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BUILDING SERV ENG RES TECHNOL 2011 32: 73
DOI: 10.1177/0143624410394536

Building Serv. Eng. Res. Technol. 32,1 (2011) pp. 73–84

Urban form, thermal comfort and building CO_2 emissions – a numerical analysis in Cairo

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This paper describes a modelling analysis of the role different urban forms might play in reducing building CO_2 emissions. The study was based on a residential building in a Cairo neighbourhood under summer conditions and developed a base case urban layout covering an area of $1\,km^2$. Three alternative urban strategies were then created around the same residential building. The software package EnviMet was used to assess external microclimate and thermal comfort conditions in each urban layout. Localised weather files were then created as inputs to the dynamic thermal modelling package DesignBuilder, which predicted the CO_2 emissions associated with mechanical cooling to achieve comfort in the building. It was possible to observe some differences in CO_2 emissions as a result of the different urban forms.

1 Introduction

It is generally believed that climate change is the result of increased greenhouse gas (GHG) emissions resulting from human activities such as the burning of fossil fuels. Potential impacts from climate change include higher air temperatures, health issues, flooding, increased energy consumption for cooling and different master plans for urban developments to enable cities to adapt in the coming decades.[1–12] Reducing GHG emissions through efficient mitigation methodologies has become a feature of many governmental policies, but for the built environment these policies are normally set at the individual building scale. Reducing carbon emissions could be more effectively done at the urban form scale in tandem with single building scale policies by, for example, the use of urban passive cooling techniques such as the layout of the urban fabric, the creation of landscaped spaces and the use of cool (high solar reflectance) surfaces.[2, 13–17]

As the neighbourhood is considered the traditional planning unit of a city[18–22] then it should also be considered as the climate-based adaptive planning unit for the city. Oke[23] classified the city, from an urban climate perspective, into seven zones from UTZ1–UTZ7, but he did not specify how urban spatial form could be of benefit in urban planning and community development. Duany[22] classified the city from a transect perspective into five zones, from T1–T5, but did not demonstrate how traditional neighbourhood developments could address different climates. Fahmy and Sharples[16] introduced an intermediate parameter for climate-based urban planning – the degree of compactness, *D*c. It represents three parameters: first, the population that occupies

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10.1177/0143624410394536

the built up area; second, its height in terms of number of building floors to accommodate the population and, thirdly, the climate response within the local canopy height of a specific climate region. In this way different city zones can be classified into five circles (city centre = very compact; central urban = compact; general urban = medium; suburban = open and rural urban = very open). Consequently, each climate region's local scale form and, in turn, city landscape, can have different urban forms despite having the same compactness classification. Very few numerical models are capable of simulating and assessing thermal performance on an urban scale due to the complexities of the transient environments.[24–26] Moreover, the relationship between the outdoor climate and the indoor environment is usually examined using compiled weather data files that cannot represent actual localised urban microclimate conditions. Very few studies have discussed coupling outdoor and indoor climate conditions in order to investigate how urban planning impacts upon indoor comfort levels[27–29] which can, in turn, influence building energy consumption and CO_2 emissions. In this paper the results from coupling outdoor–indoor environmental data outputs and urban form will be presented along with the numerical simulations of urban forms to generate ambient microclimate values and to study the corresponding indoor thermal comfort levels and CO_2 emissions.

2 Methodology

2.1 Base case site planning and design suggestions

In order to study local scale urban passive performance a case study was chosen in the hot, semi-arid climate of Cairo (latitude 30° 38′ N, longitude 31° 11′E). Simulations were made for a development called the Fifth Community, which was built in the late 20th century as one of the New Cairo communities. It lies to the east of the 1st Greater Cairo Ring Road and is the extension of Cairo arising from the urban development plan of 1982 and its modifications in 1992[30,31](Figures 1 and 2).

The Base Case (BC) urban layout used in this study can be described as a dot pattern of single family villas, which is a common house form in New Cairo. It has been converted into urban sprawl accommodation due to the rapid growth that increased the problems of Greater Cairo and created environmental sustainability problems due the settlement's complete dependency on mechanical cooling. Following Fahmy and Sharples,[16] and to limit the variation of urban form Dc to only the population, the number of floors for the Fifth Community case study buildings was set the same as the base case in all design suggestions.

