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Impact of urban geometry on indoor air temperature and cooling energy consumption in traditional and formal urban environments

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Abstract: This study explores the effect of outdoor microclimatic environment on indoor conditions in a tropical warm-humid climate. An indoor air temperature and building energy performance analysis is carried out for the real case-study areas to examine the impact of urban geometry on building indoor conditions. The study incorporates microclimatic data from CFD, micro-climatic tool ENVI-met into building energy performance analysis using IES-VE. Findings reveal that diversity in urban geometry in deep urban canyons is helpful in reducing the indoor air temperature and cooling load. On average, cooling load in model rooms in the formal area is 21% higher for 1st floors (40% for top floors) compared to the corresponding rooms in the traditional area. In terms of solar gains, the difference was 30% for the 1st floors and 91% for the top floors, with rooms in the formal area having the higher ranges. Furthermore, the room air temperature in the traditional area was found to be 0.6-1.6^{0}C lower than those in the formal area.

Keywords: ENVI-met(V4); IES-VE; building energy performance; tropical climate; urban geometry

1. Introduction

The geometry of urban forms can affect the heating, cooling, lighting and ventilation of the individual buildings as well as the microclimate of the streets, squares, courtyards or gardens that contain them (Strømann-Andersen & Sattrup 2011). Their study had found that the geometry of urban canyons can create a variation on total energy consumption in the range of up to +30% for offices and +19% for housing for North-European cities. Traditional, compact urban form in other European city centres were also found to minimise undesirable building heat losses or gains (Vartholomaios 2017; Rode et al. 2014). Strong correlation between the urban geometry parameters (Aspect ratio, Sky View Factor (SVF), etc.) and microclimatic conditions is found in studies in high-density tropical regions (Sharmin et al. 2015). Kikegawa et al. (2006) have conducted a geometrical analysis for 23-wards in urban Tokyo and identified the Sky View Factor (SVF), an urban geometry parameter, to be the most crucial geometrical index of urban canopies that directly affects the cooling energy demand. Furthermore, one of the main microclimatic factors to affect energy consumption in an urban area is the variation in air temperature, i.e., lower air temperature resulting in lower cooling load. According to Santamouris et al. (2001), air temperature distribution in urban areas is highly affected by the urban radiation balance, which is basically a repercussion of urban geometry.

Findings from microclimatic monitoring in Dhaka as discussed in Sharmin et al. (2015) suggest that urban forms that are more variable with irregular plot sizes and building heights, mostly in traditional areas, have positive responses with respect to the synoptic climate, while planned areas with uniform plot sizes and building heights show a tendency to develop daytime urban heat island effect. An east-west orientated street in a formal residential area was found to be up to 6.2^{0}C warmer than a street in a Traditional Residential Area (TRA) in the same orientation. It is apparent that the differences are directly linked to the specific geometric pattern of the areas and can be defined by parameters like uniformity versus diversity and compactness versus openness. Uniform heights, equal building separation and plot sizes can lead to a harsher urban microclimate, while variety in these may foster positive changes. Lack of such variety can affect even the compact urban areas and deep urban canyons. A statistical analysis of climatic variables in the above study showed moderately strong and significant correlations. This reveals that urban geometry and the resultant climatic variables may be one of the most important factors for affecting the microclimatic conditions in a tropical climate.

From the finding of the above study, it can be speculated that the diversity in urban geometry in the traditional areas will affect the internal conditions of the adjacent buildings as well. The deep canyons with variable building heights will modify the radiation balance through mutual shading and, consequently, the solar gain in the indoor surfaces in the urban canyon. Thus, it will create an altered and perhaps cooler indoor ambience in the adjacent buildings. At the same time, the top floors of the tallest buildings in the traditional areas will presumably suffer worse conditions due to higher solar exposure. In formal areas, on the other hand, almost all top floors will have a similar high solar exposure due to their equal heights. It is assumed that the modified radiation budget due to the morphological diversity will play a greater role in altering the indoor conditions compared to air temperature differences recorded in the actual sites.

The methodology and findings from the study will aid in devising strategies to lower energy consumption and room air temperature in buildings by considering the impact of the neighbouring urban textures in a tropical, warm-humid climate. However, it should be emphasised that energy models are simplified for easy comparison and the internal gains, ventilation and cooling profiles are kept the same across all models. Therefore, despite using real case study sites, the energy calculation in the simulation models will differ from the real buildings, not least because buildings are rarely air conditioned. Nevertheless, the analysis will reveal important comparative outcomes and lessons related to urban form.

2. Methodology

This study compares the results of an indoor air temperature and cooling load analysis between two residential sites in Dhaka city with different urban geometry characteristics: one is a Traditional Residential Area (TRA), which has mainly grown out of spontaneous development under loose planning controls. A traditional area is predominantly residential with small-scale commercial activities and variable building forms, heights and plot sizes. The street layouts in these areas often create varying patterns with narrow and twisting streetscapes. Green spaces, especially community areas like parks or gardens, are not common. The other residential type in this study is planned area or Formal Residential Areas named as FRA, with buildings of equal height and width, and roads laid out in a grid-iron pattern.

The study mainly discusses residential sites as residential energy consumption in the LDCs (least developed countries, as the case-study area) comprises of 30-95% of the total energy use compared to 25-30% in the developed countries (DCs) (Foysal et al. 2012). This means that reducing the residential energy consumption can significantly aid in lowering the total energy requirements in the case-study area.

The study has been carried out in two steps. Firstly, an indoor air temperature analysis is carried out for the buildings located in both formal and the traditional areas. In this scenario, buildings are running in a natural ventilation mode. Secondly, a cooling load analysis is carried out with the application of a cooling (air-conditioning) system in the buildings. The study has adopted the dynamic simulation software IES-VE for running the indoor analysis. The application of IES-VE was confirmed for other similar micro-scale studies, such as, Skelhorn et al. (2016); Lee and Steemers (2017) and Lau et al. (2016).

2.1. Case study areas

The case-study areas TRA1 (Traditional Residential Area 1) and FRA2 (Formal Residential Area 2) were chosen for their apparent variation of urban textures. In each area, an East-West (EW) and a North-South (NS) oriented urban canyon were chosen for the comparison. The urban canyons for this study are named as: TRA1EW, TRA1NS, FRA2EW and FRA2NS. Measurements were carried out in the urban canyons in autumn and in summer.

