Topic: T1.3 Urban and Indoor Environment Quality Reference number: 1025

Exploring the Effect of Micro-climate Data on Building Energy Performance Analysis

Tania Sharmin[1,*], Koen Steemers[2]

1,2 University of Cambridge, Department of Architecture, 1-5 Scroope Terrace, Cambridge, CB2 1PX

Abstract: A limitation in the current research is most studies on energy performance of buildings concentrate on individual buildings while its interaction with neighbouring urban context remains largely unexplored. Buildings are considered as isolated masses, disregarding the fact that they belong to an urban environment. Consequently, the energy performance of buildings is generally analysed with the aid of general climatic data, in case of building simulations in particular, which varies significantly with micro-scale climates. Indoor conditions are determined through the interaction between the building surface and synoptic-climatic data uploaded as a weather file. Predicted energy consumption this way by ignoring its urban settings can vary significantly from the actual value. Several studies have demonstrated that microclimate inside urban canyons has substantial influence upon the building energy consumption. Therefore, it is important to incorporate micro-climatic data in energy performance research. This study shows how much difference the micro-climate data can make when used instead of synoptic-climate data by coupling micro-climatic tool Envi-met with Building energy simulation (BES) programme IES-VE. The study also endeavours to identify the best urban arrangement in terms of energy performance among four simple urban arrangements in a hot-humid tropical climate under the hottest scenarios. The results reveal the surface-to-volume ratio as an important parameter in achieving energy efficiency. Among four simple urban blocks, the pavilion model was found to have the lowest cooling demand. However, the pavilion model, mostly made up of non-passive zones is unable to interact with the outdoor environment and therefore, in spite of its energy efficiency, cannot be termed as the best possible option as far as passive buildings are considered.

Key words: Urban Micro-climate, Building Energy Performance, Synoptic Climate, ENVI-met, IES-VE

1 Introduction

Urban microclimate is a complex consequence of different parameters which involves innumerable natural and urban processes. The natural parameters like air temperature and humidity, vapour pressure, wind speed, solar radiation, soil temperature and humidity are very sensitive to any 3-dimentional changes in the urban settings. Therefore it is important to recognize the impact of this altered micro-climate into building energy performance analysis. As suggested by Givoni [Cited in 1]: “The outdoor temperature, wind speed and solar radiation to which an individual building is exposed is not the regional ‘synoptic’ climate, but the local microclimate as modified by the structure of the city, mainly of the neighbourhood where the building is located”. Trapping and absorption of solar radiation in between buildings, constricted long-wave heat release due to limited sky-view factor, inadequate convective heat removal through wind, anthropogenic heat release and finally reduced vegetation and evapotranspiration can lead to an urban environment, which is considerably different from the neighbouring countryside. This phenomenon, typically known as urban heat island and assumed to be non-detrimental for cold climates, can be seriously deleterious to warm-climate cities by affecting the overall energy consumption of the urban area as well as health and thermal comfort of its inhabitants [2]. There has already been some interest [3] to examine the impact of urban micro-climate on energy consumption, but very few of that actually attempt to

* Corresponding author: PhD Candidate, Department of Architecture, University of Cambridge.
E-mail address: ts531@cam.ac.uk

determine the difference between micro-climate data and synoptic-climate data in energy performance studies. IES-VE (Integrated Environmental Solutions-Virtual Environment), a dynamic energy and thermal simulation tool, coupled with ENVI-met, a numerical microclimatic tool, has been used as the main tool to measure building energy performance in this study.

Building energy simulation (BES) programmes are increasingly recognised as a competent tool among built-environment researchers and professionals for analysing building energy performance. The indoor thermal environment recreated through detail modelling of building geometry, construction, natural ventilation and HVAC system can produce rational results which often assist in pre-design decision making process. However, these programmes are generally unable to consider the detail energy exchange processes occurring between different natural and artificial elements within the building surroundings and the building envelope itself and thereby overlook its effect in the building thermal performance and energy consumption calculations [3]. Predominantly, they concentrate on individual buildings while the interaction of this with the neighbouring urban context remains greatly unexplored [4]. Buildings are somewhat considered as isolated masses, being apathetic to the fact that they exist in an urban environment.