Design Suggestion 1, DS1, is a clustered urban form planned over the BC zoning in order to study the effect of only the clusters regardless of orientation. With a ground floor and 3 typical floors, (G + 3), all housing units had either a single flat of 150 m^2 or a duplex of 300 m^2 (Figure 3).

Design Suggestion 2, DS2, had the same land uses percentage but allocated in different zones. DS2 is designed after El Araby[32] who argued for a cluster aspect ratio (width: length: height) W/L/H of 1 : 3 : 1.3 (Figure 4).

Design Suggestion 3, DS3, (Figure 4), is the same master plan as DS2 but with a different albedo (reflectance to short wave solar radiation) for walls and roofs. The clustered fabric form with urban tree arrangements and the green infrastructure also gives psychological benefits. Fahmy and Sharples[33] have investigated how urban green form can allow wind access for cooling and health purposes whilst providing shelter from excessive heat gain.

DS2 and DS3 clusters are oriented 15° about an E-W axis, which is optimum for a mid-latitude location whilst at the same time

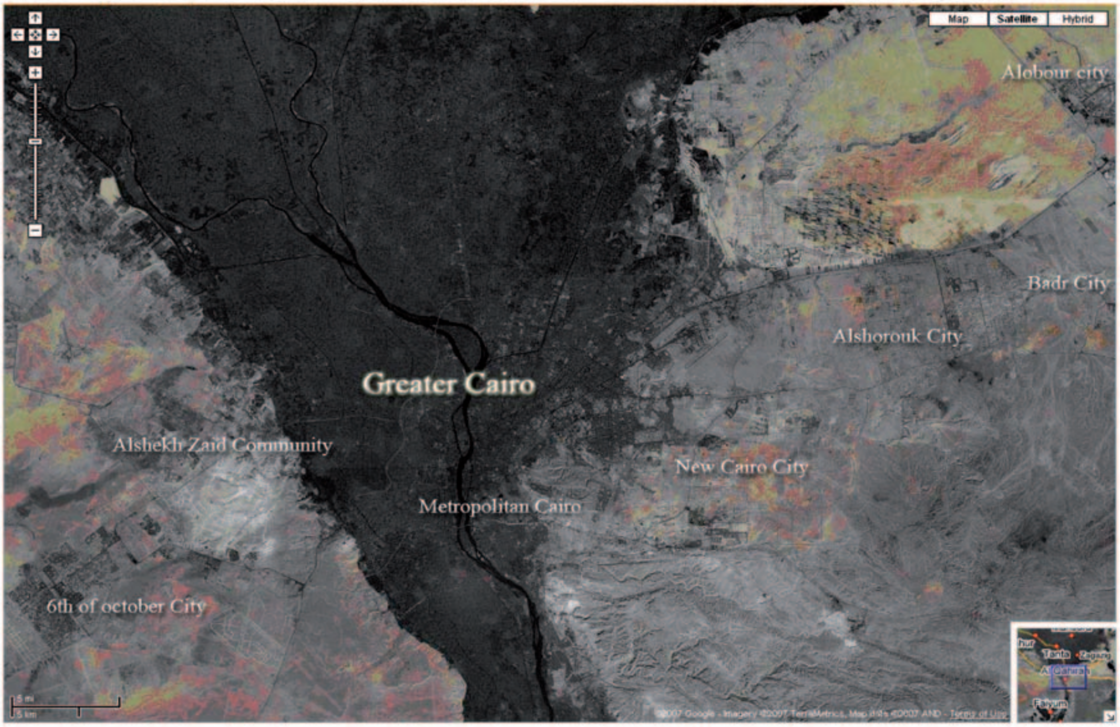
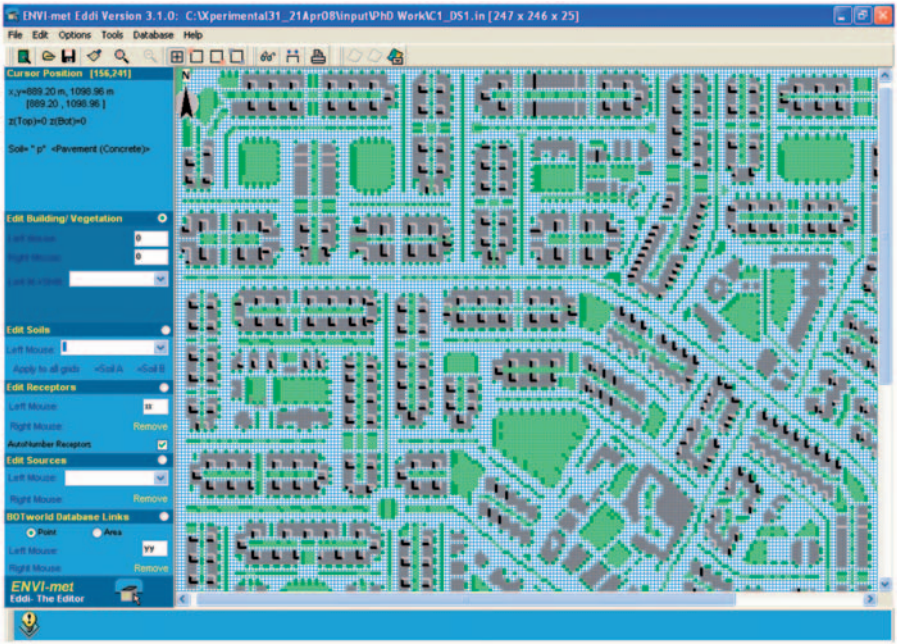


