: Field data on air temperature, relative humidity, and wind speed were recorded at 12 locations in the chosen neighborhood on a typical winter day (2nd February,2023).

3. Envi-met simulation & Validation: Built environments around each location were mapped with a plan and section for a 100m x 100m site. The built environment characteristics around each measurement location were modeled in a 50 x 50 x 40 grid in Envi-met-lite (version 5) with each grid representing 2m. The model was then simulated using the field measurements and wind data from Matunga station located closer to the neighborhood. The simulation outputs were compared with the onsite field measurements for validation. The study revealed a higher correlation (R2 value of 0.75) hence taken forward for further iterations.

4. Urban parameters and thermal comfort analysis: After validation, simulations were done for a typical summer day (20th May 2022) and the median meteorological and comfort parameters were analyzed for three time periods in a day. Further, different proposed iterations of the identified parameters (open spaces, aspect ratio, setbacks, and boundary conditions) were modeled from macro to micro scale and simulated . Based on the analysis, the best-case iterations of open space were further analyzed for varying aspect ratio iterations until noticeable improvements in comfort conditions were observed. Table 1 shows the iterations considered for the study. Similarly, other parameters were also analyzed. The analysis focussed on five output parameters: wind speed, air temperature, relative humidity, mean radiant temperature, and PET. Rayman Pro was used to analyze PET with personal parameters of a 1.75m tall individual with 75kg weight, and 80W metabolic rate. A CLO value of 0.6 was considered for the study.

5. Recommendation: Based on the analysis of results, Urban design guidelines were recommended and a structure to incorporate the research in implementable ways was suggested.

Table 1: Neighborhood and plot level iteration considered for analysis

Scales	Iteration	
Base case 	-	-

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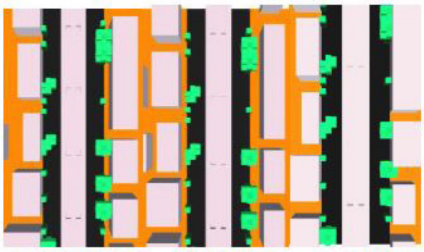
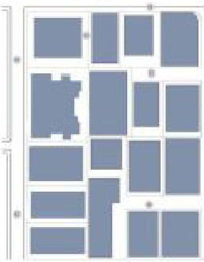
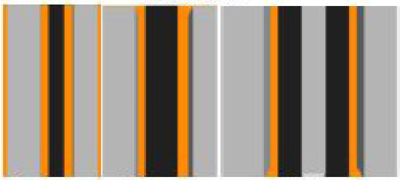
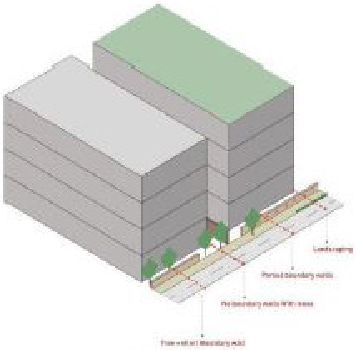
Neighborhood Level 	**S1 Size and location of green open spaces**	S1.1 A central open space S1.2 Fragmented greens on the edges S1.3 Fragmented greens within the neighborhood
 Existing FOS 4.5 FOS 0 FOS	**S2 Aspect ratio 34 meter wide street**	S2.1 Aspect ratio 0.9 with existing Front Open Space (FOS) S2.2 Aspect ratio 0.6 with 4.5m FOS S2.3 Aspect ratio 0.8 with 0m FOS All scenarios have flyover running centrally in the street and have fragmented building blocks.
Base case 	-	-
Neighborhood Level 	**S1 Size and location of green open spaces**	S1.1 A central open space S1.2 Fragmented greens on the edges S1.3 Fragmented greens within the neighborhood
Plot Level  9 meter 18 meter 34 meter	**S3 Side Setbacks and road widths**	S3.1 road width 9 meter continuous built S3.2 road width 18 meter continuous built S3.3 road width 34 meter continuous built The 34 meter wide street scenario has a flyover running centrally.
 Plot Level	**S4 Boundary conditions :** (The interface between the built and street which includes, margins , footpath, materiality etc) The pavement material assigned was granite single-stone pavement along with low LAD deciduous trees, and this iteration was simulated only for peak hours from 12-4 pm.	S4.1 had compound walls as per the DCR and street design guides to bifurcate the street into different parts with vegetation on the footpaths. S4.2 replaced the compound wall with trees to create barriers S4.3 had a porous compound wall along with trees in the setback area.