Such tools mostly depend on synoptic climate data derived from long term observation of the local weather stations (typically a statistical summary of 30-year weather data). The suitability of the synoptic climate data for building energy research can be rather disputed as this is measured at the meteorological stations (typically located at the countryside), which can differ substantially from urban areas or cities. In this situation, the use of microclimate simulation tools, which are able to measure microclimatic dynamics, in building energy performance analysis can prove to be useful. Again, the micro-climate tools cannot generate detail building energy/ thermal performance results rather their role is to replicate the major microclimatic processes inside complex urban arrangements. Therefore, coupling of BES programmes and micro-climatic simulation tools is necessary to produce better results for assessing micro-climatic effects on building thermal/ energy performance.

The shortcoming of calculating building energy performance by disregarding its interaction with the neighbouring urban context has been identified by many researchers. Allegrini et al. [5] has identified substantial difference in energy demand by comparing a stand-alone office building with a building surrounded by street canyons. Modified radiation balance seems to have played the major role in this energy difference rather than the heat island effect or convective energy loss. Bozonnet et al. [2007, Cited in 6] has shown a 30% difference in cooling energy demand when used outdoor air temperature data inside the street canyon against air temperature data from meteorological station by linking an aeraulic zonal model with a BES model. Steemers et al. [7] has carried out an energy performance analysis for six simple archetypes with LT Method, but not including the micro-climatic effects. Yang et al. [3] has demonstrated the benefit of coupling simulations using Envi-met and Energy Plus for the humid sub-tropical climate of Guangzhou and temperate marine climate in Frankfurt am Main. Only a single simple urban arrangement was investigated in this study using different cases such as, stand-alone building, building in urban setting, coupling with and without greenery etc. It did not attempt to compare the examined urban arrangement with other simple arrangements.

Nevertheless, there was no research so far to link micro-climate models with BES programmes in a hot-humid climate to compare energy performance of simple urban arrangements. Therefore, in this study, energy performance of simple urban arrangements while considering the respective surrounding micro-climate was achieved by using outputs of ENVI-met micro-climate simulation model as the input of a BES programme IES-VE.

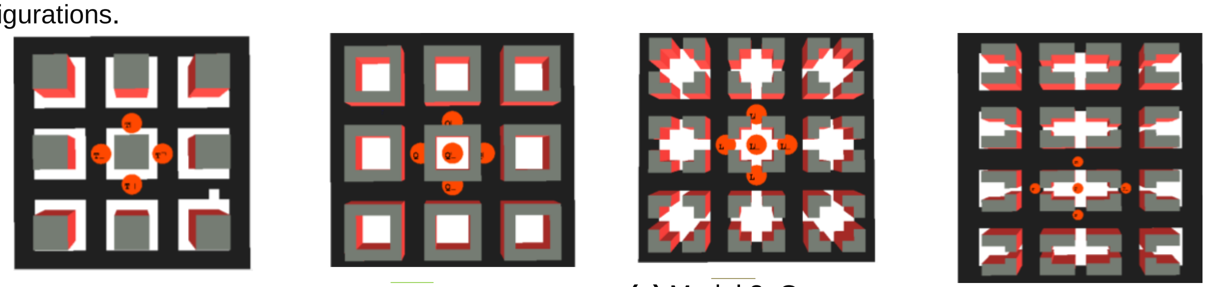
2 Methodology and numerical modelling

Micro-climatic simulation in this study is carried out by ENVI-met, a numerical microclimatic tool with high temporal and spatial resolution. Founded on the fundamental equations of fluid-dynamics and thermo-dynamics, ENVI-met is able to recreate the major microclimatic processes inside complex urban arrangements. The validity of ENVI-met was long-established in previous research in many different locations like Curitiba, Brazil [8], Singapore [9] and Colombo, Sri Lanka [10].

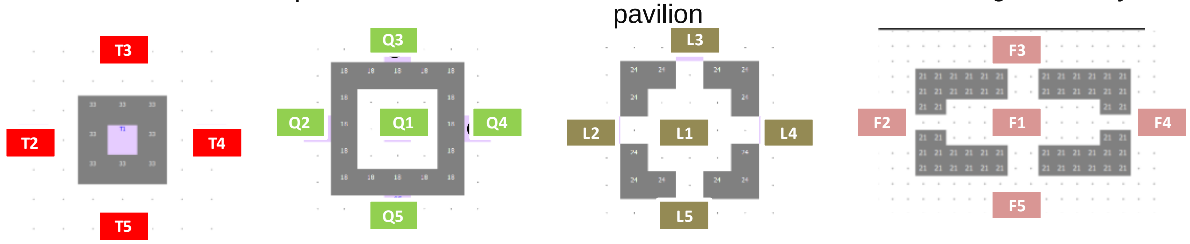
IES-VE (Integrated Environmental Solutions-Virtual Environment), on the other hand is a dynamic thermal simulation tool extensively used in contemporary research and practice. The application of IES was confirmed for tropical hot-humid contexts [11]. Its proficiency in reproducing the performance of multiple buildings within an urban context while considering the mutual shading and radiation exchanges between buildings [4] makes it particularly appropriate for the current study.