2.2. Use of microclimatic data for indoor simulations

In this study, microclimatic information was incorporated into building energy performance analysis. This uses the microclimatic data simulated using ENVI-met V4 with the field measurement data as a boundary condition for existing urban areas. Statistically significant and strong correlations were found between the measured and simulated air temperature (Ta) and relative humidity (RH) for the case-study sites (Sharmin & Steemers 2016). As the microclimatic data used in this study are generated using the actual boundary conditions for individual case-study sites, they closely predicted the actual air temperature variations that had occurred during the microclimatic monitoring (Table 1).

Table 1. Correlations between climatic variables in measured and ENVI-met (V4)-simulated scenarios

Site Name	Ta	Tmrt	*v*	RH
	Pearson's r (p value)	Pearson's r (p value)	Pearson's r (p value)	Pearson's r (p value)
TRA1EW	0.79 (0.000)	0.60 (0.01)	-0.75 (0.000)	0.72 (0.000)
TRA1NS	0.80 (0.000)	0.32 (0.7)	-0.56 (0.01)	0.71 (0.000)
FRA2EW	0.90 (0.000)	0.76 (0.000)	0.42 (0.07)	0.92 (0.000)
FRA2NS	0.87(0.000)	0.68 (0.001)	0.69 (0.002)	0.75 (0.000)

2.3. Selection of model rooms

Both east-west (EW) and north-south (NS) oriented urban canyons are examined in the traditional and formal sites. In each east-west urban canyon, two opposite buildings located at the middle-length of the canyon are chosen, one of which is north-facing and the other one south-facing. Likewise, an east-facing and a west-facing building are chosen in the north-south oriented canyons. In the case of TRA1EW, two buildings on each side of the canyon are selected to see the impact of horizontal location.

The first and the top floor of each building are considered assuming that the first floor will be affected by the mutual shading conditions inside the canyon, whereas the top floor will be subjected to the highest solar exposure. Each floor is divided into 5m x 5m rooms. For easy comparison, similar floor-plans are assumed throughout the buildings rather than the actual layout. Energy calculations were carried out for the middle rooms at the front facade. Figure 1 shows the location of the case study buildings and studied rooms in each urban canyon.

2.4. IES-VE model set-up

Indoor conditions are compared in terms of room air temperature, solar gain and natural ventilation conditions. Table 2 lists the thermal conditions, systems, internal gain, air exchanges and construction details for the model set-up in IES-VE. In IES-VE, solar gain is considered as the solar radiation absorbed on the internal surfaces of the room, plus solar radiation absorbed in glazing and transferred to the room by conduction.

Natural ventilation is compared in IES-Ve with *MacroFlo ext vent* defined as the sum of *MacroFlo* calculated air flows entering the room from the external environment. *MacroFlo* is the airflow simulation program in IES-VE for analysing infiltration and natural ventilation in buildings. Opening types and pressure differences are the main parameters considered during the airflow calculations in *MacroFlo*. Airflow rate q_n (m^3/s) is calculated using the following equation (Cheng et al. 2016):

$$q_n = C_d A_{op} \sqrt{2\Delta P/\rho} \quad (1)$$

Here, C_d is the discharge coefficient specified to be 0.62 in IES-VE, applied when openings have a small ratio to the adjacent space; ΔP *(Pa)* is the pressure difference across the opening; ρ (kg/m3) is the density of the incoming air; and A_{op} (m^2) is the net open area of the orifice (opening).

Energy performance is examined by comparing the cooling plant sensible load defined as: "the sensible cooling (non-negative) supplied to the room by its *Apache System room conditioning plant* or *ApacheHVAC* room units (radiators, direct acting heaters and chilled beams)". The dynamic thermal simulation in IES-VE is carried out by the *ApacheSim programme*. *ApacheSim* is established on the fundamental mathematical modelling of the heat transfer process occurring within and around the building (IES Virtual Environment, 2016).

Internal gain and construction details for the model set-up in the cooling load scenario is the same as the indoor air temperature scenario. Table 3 lists the thermal conditions, systems and air exchanges for the models in the cooling load scenario.

2.4.1. Internal gain

Internal gain has been adopted from the IES-VE ASHRAE database for a single-family housing. Internal gains from lighting, people and miscellaneous household equipment are considered. A customised occupancy profile for a family of six in Dhaka, as mentioned below, is used in the study.

2.4.2. Occupancy profile

The occupancy profile is assumed for a typical family structure considering the socio-cultural situations in Dhaka city. The family is made up of two working parents with two school-going children, one grandparent and a maid. In a working day, 30% occupancy is assumed between 08:00-14:00 with the grandparent and maid at home. 60% occupancy is assumed from 14:00 after the children return from the school. Full occupancy is assumed at 18:00 after both parents return from work. During weekends, 60% occupancy is assumed between 10:00-12:00 and 30% between 16:00-21:00. Full occupancy is assumed for the rest of the day.

