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Optimizing the Thermal Performance of Street Canyons in New Cairo, Egypt, Using ENVI-met

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ABSTRACT: This paper optimizes the orientation and aspect ratio (H/W) of street canyons in the hot eastern desert of Egypt to increase daytime thermal comfort level while mitigating nocturnal urban heat island (UHI). The study first examines the thermal performance of a simple north-south/east-west oriented gridiron pattern given H/W proportions from 1 to 5 on the hottest summer day with predicted mean vote (PMV), and sky view factor (SVF) readings using ENVI-met v3.1. Second, it tests the thermal performance of extra seven orientations identifying the best combination of orientations and aspect ratios. The paper finds that north-south oriented streets have to be given a 1:3 proportion, not less, to maintain better pedestrian daytime thermal comfort and, not higher, to permit an acceptable amount of heat release during night time. For east-west oriented streets, because of the limited impact of increasing aspect ratio daytime, a 1:1 proportion is recommended to mitigate nocturnal UHI. The paper also finds that the diagonal urban form with 1:2 and 1:3 aspect ratios given to its NE and NW streets respectively is thermally the best along the day on average. Further, to help designers make climatically responsive geometrical decisions, the paper develops a thermal comfort wheel which collectively shows the thermal performance of different aspect ratios and orientations.

KEYWORDS: Urban design, Street canyon microclimate, Thermal comfort, Urbanheat island, Hot arid climate, ENVI-met.

I. INTRODUCTION

Egypt has recently embarked upon an ambitious sustainable developmental urban plan to redistribute its population outside its congested Nile valley into the unoccupied no-man’s hot deserts which constitute around 94% of Egypt's lands. To be environmentally friendly, the planned urban development requires special urban design criteria that passively secure good ambient conditions in such a harsh climate [1]. Specifically in hot deserts with intense solar radiation, the height and spacing of buildings significantly affect the amount of radiation received and emitted by urban structures [2–4]. Therefore, they have to be shaped in such a way that could enhance their thermal performance [5,6].

In this regard, a considerable literature came up with lessons learned from traditional settlements in subtropical hot deserts that could constitute together a holistic urban form model, albeit not tested, e.g.[7–11]. This urban form is conclusively a compact one with narrow winding streets to secure maximum shade and obstruct hot sand-laden winds. Other literature took field measurements to compare thermal performance of traditional forms with its deep street canyons with modern ones with its shallow ones in favour of the former,e.g.[12–17]. A third set of literature added a social dimension by conducting qualitative research, investigating the extent to which users are thermally satisfied with these different urban forms,e.g.[13,18,19].

Furthermore, making use of the boom in computer simulation programs, plenty of research tested and hence developed numerical climatically-responsive urban forms. These research efforts could be categorised into three groups. The first tested the thermal performance of existing urban forms and therein came up with recommendations to consider in the design of new developments, e.g.[20–27]. The second built virtual urban form models and tested their thermal performance as whole entities, e.g. [28], or the thermal performance of one or more of its components such as street canyons, e.g.[13,29–31], courtyards, e.g. [32,33], and towers, e.g. [29,34]. The third investigated the contribution of the additional layer (to urban geometry) of vegetation and materials to the thermal performance of urban geometries, e.g. [30,35–43].

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Yet, what is lacking in these research efforts is the consideration of mitigating nocturnal Urban Heat Island (UHI) while increasing thermal comfort during daytime. On one hand, most literature focused on achieving thermal comfort during daytime without considering how this could impact nocturnal UHI and hence the night-time thermal comfort. This is seemingly justifiable on their part as some considered observing night-time thermal performance insignificant as “the burden of heat stress is minimal” ([44], p.795) when compared to that of the daytime; and that “the nocturnal heat island is observed in extremely deep canyons” ([12], p.107) only. On the other, some literature,e.g.[45,46],*solely* studied night-time thermal performance relying on Sky View Factor (SVF) readings[1]. Others used readings of long wave radiation released from the urban envelope, e.g. [47]. Relatively limited literature either recommended comparing diurnal and nocturnal situations in-canyon when making geometry choices, e.g.[48], or effectively attempted to consider increasing thermal comfort during day and night [20,29,30,33,49,50], albeit that some cases are mere theoretical studies, e.g. [2].