Four archetypal urban arrangements, from Martin and March (1975) [12] have been investigated in this study under the hot-humid climate of Dhaka. This includes: pavilions, enclosed courtyard pavilions, open square and open rectangular courtyard pavilions (Fig 1, a-d). Since this can only be achieved hypothetically, numerical modelling and computer simulation techniques were adopted in this study. It is also more convenient to understand the basic relations between comfort, energy consumption, climatic variables and geometry parameters in a theoretical model before dealing with the complex real examples.

Building height (for all models) and depth (for courtyard models only) were kept same for all models to avoid the varying shading impact of different building height which my affect the cooling load for different urban block configurations.



(a) Model 1: Pavilion **(b)** Model 2: Courtyard pavilion **(c)** Model 3: Open square courtyard pavilion **(d)** Model 4: Open rectangular courtyard



(e)

Fig 1 (a-d) Top-view of four archetypal urban arrangements in Envi-met **(e)** Showing receptor points (measurement points) in each model.

2.1 Analysis of Synoptic-climate and Micro-climate Data

In order to understand the impact of micro-climate data on building energy-performance analysis two sets of climate data was used in this study. One is, synoptic climate data: the standard EPW weather data for Dhaka. This is the adjusted data collected from long term observation of the local weather stations. The other is micro-climate data calculated by Envi-met (V4). Simulation was carried out for a hot-summer day, with the highest maximum air-temperature in early-April when a high air temperature is coupled with high relative humidity and creates a challenging comfort environment. In order to obtain micro-climate data different receptor points were placed at critical positions in each model (Figure 1, e). Average air-temperature is .9 to 1.2^0 C lower and relative humidity is 11.5 to 14% higher in synoptic climate data than the micro-climate data.

Indoor simulation using IES-VE in this study was parameterised in the following manner:

2.1.1 *Construction.* Construction material for the roof, floor, ceiling, external wall, glazing etc. was parameterised in the simulation with the following data in Table 1.

2.1.2 *HVAC.* In order to compare energy consumption between models, HVAC Cooling system (air-conditioning) was adopted in the study with electric fuel consumption. Cooling set-point was set to 28^{0}C, considering the comfort zone lies between 24.6 to 28.6^{0}C during the month of April for the case-study area [13]. No heating system was considered in the study as heating is not a requirement during the mentioned period in the study. Even during the winter it is not customary to install heating system as temperature rarely go below 15^{0}C.

2.1.3 *Natural Ventilation.* Natural Ventilation was assumed when room air-temperature remained between 24 to 28^{0}C. Since the temperature never went below 28^{0}C during the simulation period, the rooms were always in HVAC mode. The infiltration was on continuously with a maximum flow of .250 ach.

2.1.4 *Occupancy profile.* 50% occupancy during daytime was assumed concerning the social practice as older parents are very likely to live with the adult children and mostly are taken care of by the house-hold maids.

From the comparison of temporal variation of DBT in Fig 2 (a), it is visible that, although DBT in synoptic climate data is 1 to 2^{0}C higher during the peak hours of the day, it is almost 3^{0}C lower during the night (12:00 pm) in comparison to the DBT at micro-climatic receptor points. This indicates the consequence of heat-island effect in micro-climate data, which synoptic-climate data is apparently unable to take into consideration. As relative humidity is inversely related to DBT, an opposite pattern can be seen in Fig 2(b).

Regarding wind speed, since both speed and direction at the model boundary level remains constant throughout the simulation period, the resultant wind-speed and direction is the outcome of modification due to the model geometry only. On the other hand, wind-speed measures from the synoptic-climate data is subject to constant changes which may or may not be perceptible at the local micro-climate level Fig 2 (c), specially in a high density urban area located away from meteorological stations.