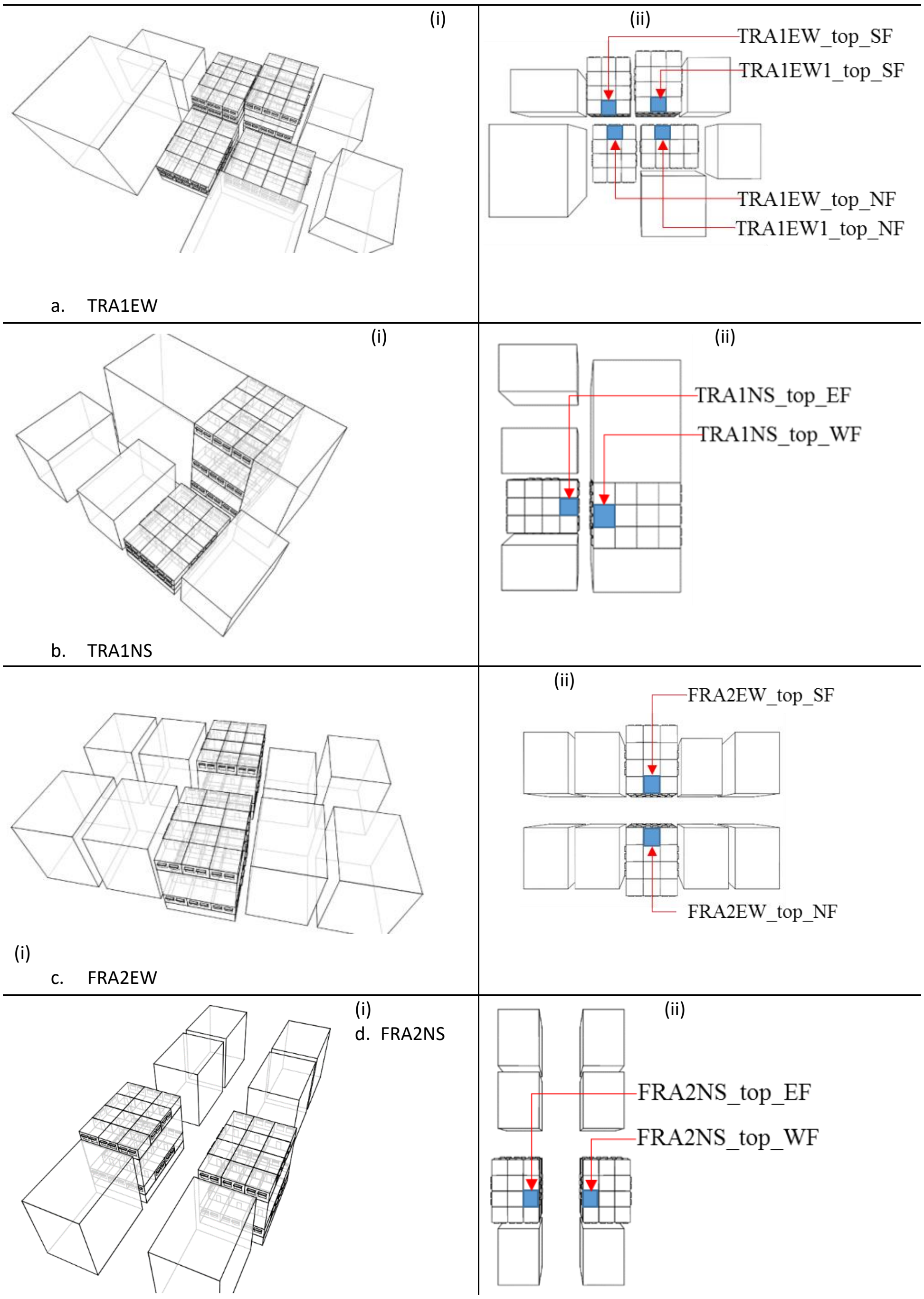

Figure 1. Perspective and top views of the case-study models for energy simulations TRA1EW, b. TRA1NS, c. FRA2EW and d. FRA2NS.

2.4.3. Opening type

For indoor air temperature analysis, sliding windows with a 50% openable area are selected as these are the most common window types in Dhaka. Considering the typical indoor comfort range between 24.0^{0}C and 33.0^{0}C (Mallick, 1996), windows are set to open when the indoor air temperature exceeds 24.0^{0}C and below 35.0^{0}C. Beyond these limits, windows are set to remain closed. It is assumed that above 35.0^{0}C air temperature, natural ventilation will increase thermal discomfort.

Table 2. Model Set-up in IES-VE for evaluating indoor air temperature

Building Template Manager: Thermal Conditions		**Construction**
○ **Building regulations:** Heated or occupied room ○ **Room conditions:** ○ **Heating**: Heating Profile> Off continuously ○ **DHW**: Consumption> 0.0000 l/(h.pers) ○ **Cooling**: Off continuously ○ **Plant:** (auxiliary energy)> Off continuously		○ **Roof**: Customised Roof for Dhaka U – value: 2.9797 W/m^2K, Total R value: 0.1956 m^2K/W, Thickness: 228.3 mm Composition: Felt/Bitumen Layers 12.7mm, Plaster (Dense) 6.3 mm, Cast Concrete (Dense) 203mm, Plaster (Dense) 6.3 mm ○ **Ground /exposed floor**: IES-VE Construction database Name: Solid ground floor U – value: 1.3479 W/m^2K, Total R value: 0.000 m^2K/W, Thickness: 750 mm Composition: London Clay 750mm ○ **External Wall**: Customised Brick Wall for Dhaka U – value: 2.0097 W/m^2K, Total R-value: 0.3276 m^2K/W, Thickness: 266mm Composition: Plaster (Dense) 6.3 mm, Brickwork 254mm, Plaster (Dense) 6.3 mm ○ **External glazing**: Customised External glazing for Dhaka U-value: 5.1742 W/m^2K Thickness: 6mm Composition: Outer Pane 6mm ○ **Wooden Door**: U-value: 2.194 W/m^2K Thickness: 40mm ○ **Internal Partition:** Customised Internal Partition for Dhaka U – value: 2.0411 W/m^2K, Total R value: 0.2299 m2K/W, Thickness: 139.6mm Composition: Plaster (Lightweight) 6.3 mm, Brickwork 127mm, Plaster (Lightweight) 6.3 mm ○ **Internal glazing:** Customised Internal glazing for Dhaka U-value: 5.1742 W/m^2K
System		
○ **HVAC system**: None ○ **Auxiliary vent**: None ○ **DHW system**: None ○ **System outside air-supply**: Off continuously		
Air Exchanges		
○ **Natural Ventilation:** Max Flow: 4.000, Unit: ach, Variation- when indoor air temperature exceeds 24^0C and remains below 35^0C, Adjacent condition: external air ○ **Infiltration:** Max Flow: 0.250[1], Unit: ach, on continuously, Adjacent condition: external air		
Internal gain		
○ **Fluorescent Lighting:** Reference: 1 - Single Family Lighting, Max sensible-10.764 W/m^2, Max power- 10.764 W/m^2, Rad Frac- 0.45, Fuel-Electricity, Variation- Occupancy Dhaka 6 member family_Weekly Profile, Dimming- off continuously ○ **People:** Reference: 225 - Single Family - 400, Max sensible- 65.941 W/person, Max Latent Gain- 30.772 W/person, Occupancy- 37.161 m^2/person, Variation- Occupancy Dhaka 6 member family_Weekly Profile, Dimming- off continuously ○ **Miscellaneous:** 0.4 - Single Fam Equip, Max sensible- 4.306 W/m2, Max Latent Gain– 0 W/ m^2, Max power- 4.306 W/m^2, Rad Frac- 0.22, Fuel-Electricity, Variation- Occupancy Dhaka 6-member family_Weekly Profile		

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[1] The value represents a theoretical condition. Actual infiltration rate in a tropical country context would be much higher. This has been discussed in the limitations.