3. Results

The relationship of various urban parameters from the neighborhood level to the plot level was analyzed to identify its significance in modifying the microclimatic and comfort parameters of each iteration.

3.1 Size and location of green open spaces

Micro climatic parameters: Fig.1 shows the microclimatic variation of three iterations (S1.1, S1.2 & S1.3). The analysis revealed that introducing new greenery in the neighborhood (S1.1) resulted in a 1°C decrease in air temperature compared to the base case. The reduction may be attributed to an increase in average wind speed of 1.2m/s throughout the day, which helps in maintaining a comfortable environment, especially in humid conditions. The maximum temperature was recorded at 16:00 hrs, with 33.6°C, while the minimum temperature was recorded at 10:00 hrs with 28.7°C. It was also seen that except for air temperature and wind speed, variation in other parameters was minimal. The surrounding built forms created a tunnel effect from all four edges, which channeled the wind into the central space. It was observed that even though open spaces were placed at the periphery of the neighborhood (S1.2), as they were shaded and parallel to the wind direction, the variation in air temperature was minimal. **Comfort parameters:** The study revealed that the mean radiant temperature (MRT) values varied significantly during the peak hour of 14:00, with a drop from 59°C (base case) to 55.8°C, 57°C, and 58°C in iterations S1.1, S.1.2, and S1.3, respectively, indicating that green open spaces have a positive impact in reducing the urban heat island effect and improving human comfort in urban areas. PET values revealed a maximum reduction of 7°C in S1., maintaining moderate heat stress levels for six out of the twelve hours, ranging from 29-35°C. S1.1 resulted in an overall reduction of 3.2°C in MRT. The highest MRT recorded was 58.6°C at 15:00 hrs, while the lowest was 23.6°C at 21:00 hrs.