Figure 1 The Fifth Community in relation to Metropolitan Cairo (source: Googlemaps.com.)

Figure 2 GIS 3-D modelling built over a Quick Bird 2008 satellite image for the existing dot pattern base case BC (neighbourhood in scale of about 1 km^2 area)


ENVI-met Eddi Version 3.1.0: C:\Xperimental31_21Apr08\input\PhD Work\C1_DS1.in [247 x 246 x 25]

Cursor Position [156,241]
x,y=889.20 m, 1098.96 m
[889.20 , 1098.96]
z(Top)=0 z(Bot)=0

Soil= " p" <Pavement (Concrete)>

Figure 3 Design Suggestion 1 (DS1) layout in the modelling tool interface of ENVI-met


ENVI-met Eddi Version 3.1.0: C:\Xperimental31_21Apr08\input\PhD Work\C1_DS2.in [249 x 249 x 25]

Cursor Position [109,209]
x,y=708.50 m, 1212.20 m
[708.50 , 1212.20]
z(Top)=0 z(Bot)=0

Soil= " p" <Pavement (Concrete)>

Figure 4 Design Solutions 2 and 3 (DS2 and DS3) in the modelling tool interface of ENVI-met the cluster aspect ratio is optimum for summer cooling/shading and winter warming.

The BC has almost no trees planted whilst DS1, DS2 and DS3 have 8 cm high grass and 15 m high *Ficus elastica* trees that are numerically modelled in arrangements using a leaf area index, LAI, of 3.[34] The green structure is formed so that a pedestrian can reach their private or public green area within a 10-min walk from their home. Furthermore, to reach the central neighbourhood park it will not take more than 10 min; refer to Figures 2 and 3 for the local green structures of the BC and DS master plans. Table 1 shows land use percentages and urban planning parameters of all cases. The *feddan* shown in Table 1 is a traditional Egyptian unit of area equivalent to 4200 km^2.

2.2 Numerical simulations

There are very few software packages that can model urban environmental conditions over a scale of 1 km^2. ENVI-met is a 3-D CFD numerical model that is capable of simulating the built environment surface-air-plant thermal interactions based on fluid dynamics and heat transfer fundamentals, solar movement and vegetation databases. ENVI-met has many proven advantages over other built environment simulations packages but it also has some limitations,[16,26,33,34–38] of which the most significant is the fixing of meteorological inputs at the boundary condition. Simulations for the Cairo urban designs using ENVI-met[35] were run for a designated 12 h period from 06.00–18.00 LST (GMT + 3) on the 1st July. Typical meteorological and other data used in the simulations are shown in Table 2.

The main criterion used for assessing outdoor conditions was the comfort level in terms of the modified PMV,[39] which is considered preferable for transient conditions to the stationary PMV of Fanger.[40] The ambient conditions corresponding to a specific outdoor PMV, PMVo, if close to accepted levels for native people by adaptation, will in turn lead to the consumption of more optimised amounts of energy to achieve indoor comfort, PMVi. These coupled comfort levels will affect CO_2 emissions from the matched buildings. Table 2 illustrates the meteorology, human outdoor biometeorology and model area resolution parameterisation for the urban simulations. PMVo, from a pedestrian comfort point of view, can be recorded at heights between 1.2–1.75 m above ground level (agl) and a height of 1.60 m has been selected to record PMVo in this study.