Table 3. Model Set-up for IES-VE model for the cooling load scenario

<table>
<tr><th>Building Template Manager: Thermal Conditions</th><th></th><th>System</th></tr>
<tr><td>○ Building regulations: Heated or occupied room
○ Room conditions:
○ Heating: Heating Profile> Off continuously
○ DHW: Consumption> 0.0000 l/(h.pers)
○ Cooling: Cooling system_Dhaka weekly (when outdoor air temperature exceeds 28^{0}C)
Set point: Constant at 26.0^{0}C
○ Plant: (auxiliary energy)> Set to cooling profile</td><td></td><td>○ HVAC system: Dhaka System
Cooling mechanism: Air conditioning
Fuel: Electricity
○ Auxiliary vent: same as HVAC
○ DHW system: None
○ System outside air-supply: Set to cooling profile</td></tr>
<tr><th colspan="3">Air Exchanges</th></tr>
<tr><td colspan="3">○ Natural Ventilation: Max Flow: 4.000, Unit: ach, Variation- when outdoor air temperature is below or equal to 28.0^{0}C, Adjacent condition: external air
○ Infiltration: Max Flow: 0.250^2, Unit: ach, on continuously, Adjacent condition: external air</td></tr>
</table>

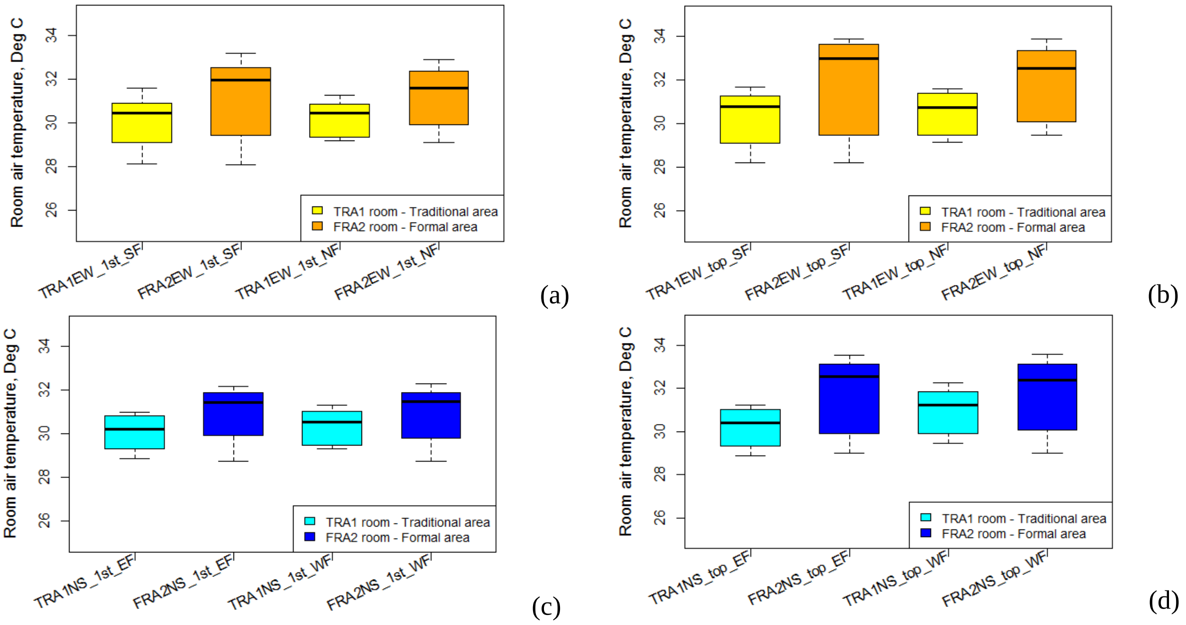

Figure 2 Room air temperature per hour over 24 hours: a. 1st floors in EW canyons, b. top floors in EW canyons, c. 1st floors in NS canyons and d. top floors in NS canyons

For cooling load analysis, windows are set to open when outdoor air temperature is less than or equal to 28.0^{0}C. The cooling system is activated when the temperature exceeds 28.0^{0}C. 28.0^{0}C is chosen as it is between the halfway in the comfort limit. Cooling set point temperature is set to 26.0^{0}C as this is typical to the case study area.

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[2] The value represents a theoretical condition. Actual infiltration rate in a tropical country context would be much higher. This has been discussed in the limitations.

2.4.4. Air exchanges

For indoor air temperature analysis, air exchanges occur through natural ventilations with 4 air changes an hour (ach) and infiltration that is turned on continuously with 0.250 ach.

3. Results

3.1. Indoor air temperature analysis

3.1.1. Room air temperature

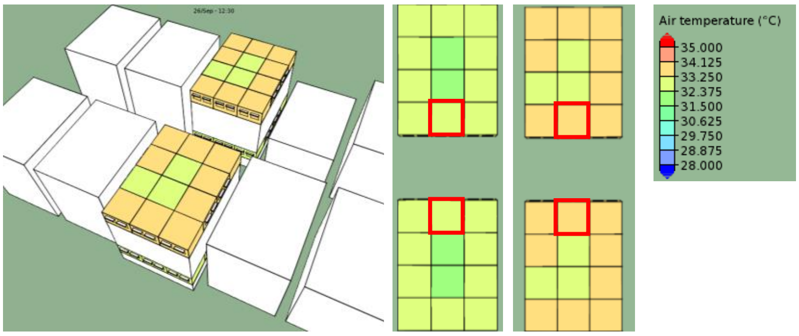
Comparing the mean indoor air temperature, rooms in traditional areas are found to be 0.6 - 1.6^{0}C cooler than the corresponding rooms in the formal areas in both EW and NS canyons. Figure 2 shows the boxplots of individual room air temperatures on an hourly basis for both 1st and top floors in EW and NS canyons. Each room air temperature is presented in terms of median, upper quartile, lower quartile, maximum and minimum values. Three-dimensional graphical images of air temperature ranges in the subject rooms are presented in Figure 3 and Figure 4.