3 Results

In order to understand the effect of mutual shading, 2nd floor level were considered in this study. Firstly, total cooling load at 2nd floor level is measured separately for each model including all passive, non-passive and corner rooms in the floor. Passive rooms are those located along the building periphery with direct contact with the outdoors, non-passive are those with no direct contact with outdoor and finally corner rooms are those located at the building corners.

Considering all passive, non-passive and corner rooms at the 2nd floor level of each model the average cooling load in Model 1 is found to be the lowest (Fig 3 a). This is due to the fact that Model 1 has the lowest surface to volume ratio (Table 2) and therefore has lowest interaction with the outdoors. Except the peripheral and corner rooms, rest of the rooms in Model 1 are non-passive rooms which are protected from direct solar gain. Clearly, during the worst case scenarios, when outside temperature is very hot, these rooms will result in a lower cooling load than the peripheral passive rooms.

In case of Model 3, it has higher surface to volume ratio than Model 2, therefore its cooling load is also higher (Fig 3 a). On the other hand, Model 4, which has equal surface to volume ratio as Model 3, has lower cooling load than Model 3(Fig 3a), due to lower ratio of east-west facing room to north-south-facing rooms. In separate measurement from all model average (both synoptic and micro-climate models), cooling load in north and south facing rooms were found to be lower than east and west-facing rooms (Fig 3b).

A maximum decrease of 5.7% in cooling Load in synoptic climate model from the micro-climate model is found in case of Model 2 (Fig 4a). Air-temperature difference between synoptic-climate data and micro-climate data seem to have played a role for lowering cooling load in synoptic model, as can be seen air-temperature in synoptic-climate data is always at least 0.9^{0}C lower than the micro-climate data. In each case, synoptic models have lower cooling loads than micro-climate models (Fig 3a).

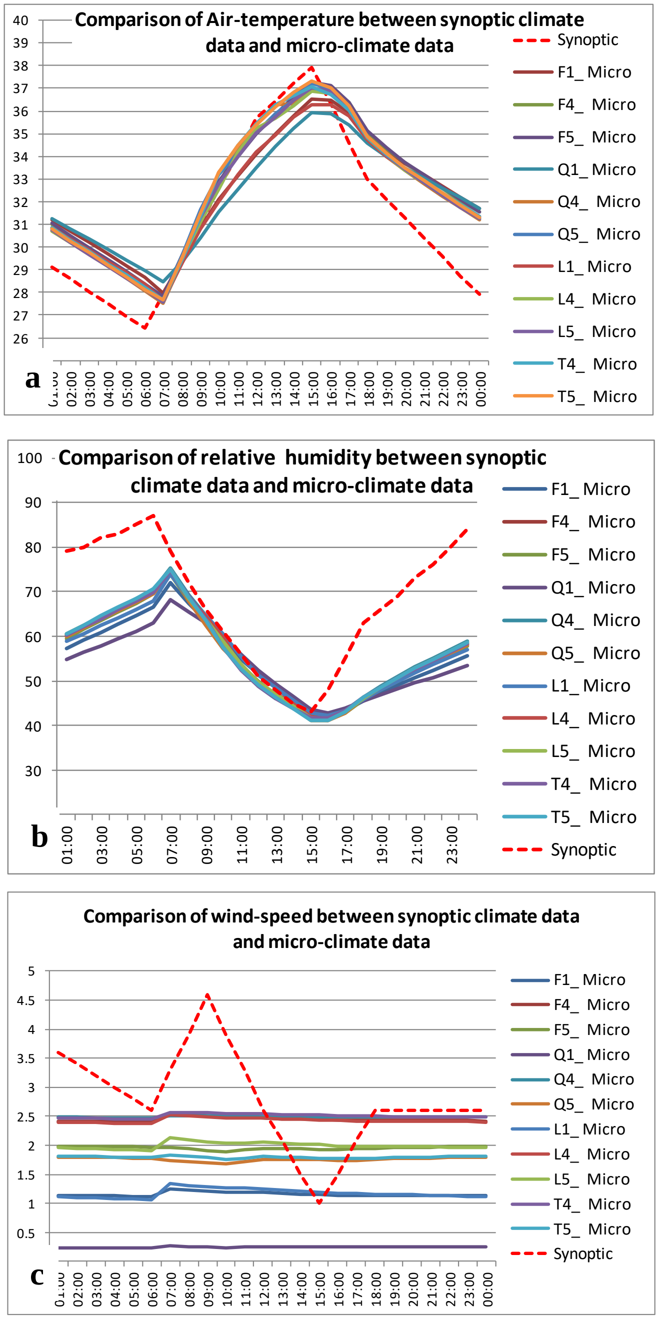


Fig 2. Comparison of (a) Air-temperature, (b) Relative humidity and (c) Wind-speed between synoptic climate data and micro-climate data