2.3 Output extraction and slice criteria

ENVI-met allows meteorology outputs for each grid in the model area and in slices at different heights within the model. It can produce any meteorological value for all grids of the model. The mean values of meteorological parameters at a height of 1.6 m agl from 06.00 to 18.00 LST were averaged to be used as hourly inputs. Slices of extracted numerical output allow the selection of specific heights to be used up to the model boundary. This is decided before running the model, where one of two vertical grid systems can be chosen.

Table 1 Land use percentages and urban planning parameters

	Urban area, *feddans*	Green coverage %	Cluster H/W/L	Construction %	Average no. of floors	*Dc*	Population in persons	Population density persons/ *feddans*
BC	380.15	0.368	–	0.252	3.171	0.799	14950	39.7 p/f
DS1		0.291	Various	0.299	3.911	1.169	46662	123 p/f
DS2		0.476	1 : 1.3 : 3	0.310	4.077	1.264	50448	133.0 p/f

Table 2 Meteorology, Biometeorology and model resolution inputs used in simulations

No.	Parameter	Value
1	*Ta*	301.95° K
2	*RH*	59%
3	*V*	3.5 m/s at 10 m height
4	Ground temperature	301.65 ° K from 0 to 0.5 m and 297.45° K from 0.5 to 2 m
5	Ground humidity	BC & DS1; 20% from 0 to 0.5 m and 30% from 0.5 to 2 m DS2 & DS3; 70% from 0 to 0.5 m and 80% from 0.5 to 2 m
6	U value Walls	1.7 w/m^2.K
7	U value Roofs	2.2 w/m^2.K
8	Albedo Walls	0.25 for all except DS3; 0.15
9	Albedo Roofs	0.15 for all except DS3; 0.40
10	Albedo Pavement	0.40
11	Pavement Emissivity	0.90
12	Human walking speed	1.1 m/s
13	Pedestrian Clo.	0.50
14	BC resolution	5.70 × 4.56m^2
15	DS1 resolution	5.70 × 4.56m^2
16	DS2 resolution	6.50 × 5.80m^2
17	DS3 resolution	6.50 × 5.80m^2

2.4 Coupling outdoor–indoor meteorology

As ENVI-met does not have the capability to simulate indoor climate (it just deals with it as heat sink through a steady state conduction), the thermal simulation package DesignBuilder v2.0.5 was used for investigating the mean comfort level and CO$_2$ production for the whole selected building. DesignBuilder is a 3-D comprehensive interface built over EnergyPlus v3.1,[41] a dynamic model that can simulate indoor thermal interactions, calculate comfort levels and CO$_2$ production.[42] The building is designed by the first author as being three storeys high (Figure 5), built in 2006 as small multifamily housing containing six typical flats, with five people/flat. The ground floor area is 300 m^2, and the other floors are 330 m^2; it has a window-to-wall ratio of about 15% and it is oriented along the N-S axis. This building already existed in the Base Case, and it has been decided that the same building would be used in the other three Design Strategies in order to relate any differences in CO$_2$ emissions to the ambient and built environments. The mechanical cooling system is split with separate mechanical ventilation in a multi zones model for all zones except for bathrooms, kitchens, stair cases and the whole basement.

Means of air temperature, wet bulb temperature, relative humidity, global radiation, short-wave direct and diffuse radiations and wind speed of all site outdoor grids were added in their time places in a comma separated file (CSV) file extension. This allows for the easy editing of hourly meteorology in a typical meteorological year (TMY2) weather data format which can be used for Egypt.[43] As DesignBuilder uses (EPW) weather files, the EnergyPlus converter tool has been used for conversion after writing new hourly data in the CSV file. Wet bulb temperatures were needed to complete the new hourly weather data and was calculated from *Ta*, *RH* and air pressure at the elevation of the site (100 439 Pa at 74 m above sea level). The buildings' design temperature was 23°C whereas ambient external air temperature calculated statistically by EnergyPlus and used in DesignBuilder were a maximum of 44°C and 43°C for BC and DS1-3, respectively, with a minimum of 24°C for all of them.