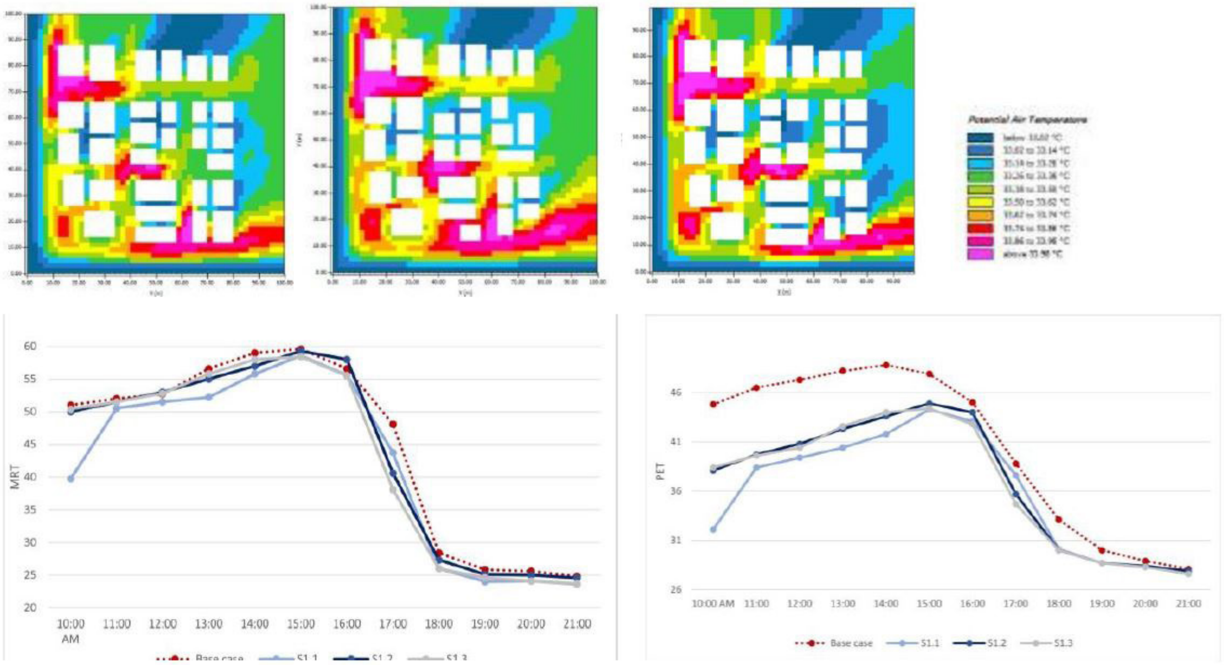


Figure 1: Air Temperature variation in S1 during peak hours (14:00) along with PET and MRT graphs comparing S1 to base case

3.2 Aspect ratio

Micro climatic parameters: S2.1 showed 0.3°C increase in air temperature compared to base case whereas S2.2 and S2.3 saw 0.1°C decrease than base case. In all three cases, there was a decrease in wind speed compared to the base case. The wind speed varied in all three cases from 1.15 m/s to 1.05 m/s. The humidity increased in all three iterations compared to the base case. Overall, 0.6 (S2.2) and 0.8 (S2.3) aspect ratio in the 34-meter-wide street iteration showed improved microclimatic parameters. **Comfort parameters:** MRT reduced considerably during the peak hours from 61.9°C in the base case to 48.4°C, and 49°C in S2.2 and S2.3. PET ranges for iterations S2.2 and S2.3 were decreased from extreme heat stress to strong heat stress. The decrease in MRT and PET values can be because of the change in the aspect ratio. Decreased MRT values were recorded in S2.2 with an aspect ratio of 0.6.