However, while considering the whole floor including all passive, non-passive and corner rooms, the effect of different orientation and court-yard spaces could not be understood. Therefore, detail analysis was carried out at room levels excluding the non-passive and corner rooms. The cooling load follows the same pattern when only passive rooms are considered and Model 1 is again found to consume lowest cooling energy (Fig 5).

While, only passive rooms have been considered in this section, the effect of non-passive rooms cannot be ignored. For example, solar gain in Model 1 is equally high as in other models, but its cooling load is lowest due to the fact that much of its heat is carried away (through internal conduction loss) to the neighbouring non-passive rooms which are protected from direct solar gain (See Fig 5 Internal Conduction Gain/Loss).On the other hand, Model 3 and 4 have higher number of corner rooms (16 in each floor), therefore, the internal conduction loss from the passive rooms towards the neighbouring rooms (as corner rooms already have higher gains) are lower in these models than Model 1 and 2.

With the micro-climate data, Model 3 consumes higher cooling load, whereas for synoptic-climate data both Model 3 and 4 consumes equal cooling load (Fig 5). This indicates the behaviour of different models may not remain same in case of micro-climate data. At passive room levels, the reduction in cooling load is presented in Fig 4 (b).

Another detail analysis was carried out at model levels to understand the impact of courtyard spaces on energy consumption of the flanking rooms (passive only) (Fig 6). Cooling plant load for north-facing rooms are found the lowest in all model cases. It is also found, all north-facing rooms along the courtyard in Model 2 and 3 have lower solar gain than the same along the streets due to mutual shading inside the court, but higher cooling load due to higher Macroflo internal ventilation gain (heat gain from air-flow entering the room from adjacent rooms). As wind speed is lower inside courtyard spaces, all north-facing rooms along the courtyard have higher internal ventilation gain (Fig 6). Cooling load in south-facing rooms in all models is also lower inside the courtyard than the street-facing rooms due to lower solar gain. This indicates courtyard models are able to reduce solar gain inside courtyard spaces for north and south- facing rooms.

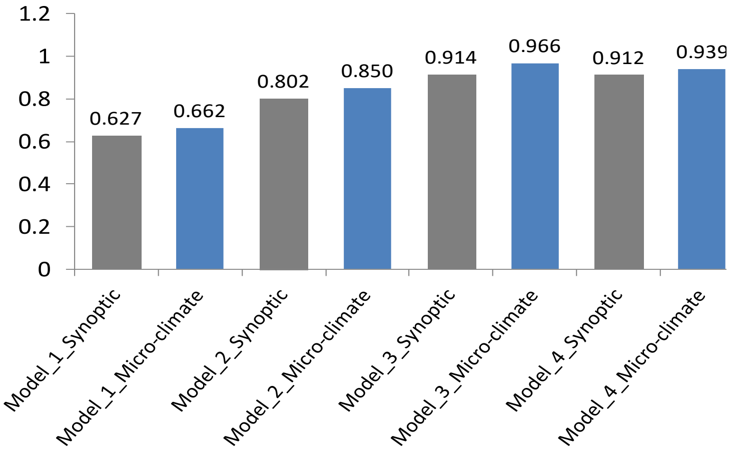
Table 1: Model Set-up for IESVE model

Construction

- *Roof:* 8 in. Light Weight Concrete
- *Ground /exposed floor:* Un-insulated solid ground floor
- *Internal floor/ceiling:* 130mm Concrete Ceiling
- *External Wall:* Brickwork Single –Leaf Construction Dense Plaster, U – value 2.184
- *Glazing:* 6 mm Pilkington Single Galzing, U value- 5.562
- *Wooden Door:* U-value: 2.194
- *Internal Partition:* 13mm pll 105mm bri 13mm pll, U value: 1.473
- *Internal glazing:* 4mm Pilkington single glazing, U value: 3.689