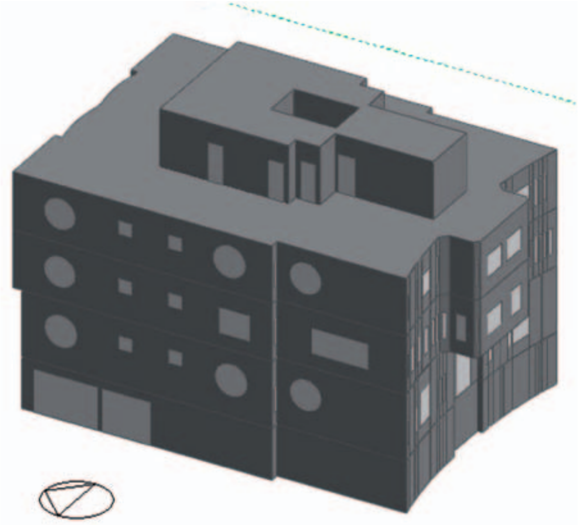


Figure 5 The building model built in DesignBuilder 2.0.5 including its basement which is not included in CO_2 production calculations

In Fahmy et al.[29] snapshot receptors were used to record the meteorological microclimatic conditions near the walls of a building for a limited area in the Fifth Community. In this paper, the urban site has been simulated at a local scale. Therefore, the mean microclimatic conditions for the whole site can be estimated for all the site's buildings, which is better than using a WMO weather station measurements at a single point to represent climate condition of a city (for Cairo this is WMO weather station number 623660 at Cairo International Airport). Simulations for each case in this work took about 7–10 days to build the model, about 7 days to simulate it and about 5 days to extract numerical data, indoor simulations and plot the outputs. Eventually, local scale meteorology means were used to compile the (EPW) file for usage by DesignBuilder.

3 Results

3.1 Urban form and comfort levels

Figure 6 illustrates the values of PMVo as the urban layouts were altered. Generally, by increasing the degree of compactness, *D*c, the level of external thermal comfort, as represented by PMVo was reduced compared with BC. As the solar altitude increased the street canyons within each case urban pattern were heated, giving a maximum PMVo at 13.00 for BC and DS1, which had the same zoning. Close to sunset, and due to the availability of sensible heat release by early evening, PMVo levels decrease significantly from 4.9 at 13.00 LST to only 2.0 at 18.00 LST by applying DS1. PMVo has recorded reductions from BC to DS1 of about 0.1–0.7 due to the clustered form which is the only difference from BC in addition to the increased compactness.

As DS2 and DS3 are the same zoning (master planning), their PMVo curves show the same trend of urban patterns and street canyon thermal behaviour but with a difference from BC and DS1. Their comfort peak was at 15.00 instead of 13.00 which is explained by the increased *D*c that offered more direct shelter, refer to Table 1. The evening behaviour is also different which cannot be due to *D*c as the neighbourhood quarters' public green areas offers nocturnal cooling nodes. It may be because of the