The maximum temperature (33.9^{0}C) is found on the top floors in the EW canyon in the formal area in rooms FRA2EW_top_SF and FRA2EW_top_NF. The reason for top floor rooms in the EW canyons being warmer than rooms in the NS canyon is that EW canyons are subjected to higher and longer solar exposure. Top floors in the formal area are on average 2.2^{0}C warmer than the top floors in the traditional area. Due to the diversity of building heights, the top floors of lower buildings in traditional areas are subjected to mutual shading from the surrounding buildings, whereas top floors in the formal area are mostly exposed to direct solar radiation due to their equal heights. Again, top floors of tall buildings in the traditional area have a slightly lower temperature than the top floors in the formal area due to cooler outdoor microclimatic conditions in the former. Lowest room air temperature (28.1^{0}C) is found in EW canyon in rooms TRA1EW_1st_SF and FRA2EW_1st_SF. As they are located on the 1st floors, the rooms are cooler due to mutual shading from the opposite building.

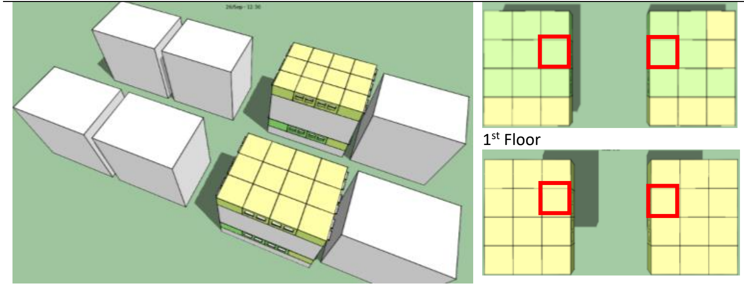
The indoor comfort air temperature ranges in Dhaka for people engaged in sedentary activities, wearing ordinary clothing (0.5 clo), is between 24.0^{0}C and 33.0^{0}C in typical indoor conditions (Mallick, 1996). Following that, the average (median) air temperatures in the top floor rooms in the formal area are above the comfort limit.

3.1.2. Solar gain

Comparison of total solar gain in EW and NS canyon in Figure 5 shows that model rooms in the traditional areas for both 1st and top floors have lower solar gains than the corresponding rooms in the formal area. For the 1st floor, the difference is 30% and for the top floor, the difference is 91% on average. 1st floors in both EW and NS canyons have lower solar gains ranged between 0.77 – 1.43 kWh per room due to mutual shading, whereas all top floors in the NS canyon, except TRA1NS_top_EF, have higher (2.32 kWh per room and above) solar gains. The reason for TRA1NS_top_EF having one of the lowest solar gain (0.77 kWh per room) is that it remains under shade from the tall building located on the opposite side of the street. Here, all comparing is done on the basis of a single model room (with an area of 25m^2). The solar gain patterns in the rooms can be observed in Figure 6. It shows that rooms in the traditional area are better protected from high solar gain due to greater mutual shading. Since the excessive solar gain can increase the indoor air temperature, rooms in the traditional area have fewer chances of becoming overheated than those in the formal area.



FRA2EW 1st Floor Top Floor (a)

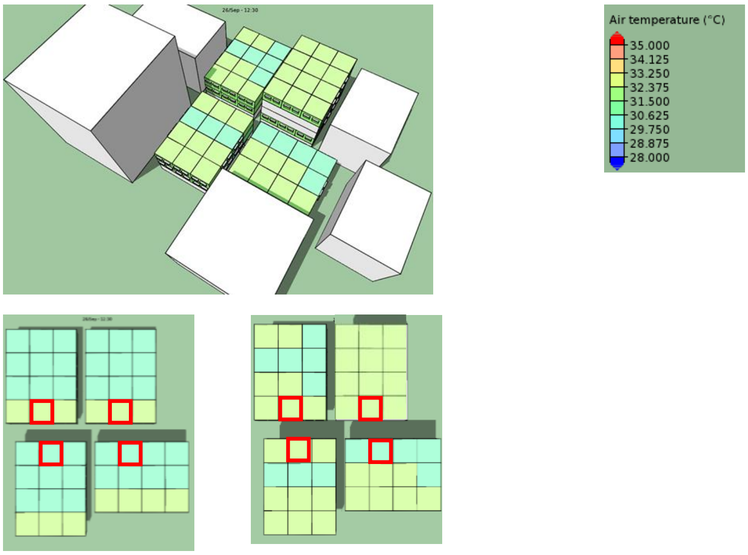


FRA2NS Top Floor

(b)

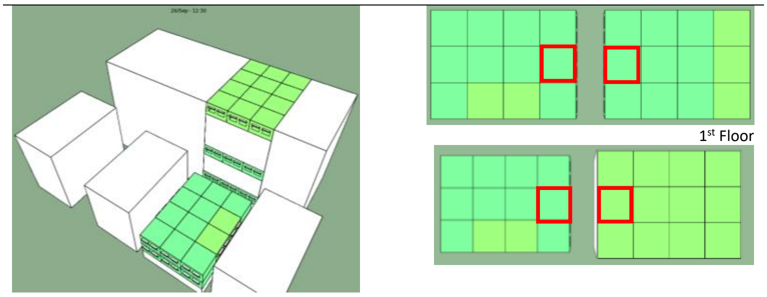
🟥 Location of model room

Figure 3. Room air temperature ranges in the formal area for 1st floors and top floors: a. FRA2EW, b. FRA2NS



1st Floor Top Floor

TRA1EW



TRA1NS Top Floor

🟥 Location of model room

Figure 4. Room air temperature ranges in the traditional area for 1st floors and top floors: a. TRA1EW, b. TRA12NS

3.1.3. MacroFlo ext vent

The incoming air flow inside the room from the external environment calculated by the *MacroFlo programme* in IES-VE is defined as *MacroFlo ext vent*. Apparently, the differences in indoor air flow conditions between the 1st and top floor in both EW and NS canyons are insignificant. The boundary condition for wind speed at 10m height is used for IES-VE simulations, however this does not seem to have an impact on indoor ventilation conditions for rooms at different heights. The reason is that all case-study buildings for the IES-VE simulations are 6-storied or lower, except a 9-storied one in the traditional area. Therefore, the model rooms in this building, TRA1NS_1st_WF and TRA1NS_top_WF, show the highest variation in indoor airflow.