Table 2. Surface to Volume Ratio and Ratio of N-S facing rooms

Model name	Surface to volume ratio	Ratio of east-west facing rooms to north-south facing rooms
Model 1	.142	1:1
Model 2	.242	1:1
Model 3	.308	1:1
Model 4	.308	3:5



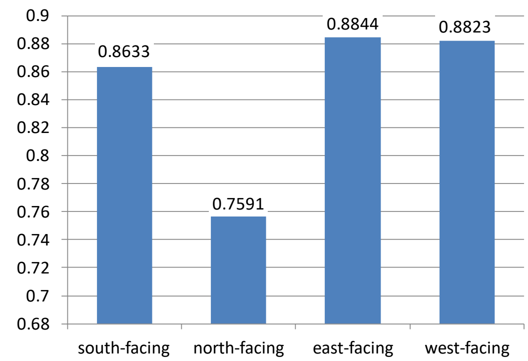
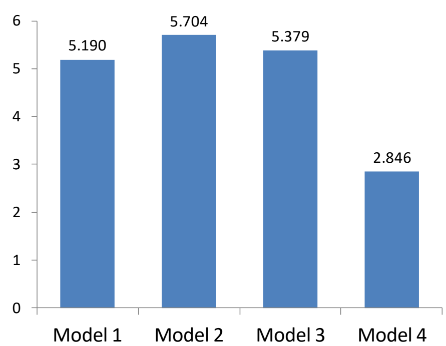


Fig 3a Average cooling plant sensible load (kw) per hour for 2nd floor in each model including all passive, non-passive and corner rooms

Fig 3b Cooling load (kw) per hour at different orientations: all model average



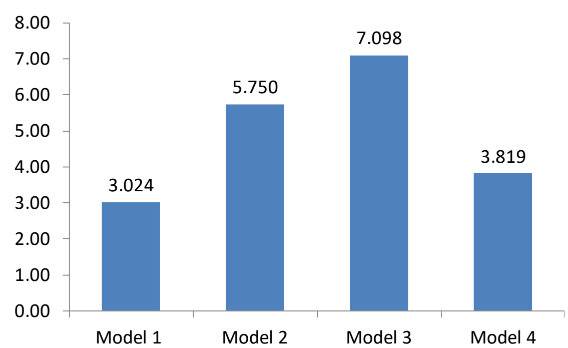


Fig 4a Percentage Decrease in cooling load in synoptic model from micro-climate model for all passive, non-passive and corner rooms

Fig 4b Percentage Decrease in cooling load in Synoptic Model from Micro-climate Model for passive rooms only

4 Conclusion

This study has shown that use of micro-climate data in energy performance research can create reasonable difference when used instead of synoptic-climate data. A decrease of 6% in cooling load is observed in case of synoptic-climate data from micro-climate data. 6% decrease may appear rather insignificant. However, we need to remember that in this study only the effect of geometric configuration has been considered. When in real scenarios, collective response of many other parameters, such as, vegetation, building material, surrounding surface materials etc. will shape the micro-climate, the resultant difference of the micro-climate data can be further noticeable. Specially for cities with higher Urban Heat Island intensity and higher density the difference can be even more pronounced. For instance, the theoretical models in the study mostly represent ideal scenarios with typically low density and the same density is repeated in all streets. So for high density cases the effect of micro-climate on energy performance will be higher.