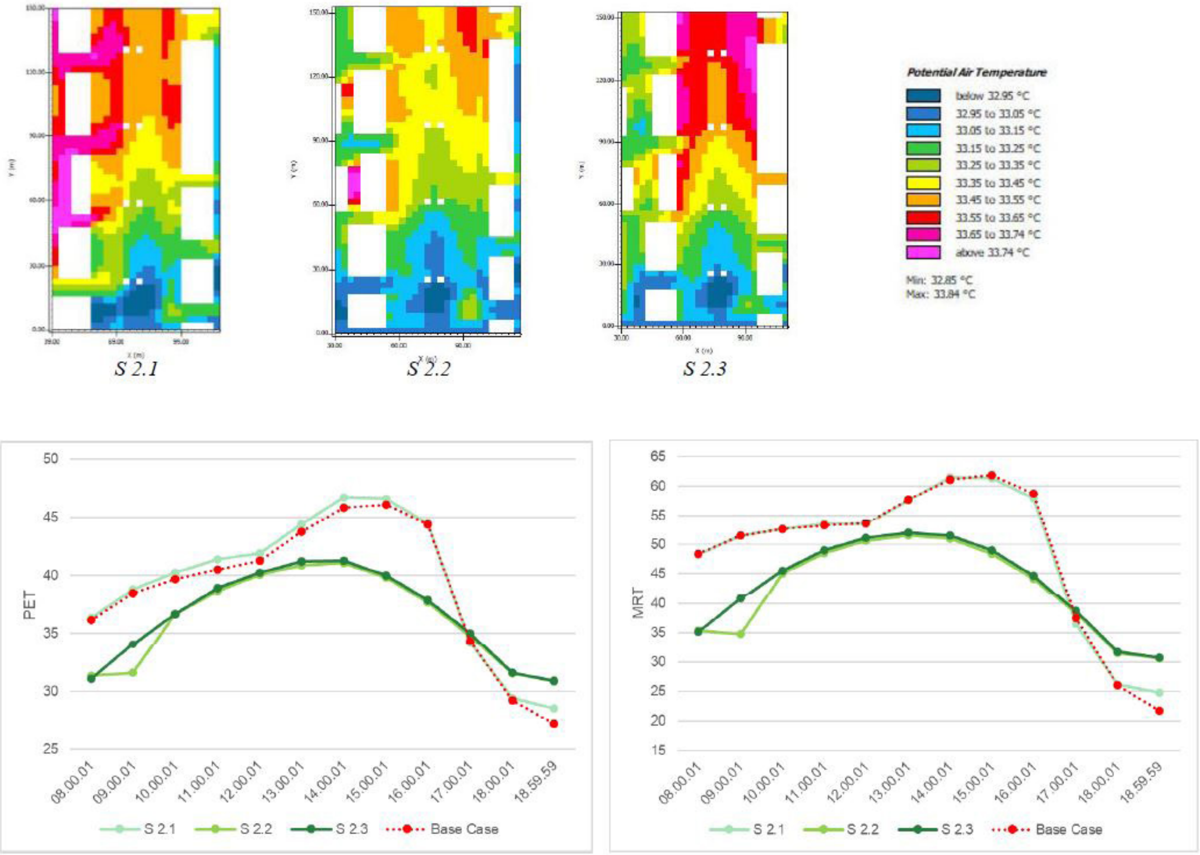


Figure 2: Air Temperature variation in S2 during peak hours (14:00) along with PET and MRT graphs comparing S2 to base case

3.3 Setbacks and road widths

Micro climatic parameters: Fig.3 shows the microclimatic changes in the different street widths with continuous building blocks. The analysis revealed that S3.2, S3.3 have recorded 1.6 m/s wind speeds which is slightly higher than the base case. The average air temperatures of S3.1, S3.2 and S3.3 were 32.4°C, 32.1°C, and 32.4°C respectively. When compared to the fragmented building blocks, S3.3 recorded slightly reduced air temperatures. Overall, changes in road widths and setbacks affect the microclimatic parameters. In the wider streets (S3.2, S3.3) with continuous building blocks, the wind speed increased while in the narrower streets, with fragmented building blocks (S2.2, S2.3) resulted in better wind speeds. This also showed that the air temperature in narrower street canyons was not reduced by side margins or by increasing pervious surfaces. The MRT values of S3.1, S3.2, S3.3 at peak time 14:00 were 54.4°C, 53.4°C, 53.2°C and PET values were 43.4°C, 41.4°C, 41.8°C respectively . The MRT in continuous building blocks(S3.2, S3.3) has significantly reduced, as compared to the fragmented building blocks(S2.2, S2.3) in both 9-meter and 18-meter streets. In

S3.1 and S3.2 (continuous building block) the peak temperature recorded was 5°C and 10°C lower than that of S3.1 and S3.2 (fragmented building block) respectively, ultimately reducing 5 hours of extreme heat stress to strong heat stress conditions. This reveals that the narrower streets work better when side setbacks are kept minimum.

The analysis of wider streets i.e. the 34-meter width (fragmented building block) iteration was more successful than the base case. The MRT and PET results of 34-meter width streets at peak time were recorded at 52.1°C and 41.6°C respectively suggesting that wider streets might act better in thermal comfort if more building frontage, side margins, and pervious surfaces were introduced. PET values of S3.3 both fragmented and continuously built have now changed from extreme to strong heat stress. The changes in material and vegetation may help lower the physiologically equivalent temperature further.