Increasing thermal comfort during daytime while observing that of night time is challenging as urban design issues required for achieving one do not necessarily fit the other [29,50,51]. To the contrary, some essential urban form design decisions, related to, for example, applying compactness/sprawl, lead to contradicting effects in the way urban form thermally performs day and night.

From among urban form geometrical components, the *street canyon* mainly controls the amount of solar radiation absorbed and reradiated by urban structures. Further, it is directly connected to peoples’ outdoor activities [46], and is a key element in urban design schemes [34,48].

A growing discourse is evident on street canyons’ orientations and aspect ratios, and their impact on the microclimate in subtropical hot desert regions. With a focus on daytime thermal performance, literature reviewed shows that that of a N-S oriented street is much better than that of an E-W oriented street [17], and that the increase in the former’s aspect ratio is more influential [31]. However, different opinions have been expressed regarding the assigned aspect ratios for both streets to improve their daytime thermal performance. N-S oriented streets could be given an aspect ratio of either 2 [13,30] or 3 (Downtown Phoenix Plan, 2008). For E-W oriented street, a recommended aspect ratio of 4 [30] is defied byAli-Toudert and Mayer[48] on the grounds that it is difficult to mitigate the heat stress in an E–W oriented street even so when given this deep canyon. Also, some literature considers the N-S orientation to be better than the NE-SW/NW-SE orientation [16,44,52] while other literature concludes the opposite [13,48]. Apparently, limiting the study of the urban form’s thermal performance to summer only, or extending the study to winter, potentially stands behind this mismatch in opinions. In summer, the N-S orientation appears to perform better. When considering the importance of solar access in winter, diagonal orientations appear to be more preferable than the N-S orientation. According toAli-Toudert and Mayer[48], the issue requires to be thoroughly investigated in further research. Alternatively, this overall difference in opinion in relation to street canyon’s best orientation and aspect ratio could be pertained to the fact that each climatic context (within the broad hot arid region) has its particular characteristics that would have their own unique impact on street canyon’s suggested orientations and aspect ratios [33].

Considering the achievement of thermal comfort during daytime while mitigating night time thermal comfort, Downtown Phoenix Plan[29] concluded that a N-S oriented street should be given an aspect ratio of 3, not less, for better daytime thermal performance. An aspect ratio of 2 is preferable for an E-W oriented street as a deeper canyon with an aspect ratio of 3 does not make a significant difference daytime. This will allow for better thermal performance during night time due to higher SVF. With focus on Egypt, Fahmy and Sharples[26] proposed a hybrid urban form which lies between the Arab vernacular compact form and the western sprawl form. This hybrid urban form should employ a combination of different components, whether geometrical or additional layer-related, for a better compromise (see also: [25]). However, research efforts on Egypt’s desert developments that investigate suitable aspect ratios and orientations which help increase daytime thermal comfort while mitigating nocturnal UHI are lacking. Hence, this research empirically attempts to help fill this gap.

[1]The rate of heat loss is diminished causing an increase in nocturnal UHI when the “sky view” available to urban surfaces is reduced as in deep street canyons [29].

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II. METHODOLOGY

A.Study Area

The study was conducted on the extension of New Cairo city into the hot arid eastern desert in Egypt. New Cairo City is situated east of Greater Cairo Region at 5km distance from Cairo, the Capital. The study area is located in the city's central business district (CBD) (30.025° N; 31.555° E, 355 m a.s.l.) (Fig 1).

Climatological data utilised were obtained for the period (1980-2003) from Cairo Airport Station (WMO 623660) (30.13° N; 31.40° E, 74m a.s.l.), the nearest meteorological station to the study area with maximum dry bulb temperature of 44 °C on July 1st, minimum dry bulb temperature of 2.4 °C on January 22nd, maximum monthly global horizontal radiation on May of 7387 Wh/m^2 decreasing to 6893 Wh/m^2 on July, minimum monthly global horizontal radiation on January of 2976 Wh/m^2, mean annual humidity of 58%, and annual prevailing north winds [53].