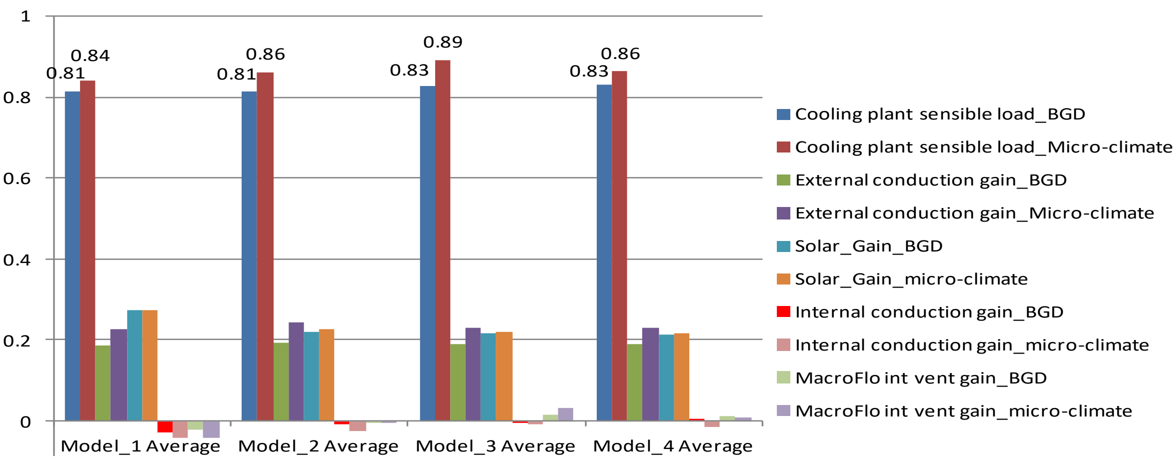


Fig 5. Comparison of all models considering passive rooms only

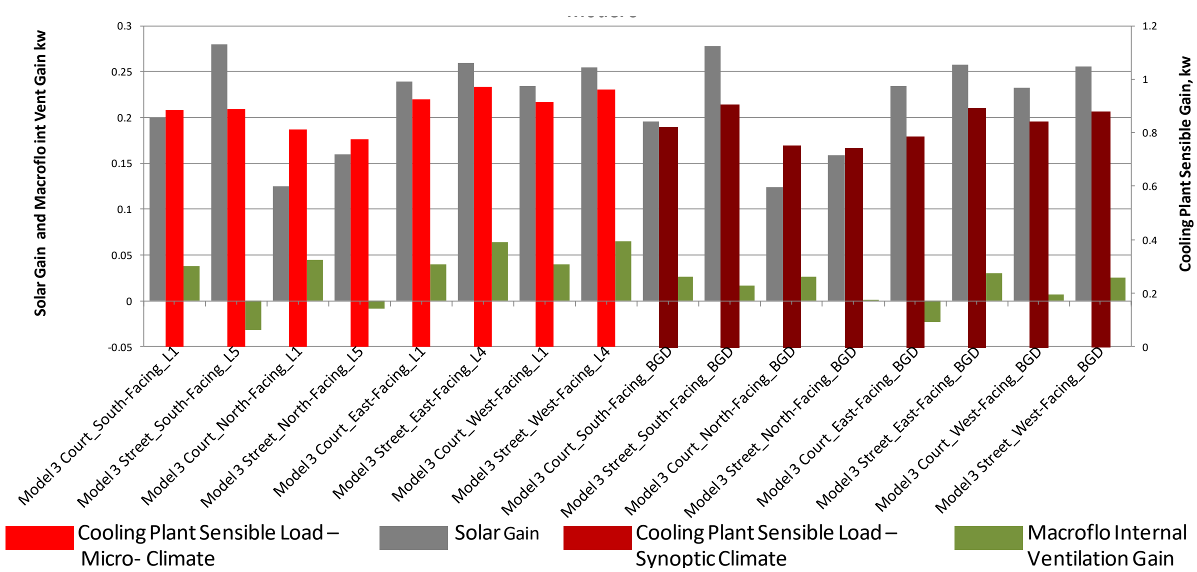


Fig 6: Model 3 detail analysis showing cooling plant load, , solar gain and macroflo int. ventilation gain

In the present scenario, the air-temperature difference between the micro-climate and synoptic climate case is between 0.9 to 1.2^{0}C. As suggested by Wong et al. (2011) [14], for every 1^{0}C drop in air-temperature, the peak electric demand for cooling may vary by 2–4%. This agrees with the findings in this study. On the other hand, studies on heat-island intensity in Dhaka showed intensity between 0.5 and 6K occurring during the night [15]. Since, the present model has shown some theoretical arrangements in the above climate for only for a single scenario, the actual UHI impact produced in the real field could not be recreated.

Another intension of this study was to identify the most favourable urban arrangement in terms of energy consumption. Model rooms were compared for two cases: one is including all passive, non-passive and corner rooms and the other is including the passive rooms only. In both cases, Model 1 (Pavilion type) was found to perform better than the courtyard arrangements because of its lower surface to volume ratio as well as higher ratio of non-passive to passive rooms. Due to the worst case scenario, the outdoor conditions were uncomfortable and all non-passive rooms in Model 1 were protected from outside gains. But non-passive rooms cannot be an ideal solution as far as passive buildings are concerned. They not only offer an inferior living quality to its inhabitants in terms of interaction with the outdoors, but can also become over-heated when passive rooms are able to release heat to the outdoor environments.