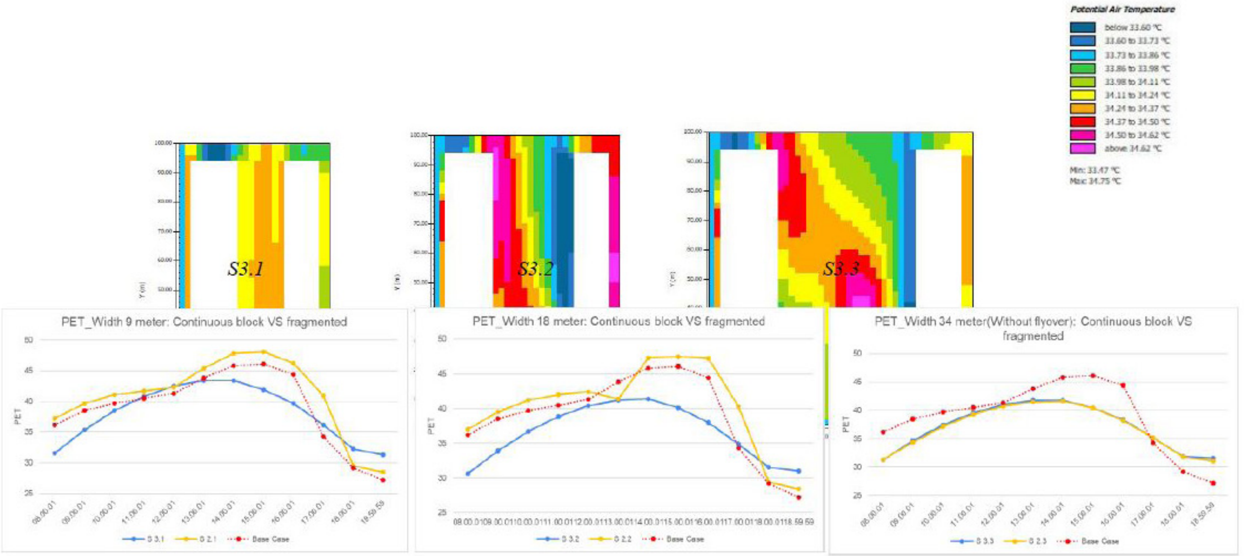
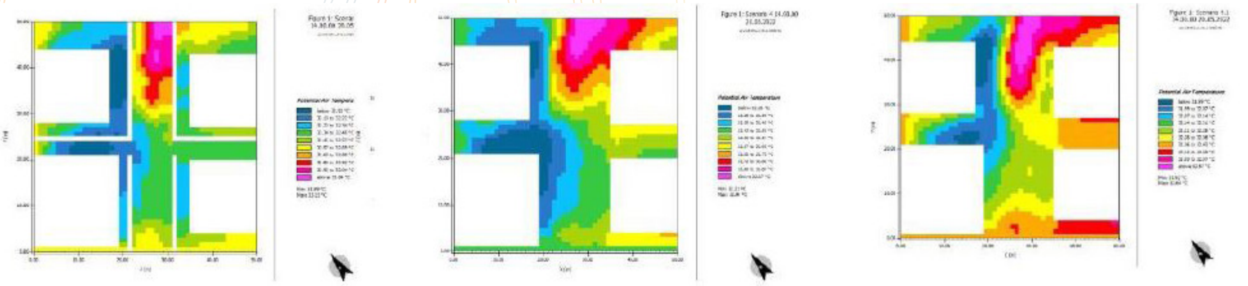


Figure 3: Air Temperature variation in S3 during peak hours (14:00) along with PET graphs comparing S3 (fragmented and continuous building blocks) to base case

3.4 Boundary conditions

Micro climatic parameters: Fig 4 reveals a substantial variation among the three iterations. As per the DCR guidelines, the air temperature values during the peak hour (14:00 hrs) were recorded as 41°C, which decreased to 36°C after the introduction of additional trees and porous compound walls in S4.2 and S4.3. An increase in relative humidity from 58% in S4.1 to 59% in both S4.2 and S4.3 was observed due to increased trees creating shade on the pedestrian walkway. However, the wind speed decreased from 1.4m/s in S4.1 to 1.2m/s in S4.3, as the trees obstructed the wind flow. MRT analysis showed a significant reduction of 10°C in iterations S4.2 and S4.3 compared to S4.1, despite having higher relative humidity values. This was attributed to increased shading by trees and an increase in pervious surface and albedo of pavement in the streetscape. PET results indicated that strategies S4.2 and S4.3 resulted in a transition from extreme heat stress to moderate heat stress during peak hours. These findings suggest that higher tree coverage can improve the pedestrian experience and contribute to the enhanced thermal comfort of users in the neighborhood.