From the ventilation pattern in Figure 7, higher MacroFlo ext vent is observed in south-facing and west-facing rooms in the traditional area. This is because wind direction was predominantly from the south and south-west directions during the simulation periods. Rooms in the formal area have lower ventilation due to lower wind speed boundary conditions.

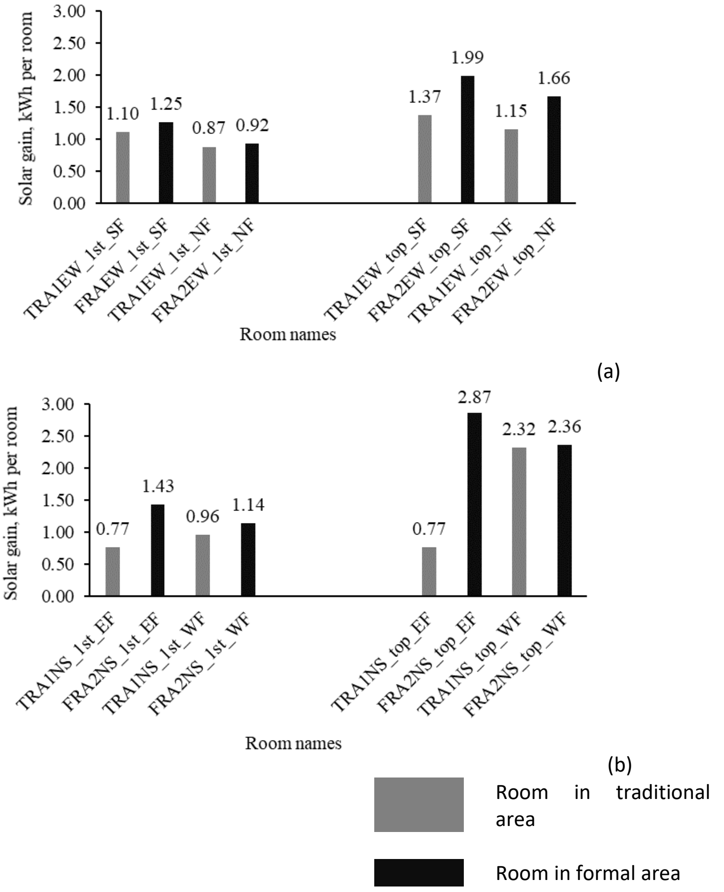


Figure 5. Total solar gain (kWh) in both 1st and top floors over 24 hours in a. EW canyon, b. NS canyon