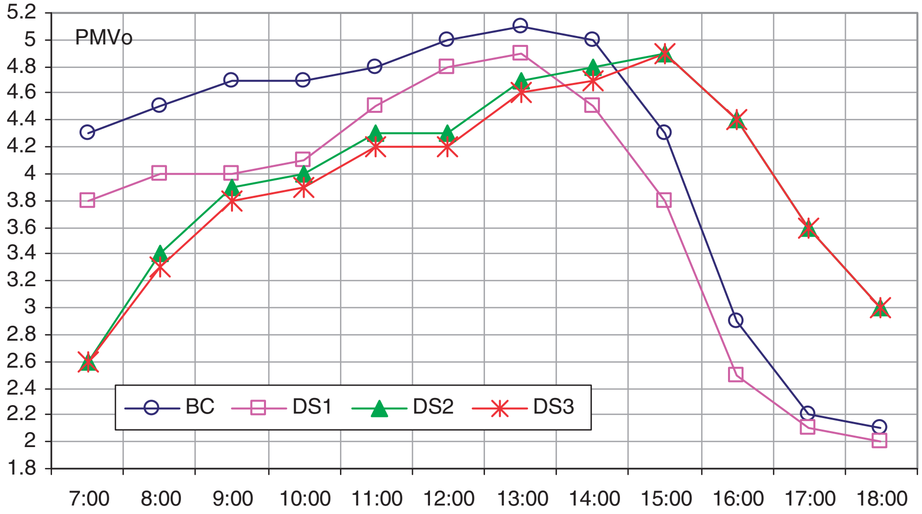


Figure 6 Mean outdoor comfort levels for all neighbourhood urban spaces

increased number of dense trees used (LAI of 3) that have been used to provide more shelter, but at the same time, it has increased the amount of long-wave radiation from the ground and near walls that is trapped by the tree canopies – this view is in good agreement with results of Fahmy et al.[34] The different zoning, *D*c, number of trees and clusters aspect ratios with orientation moved the whole comfort trend as if the urban form acted as a thermal mass wall. In comparison with BC, DS2 crossed the BC curve at almost 14.20 LST and recorded increased differences from BC of about 0.6–1.4 from early evening until sunset. The local scale clustered form with a dense tree arrangement delayed heating during the day but also reduced cooling during the night. It can be said that the whole urban passive cooling system configuration turned the neighbourhood form into *urban thermal mass* that shifted PMVo curves from BC as shown in Figure 6. The usage of high roof albedo values in DS3 resulted in less short-wave radiation being absorbed by the building fabric resulting in lower PMVo levels by day in comparison to DS2. As the solar altitude decreased the albedo effect on reducing heat gain is minimised, which can be noticed from the matching comfort levels of DS2 and DS3 from 15.00 LST until sunset.

3.2 Building CO_2 production

Figures 7 and 8 show mean building PMVi levels and CO_2 emissions per kWh corresponding to mean ambient conditions at 1.6 m agl, which in turn relate to the mean PMVo of all urban spaces of the neighbourhood at the same height. The same tendency from PMVo can be noticed in the PMVi curves, with the closer trend being linked to the mechanical cooling that kept comfort levels close to each other and close to the comfort standards of ISO7730. Surprisingly, the CO_2 emissions produced from DS1 has exceeded that of BC, starting from 12.00 LST and towards sunset, reaching 1.5 kg at 18.00 LST. The success that the clustered form of DS1 has achieved in comparison to BC for PMVo has not been achieved in terms of CO_2 emissions.

The compiled ambient conditions of DS2 reduced CO_2 production by 1.7% or about 0.6 kg from BC at 13.00 LST and started to exceed BC at 14.00 LST, at which time the urban mass effect starts to take place.