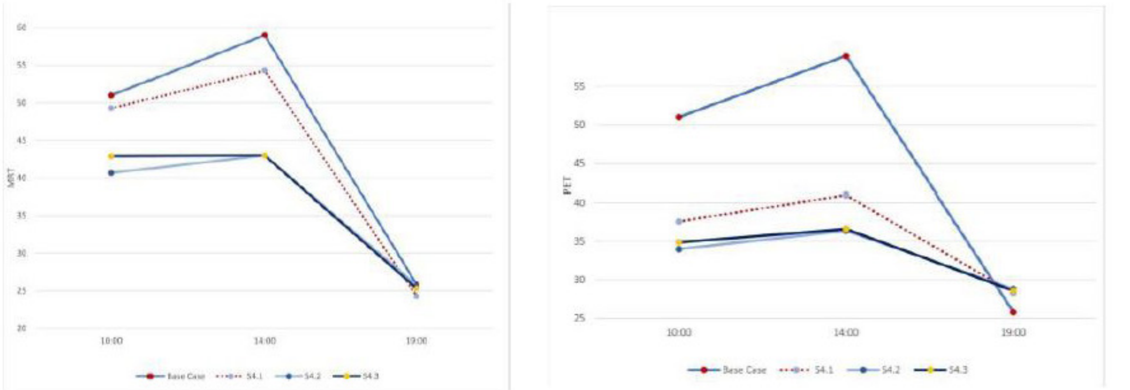


Figure 4: Air Temperature maps for S4 during peak hours (14:00) along with PET and MRT graphs comparing S4 to base case

4. Discussion :-

Impact of open space: Open spaces have been found to promote relaxation and social interaction among residents, making them an essential element of high-quality urban living. However, the literature review revealed that open spaces reduced wind speed and increased relative humidity levels within the surrounding area. Despite these challenges, introducing a large central open space comprising 10.5% of the total site area brought the neighborhood's microclimate within the moderate heat stress range for four hours out of the 12 hours analyzed. Similar results were observed when smaller, fragmented open spaces were introduced within the built fabric of the neighborhood. A study in Iran also indicated that "the changes in the geometry and morphology of the neighborhood in a constant ratio of greenspaces, water bodies, and buildings could affect the neighborhood's climate and subsequently affect their thermal comfort and satisfaction." (Ahmadi et al., 2022). Unlike the study in Iran, this study considered other parameters constant and did not introduce a water body as it would increase the humidity, especially in coastal cities like Mumbai. This suggests that multiple parameters within the open space can add to the thermal comfort of space, but what can be found through this study is that green open spaces are more effective when incorporated within the urban fabric rather than at the periphery, abutting primary or secondary roads. The study highlights the importance of providing relief points within the built environment to counteract the urban heat island effect. The introduction of new road networks within large parcels of land and open spaces can facilitate the movement of air and mitigate heat within the built environment, creating a more comfortable microclimate for residents.

Impact of aspect ratio: The study shows that the width of the street and the abutting built play a vital role in thermal comfort. The iterations with narrower streets have high shading possibilities with higher aspect ratios. The scenarios where H/W>0.6 worked better in terms of PET values. While in the wider street canyons, the smaller aspect ratio gave better results. The scenario with H/W<0.4 has worked efficiently. These findings also follow a similar trend found in other research stating that the higher the aspect ratio the lesser the PET values in the summer. (Muniz-G¨ aal et al., 2020) This finding thus concludes that the narrower streets such as pedestrian pathways, local streets, corridors, and avenues behave differently than the wider streets and need alternative recommendations for the building abutting the street.