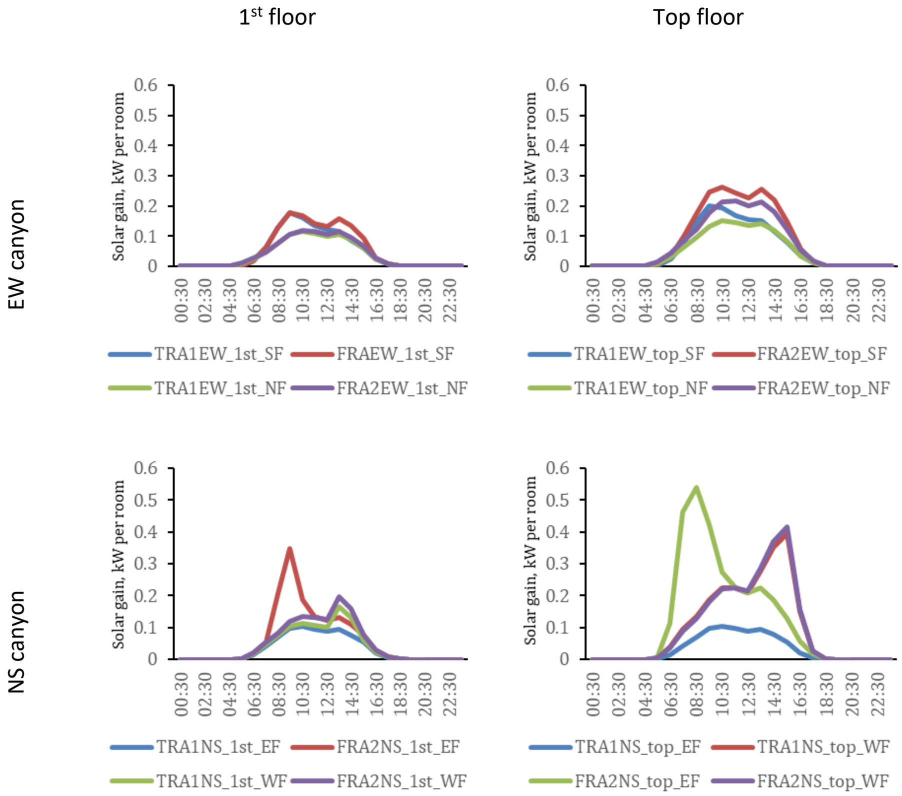


Figure 6. Solar gain (kW per hour) pattern in the model rooms

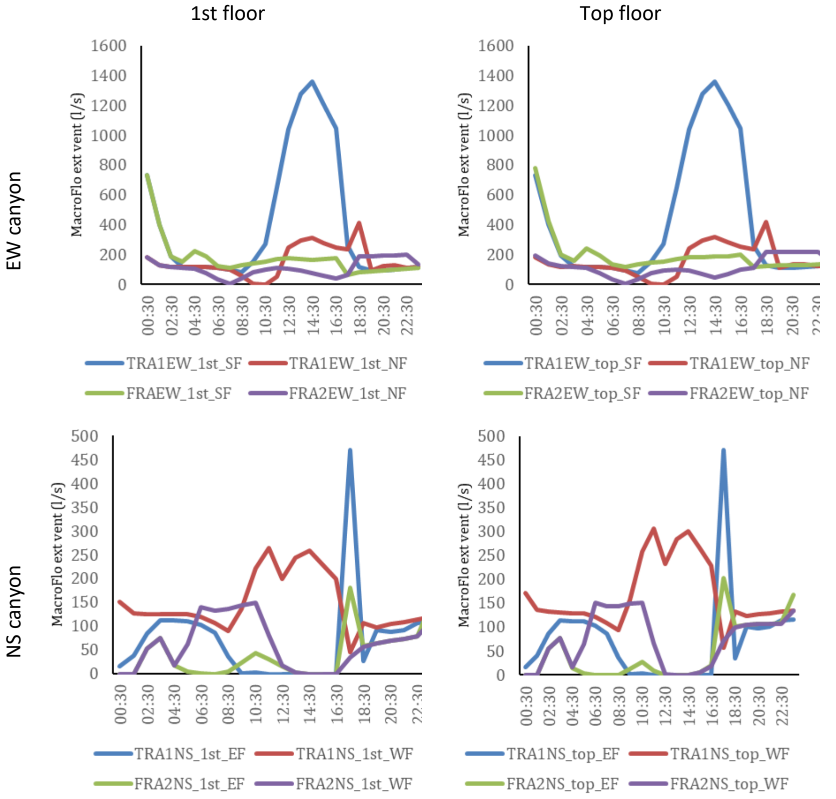


Figure 7. MacroFlo ext vent (l/s) per hour for 1st and top floors in EW and NS canyons

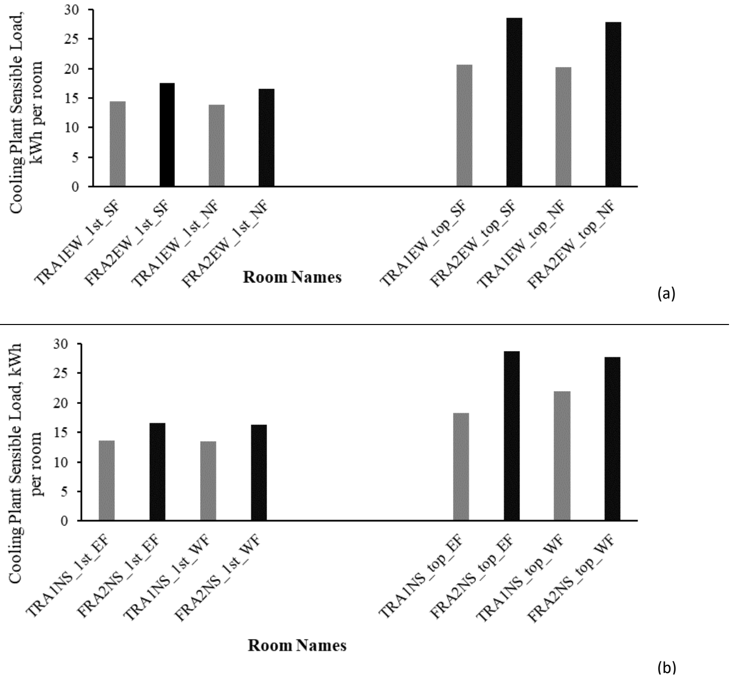


Figure 8. Comparison of total cooling load in 24 hours in a. EW canyon and b. NS canyon

3.1. Cooling load analysis

Comparison of the total cooling load over 24 hours in the east-west (EW) and the north-south (NS) canyons reveals that top floors consume 55% more energy (60% for NS canyons) than the 1st floors. Figure 8 (a, b) shows the cooling loads in EW and NS canyons respectively for both 1st and top floors. South-facing (SF) and north-facing (NF) rooms are represented in EW canyons and east-facing (EF) and west-facing (WF) rooms in NS canyons. Apparently, the south-facing and east-facing top floor rooms in the formal areas, namely FRA2EW_top_SF and FRA2NS_top_EF, consume the highest amount of energy for cooling. The other top floors in the formal area also consume a similar amount of cooling energy. This is due to the lack of mutual shading on the top floors of the formal area as all buildings have mostly similar heights.

In order to enable equal comparison in terms of cooling energy consumption, this study has used the model room as the unit of area ($25m^2$). Thus, the energy indicator is kWh, denoted for every $25m^2$.

For both 1st and top floors and EW and NS oriented canyons, rooms in the traditional area consume less energy than the rooms in the formal area. In the case of 1st-floor rooms, the south-facing (SF) and north-facing (NF) rooms in the formal areas (FRA2EW_1st_SF, FRA2EW_1st_NF) use 21% and 20% more energy than the corresponding rooms in the traditional area to maintain indoor comfort. For east-facing and west-facing rooms the differences are 23% and 21% respectively. The differences are far more evident on the top floors. For example, the south-facing, north-facing, east-facing and west-facing top floor rooms in the formal areas use 38%, 38%, 57% and 26% more energy respectively than the corresponding rooms in the traditional area. This can be explained by the air temperature differences between the areas as well as greater mutual shading in the traditional area due to the diversity of building heights.