Both Model 3 and 4 have higher cooling load than Model 2 because of higher amount of corner rooms, thereby higher surface to volume ratio which offers higher exposure to outdoor conditions. The energy performance of these two models can be easily enhanced by treating the corner rooms with appropriate design strategies. Although both Model 3 and 4 have the same number of corner rooms, the energy performance of Model 4 was slightly better than Model 3 because the ratio of north-south facing rooms to east-west facing rooms was larger.

Comparing the performance of courtyard spaces in terms of solar gain, all south, east and west facing rooms along the courtyards in Model 3 and 4 are found to have lower gains than the corresponding rooms facing the streets, thus signifying the benefit of mutual shading. However, in case of Model 2 east and west-facing rooms facing the courtyards, solar absorption is higher and so is the cooling load than the street-facing rooms. This suggests, use of enclosed courtyard spaces may not be applicable for this climate. However, courtyard spaces with permeability, as in Model 3 and 4, can be applicable in this climate if uban ventilation is available. Since they can also lead to lower convective heat loss, adequate ventilation may be necessary to carry away the accumulated heat.The role of ventilation for improving indoor conditions is not fully understood in this study due to the use of cooling system. Further study is necessary for naturally ventilated conditions.

Reference

[1] Ratti,C., Baker, N. And Steemers, 2005. Energy consumption and urban texture. *Energy and Buildings*, **37**, 762-776.

[2] Moonen, P., Defraeye , T., Dorer, , V., Blocken, B. and Carmeliet, J. 2012.Urban Physics: Effect of the micro-climate on comfort, health and energy demand. *Frontiers of Architectural Research*, 1, 197-228.

[3] Yang, X., Zhao,L., Bruse,M. and Meng,Q., 2012. An integrated simulation method for building energy performance assessment in urban environments, Energy and Buildings, Volume 54

[4] Futcher ,J. A., Kershaw, T. and Mills, G., 2013.Urban form and function as building performance parameters. *Building and Environment*, 62, 112-123.

[5] Allegrini, J., Dorer, V., Carmeliet, J., 2011. Influence on the urban microclimate on the energy demand of buildings. In: Cisbat11 conference, 14–16 September 2011. Lausanne, Switzerland.

[6] Bouyer, J., Inard, C. and Musy, M., 2011. Microclimatic coupling as a solution to improve building energy simulation in an urban context , Energy and Buildings, 43 (7), pp. 1549–1559

[7] Steemers, K., N. Baker, D. Crowther, J. Dubiel, M. H. Nikolopoulou, and C. Ratti. 1997. "City texture and microclimate." Urban Design Studies 3 : 25-50.

[8] Krüger ,E.L., Minella, F.O. and F. Rasia, F., (2011).Impact of urban geometry on outdoor thermal comfort and air quality from field measurements in Curitiba, Brazil. Building and Environment, 46, 621-634.

[9] Wong, N. H., Jusuf, S. K., Aung L.W., Kyaw T. H., Syatia N. T. & Xuchao, W. (2007). Environmental study of the impact of greenery in an institutional campus in the tropics. Building and Environment, 42, 2949-2970.

[10] Emmanuel, R. et al., (2007). Urban shading – a design option for the tropics? A study in Colombo, Sri Lanka. International Journal of Climatology, 27, 1995–2004.

[11] Al-Tamini, N.A. and Fadzil, S. F. S., (2011). The Potential of Shading Devices for Temperature Reduction in High-Rise Residential Buildings in the Tropics. Procedia Engineering, 21, 273-282.

[12] Martin, L. and March, L. 1975. Urban Space and Structures, Cambridge University Press, Cambridge.

[13] Ahmed, Z. N., Howarth, A. T., & Zunde, J. M. (1990). Thermal comfort studies and applications for Dhaka. Building Services Engineering Research and Technology, 11(3), 105-108.

[14] Wong, N. H., Jusuf, S. K., Syafil, N. I., Chen,Y., Hajadi, N., Sathyanarayanan, H. and Manickavasagam, Y. V. 2011.Evaluation of the impact of the surrounding urban morphology on building energy consumption. *Solar Energy*, **85**, 57-71.

[15] Santamouris, M., 2001. Heat-Island Effect. In: Santamouris, M., Demosthenes, D. and Asimakopoulos, N.,(eds.) *Energy and climate in the Urban built Environment*, London: James & James (Science Publishers).pp 48-66