Impact of setbacks and road widths:
The study clearly shows a strong relationship between thermal comfort with the front, side margins, and pervious surfaces of the building abutting the street canyon. The narrow streets, 9 and 18 meters revealed similar results with a drastic reduction in PET values when changes in side open spaces were made. This suggests that narrower streets work better with minimum side open spaces. A substantial drop from extreme heat street to strong heat stress for 6 hours at the peak time of the day was observed in the simulations with narrower streets and minimal side margins. The wider streets worked better in both larger side open spaces and front open spaces. The reduction of values is for 5 hours at the peak time of the day in iterations S3.2 and S3.3. This indicates that wider streets must have more pervious surfaces to reduce overall PET values. Wind speed was directly affected

by a change in the setbacks and pervious surfaces. The wind speed change was achieved in the final simulations when the side margins were altered. The 34 meter wide street recorded an increase in wind speed by 0.3-0.4 m/s and a 0.3 m/s increase was seen in the 18-meter street whereas the 9-meter street recorded reduced wind speed because of the wind shadow region created by the aspect ratio of the building. The increased wind speeds on 34 and 18 meter streets are largely because of the funneling effect that pushes the air out of the street canyon and results in overall cooling of the street. In narrower streets, the night temperatures might increase as the air will get trapped as seen in the scenario of a 9-meter street. Thus, for better wind speed with the optimum aspect ratio, the pervious surfaces need to be regulated as well to achieve thermal comfort. In wider streets, the larger setbacks will help increase the wind speed.

Impact of boundary condition: Looking at the microclimate conditions at the pedestrian level by zooming in from the macro-level iterations it was found that as per the current Mumbai DCR regulations, guidelines are related only to the height of permissible compound walls. No specific regulations are provided for a plot's street design and edge conditions. Hence, this study analyzed the impact of changing boundary conditions on the OTC of a neighborhood. Interestingly despite higher wind speeds, AT values remained constant throughout the iterations. The study observed that making 50% of the pavement porous, adding trees in setback areas, and using a porous compound wall resulted in a 10-degree drop in MRT values and a 5-degree drop in PET values, ultimately reducing heat stress in the neighborhood. Similar results were found in a study done in Chennai, which concluded that "50% of the setback area of each plot can be regulated towards a landscape with trees in the proposed new regulation, then the duration can substantially increase to moderate to no-thermal stress sensations in a given day" (Rajan & Amirtham, 2021). This suggests that simple changes to boundary walls, pavement choices, and adding trees can significantly improve the microclimate conditions of a neighborhood. Moreover, these are small but crucial decisions that are generally ignored in the regulations.

5. Conclusion

The paper underscores the significance of adopting an integrated approach to neighborhood development, wherein each successive step synergistically reinforces the previous one. Initially, the alteration of the neighborhood layout's subdivision was focused on enhancing wind speed. The outcomes demonstrated that reconfiguring the road networks to align with the prevailing wind direction generated a wind tunnel effect. This, in turn, facilitated the dissipation of accumulated heat within structures, effectively reducing the neighborhood's overall heat stress duration from 12 to 6 hours. Subsequently, an analysis of varying open spaces at the front and sides of the main street underscored that wider streets, measuring 34 meters, exhibited superior performance when complemented by such open spaces. Additionally, the study revealed that augmenting the proportion of pervious surfaces along the 34-meter street resulted in a transition from extreme to strong and moderate heat stress levels. The third phase of the research focused on investigating the impact of incorporating open green spaces within the urban fabric. Notably, the study demonstrated that integrating green open spaces within the neighborhood fabric led to a substantial 7-degree Celsius reduction in heat stress, particularly when compared to peripheral spaces adjacent to roads. This is similar to the findings drawn in research by Grover, (2015), wherein lesser green cover resulted in increased land surface temperatures in Mumbai.

Lastly, smaller-scale interventions, including implementing 50% porous pavements, strategically placing trees in setback areas, and employing porous compound walls, yielded impressive outcomes. These measures collectively contributed to a noteworthy decrease of 10 degrees Celsius in Mean Radiant Temperature (MRT) values and a 5-degree Celsius drop in Physiological Equivalent Temperature (PET) values. Consequently, these modifications effectively mitigated heat stress within the neighborhood. In summary, the comprehensive study revealed that the amalgamation of strategies on both at the neighbourhood level and the plot level resulted in a significant alleviation of heat stress at the site. This underscores the necessity of adopting a holistic approach to crafting comfortable urban neighborhoods. The study further presents the practical strategies and methodologies employed, forming a comprehensive framework that can serve as a step-by-step manual for developing thermally sensitive neighborhoods that prioritize pedestrian well-being.

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