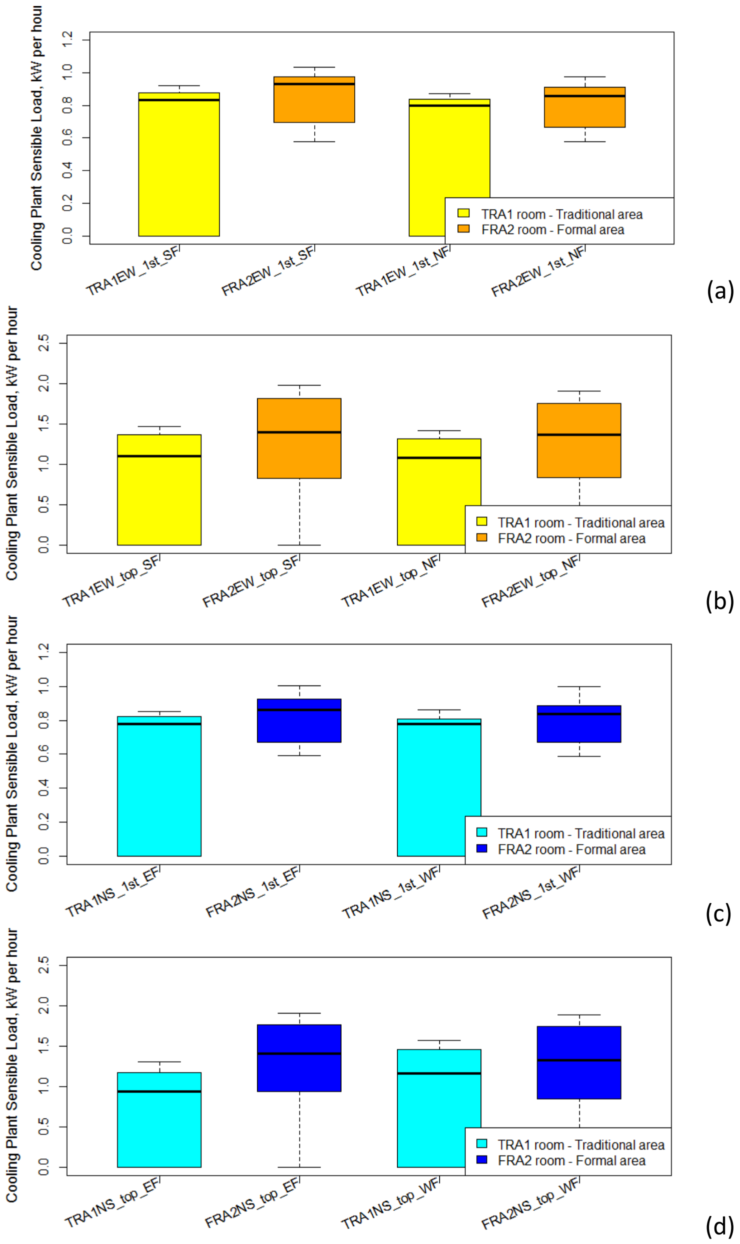


Figure 9. Average cooling load per hour over 24 hours: a. 1st floors in EW canyons, b. top floors in EW canyons, c. 1st floors in NS canyons and d. top floors in NS canyons

Figure 9 represents the average cooling load per hour over 24 hours for 1st floors and top floors in EW and NS canyons. Information for each individual room is presented in separate box plots showing the median, upper quartile, lower quartile, maximum and minimum values. It is evident that the 1st-floor rooms in the formal area are always in a cooling mode. On the other hand, all rooms in the traditional area take on a natural ventilation mode at some point of the day when the outside air temperature reduces to 28.0⁰C or below. The cooling system is deactivated when this situation is reached. The IQRs (Inter-quartile range[3]) in the boxplot show that cooling load amounts in the traditional areas are clustered in the lower ranges (0.0-1.4 kW per room) of the scale, whereas the same for the formal areas are bunched along the higher ranges (0.7-1.8 kW per room).

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[3] Represents 50% data in a boxplot

4. Limitations

The study has some limitations. Firstly, the energy simulation in this study, does not take into account the daylighting potentials. Even though the need for artificial lighting during daytime can be quite high considering the high-density urban context, it can be assumed that daylighting will save some amount of energy consumption. However, cooling energy is considered to be more important than lighting energy (during daytime) in this particular type of climate. Since the main purpose of the study is to look into the impact of urban geometry on building energy consumption, such shortcomings do not generate any critical problems.

Secondly, this study has used the default infiltration rates in IES-VE for the analysis of indoor conditions. Since the purpose here is to understand the relative differences among the models, the infiltration rate does not affect the outcome as it remains constant across the models. Nevertheless, to avoid confusion and to recreate actual situation in a tropical climate more accurately, future research should apply a more context-specific value for infiltration rates. For similar climates in Singapore, a typical infiltration rate for building energy simulation is 0.600ach with VAV (Variable Air Volume) system for centrifugal chiller plants (Shah et al. 2002).

5. Conclusion

This study has analysed indoor air temperature conditions and energy performance of a traditional and a formal residential area in a tropical, warm-humid context. The purpose of the study is to examine the effect of urban geometry on the indoor conditions of individual buildings in terms of room air temperature, solar gain and ventilation through external windows and energy demand for cooling to maintain indoor comfort conditions. The study has found that diversity in urban geometry in deep urban canyons, as observed in the Traditional Residential Areas, is helpful in reducing indoor air temperature and cooling load requirements. On average, the cooling load in model rooms in the formal area is 21% higher for 1st floors (40% for top floors) compared to the corresponding rooms in the traditional area. In terms of solar gains, the difference was 30% for the 1st floors and 91% for the top floors, with rooms in the formal area having the higher ranges. Consequently, the room air temperature in the traditional area was found to be 0.6-1.6^{0}C lower than those in the formal area. This has important implications for reducing indoor air temperature in a tropical warm-humid context. Concerning the climate, natural ventilation is another essential strategy to aid in the cooling of interior spaces through passive means. Due to apparent higher air-flow in the urban canyons in the traditional area, the interior airflow in the adjacent buildings was also higher.

There are two main reasons that contribute to better indoor conditions in the traditional area compared to the formal area. Firstly, the diversity in urban geometry in deep urban canyons ameliorates the outdoor microclimatic conditions by lowering air temperature and enhancing the airflow. Secondly, the variations in building heights provide necessary mutual-shading for the exposed roofs or top floors of the lower buildings as well as the flanking vertical facades. In the formal area, on the other hand, roofs or top floors are always exposed to high solar gain due to the equal height of the buildings. Additionally, because of wider urban canyons, vertical walls in the formal area receive greater solar radiation. Finally, the reduced airflow resulting from uniform urban morphology worsens the indoor ventilation. Overall, the findings of this study suggest that the choice of urban form has a significant impact on the indoor conditions of the adjacent buildings. This finding can be applied in practice to combat challenges of tropical climate in terms of urban planning and design guidelines by modifying urban geometry and incorporating diversity to achieve favourable indoor and outdoor conditions.

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