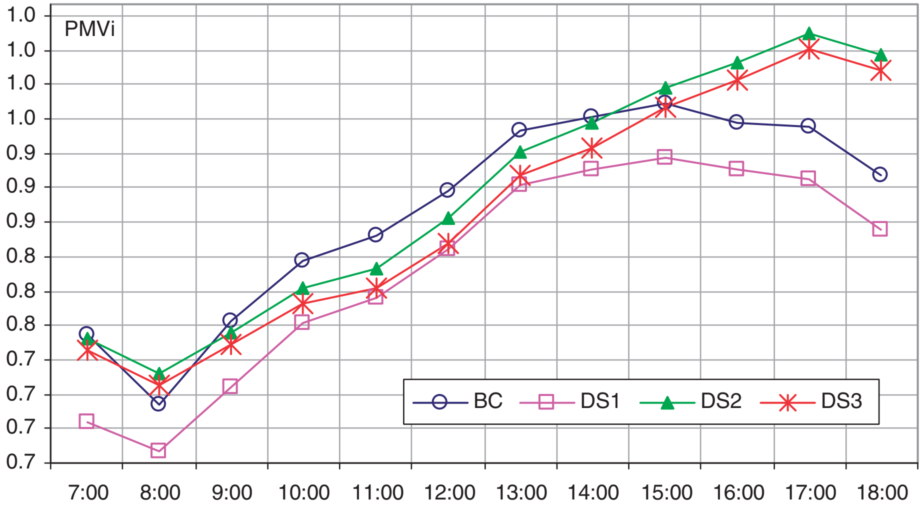


Figure 7 Mean indoor comfort levels of the selected building

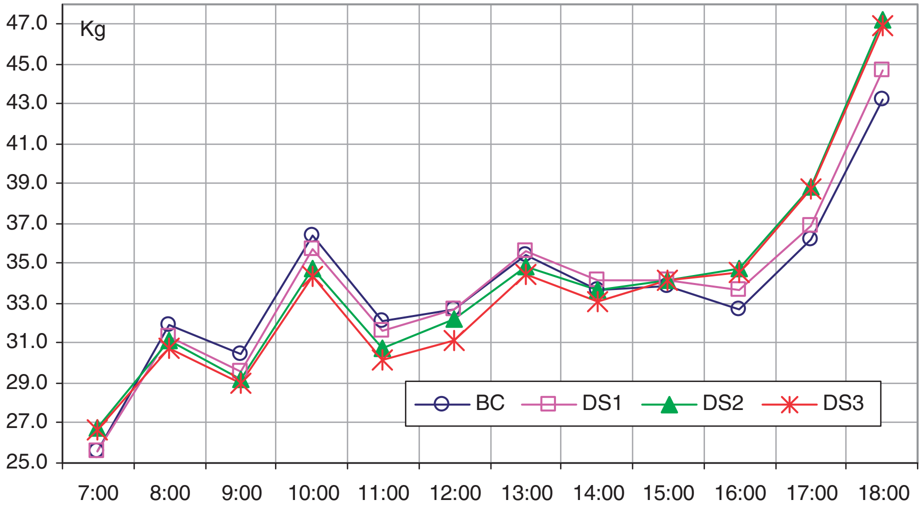


Figure 8 CO_2 emission (kg) from the selected building

DS2 had a maximum day time CO_2 reduction of 1.7 kg at 10.00 LST. The only difference of DS3 from DS2 is the roof surface albedo. In this suggested master plan, CO_2 reductions at the peak time reached 2.8% or about 1.0 kg from BC. In fact, the sum of the 12 h CO_2 emissions for BC and DS1-3 revealed that only DS3 succeeded in coupling between reduced outdoor–indoor comforts levels and reduced CO_2 production. For DS3 the cumulative CO_2 emissions over the 12 h period was 404.0 kg compared with 404.3 kg for BC, the small daily sum difference giving an idea about the homogeneity of the DS3 urban form. Its compactness could have allowed more nocturnal cooling for each cluster's group within each quarter if the local urban radiant heat island (LUHI) showed improved homogeneity, as described by Fahmy and Sharples.[16] In other words, more reductions can be achieved by decreasing *the urban mass time lag* that appeared in the early evening that lasted for about 4 h from 14.20 LST until sunset. From the authors' point of view, street canyon aspect ratios of the best coupled outputs, DS3, should be used more than the used ratio of 1 within clustered groups or more than 0.6 between clustered groups. Another solution is increasing the asphalt albedo (0.2) and reducing the emissivity of both the asphalt (0.9) and the pavement (0.9) to decrease heat gain while minimising the emitted trapped sensible heat.

4 Discussion and conclusions

In this paper, a coupled outdoor–indoor study investigated the effect of adaptive urban form design on thermal comfort and the CO_2 emission of a selected building. Three master plan urban design suggestions were numerically simulated using ENVI-met to generate the modified local climate conditions for each urban design. Eventually, these conditions were applied to an (EPW) weather data file from Cairo International Airport to be used later on a single building to calculate its CO_2 emissions. Statistical weather data file generated from EnergyPlus in conjunction with the (EPW) file were used by DesignBuilder for the second stage. Such a methodology enabled the effects of generated microclimate ambient conditions on a selected building upon the initial inputs of historical or measured data to be studied. Moreover, this approach offers the opportunity to apply climate change scenarios to study its effects on adapting future urban forms as well as on building performance.

The first suggested master plan DS1, using only a clustered form, had the same trend as the base case BC in all of the studied parameters, outdoor and indoor comfort as well as the CO_2 production, but with a downward shift in the PMVo curve over the 12-h modelling period. Both of the second and third suggested master plans, DS2 and DS3, made a delay in total urban heat gain in addition to a delay in evening heat release due to the increased compactness within the cluster groups as well as the increased number of dense trees. Building CO_2 emissions were reduced by between 1.7% and 2.8% for DS2 and DS3 whilst DS1 increased emissions by 0.6%. Moreover, as the third master plan succeeded in coupling reductions for outdoor–indoor comfort levels as well in CO_2 production, an intensive application of the fabric cool surfaces could have extended this success

Finally, an important conclusion from this work is the necessity of integrating many disciplines in such research.[23,34,44–46]. None of the three suggested master plans could have been processed without such integration.

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