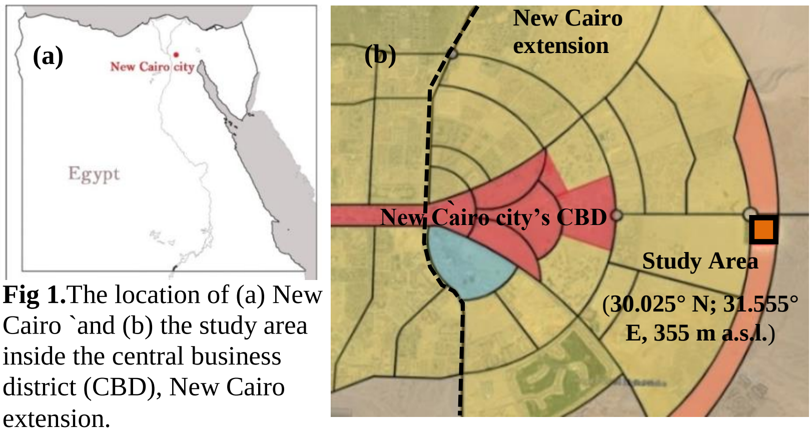

Fig 1. The location of (a) New Cairo `and (b) the study area inside the central business district (CBD), New Cairo extension.

The study area and the Cairo Airport Station are almost flat and open. Although the study area is significantly higher than the airport station, the literature reviewed shows that solar radiation plays the most important role in the determination of thermal comfort outdoors especially in hot arid regions [48,54–56]. The airport data is therefore considered to represent the study area, especially when considering that the study area is only 19 km far from the airport meteorological station; that is, the sun has the same declination angle.

B.Computer Simulations and Parameters

Following multiple literature in the field, this research simulations were conducted using ENVI-met 3.1. ENVI-met 3.1 is a three-dimensional microclimate model designed to simulate the surface, plantation and air interactions in an urban environment and is commonly used in different climatic regions including hot arid ones [31,37,39]. The study utilized the predicted mean vote index (PMV)[2], which was calculated by ENVI-met, to examine the daytime thermal performance, particularly during thermal peak time (PT) from 12 noon to 3pm (similar to, e.g.,[57]). Plenty of research has verified ENVI-met's daytime thermal readings through field measurements[35]. Therefore, the program has been frequently used to determine daytime thermal comfort (see, e.g.,[13,31,32,39]). Yet, the program does not consider heat stored in urban structures in night-time simulation [13,23] and hence cannot be used to depict the nocturnal UHI phenomenon. Nevertheless, ENVi-met calculates SVF readings which this study used to reflect the intensity of atmospheric UHI during night time and hence give an indicator of night-time thermal comfort (as in [29,33,46]).

In this study, to increase the daytime thermal comfort and mitigate nocturnal UHI, an increase in the aspect ratio of a street canyon was progressively applied as long as this increase significantly contributed to the daytime thermal comfort. Once this contribution became insignificant we excluded the excess increase for a higher SVF and hence a lower nocturnal UHI. This significant contribution to daytime thermal comfort is a PMV decrease of equal to or greater than 0.5 [58]. Implicit in this strategy is the fact that, in hot arid regions, priority should be given to daytime thermal performance (in support, see, e.g., [33]).

[2]The predicted mean vote index (PMV) is an index to evaluate the thermal sensation from the energetic balance of the human body with its surroundings [64,65].

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Although PMV values outdoors range between −4 (very cold) and +4 (very hot), extremely high PMV values were recorded in this study as well as others (see, e.g., [59–61]). Yet, "the PMV is a function of the local climate and its values can exceed the interval (−4) - (+4)" ([62], p. 9019). It is indeed extremely difficult to achieve thermal comfort outdoors in hot arid regions [48]. Nevertheless, this study attempted to make an improvement observing the consideration of ameliorating the thermal performance during daytime while mitigating nocturnal UHI.

C.Urban pattern, Ratios and Orientations

Fig 2 shows the simulated gridiron urban pattern, and the location of the two receptors (R1 and R2), elevated 1.6 m above the ground, at which PMV values were calculated for every hour using ENVI-met 3.1. PMV visualisations were obtained using LEONARDO 3.75. SVF readings were also obtained from ENVI-met 3.1 for different aspect ratios from the same two receptors. Fig 2 also illustrates different street canyon aspect ratios and orientations tested on the simulated urban pattern.

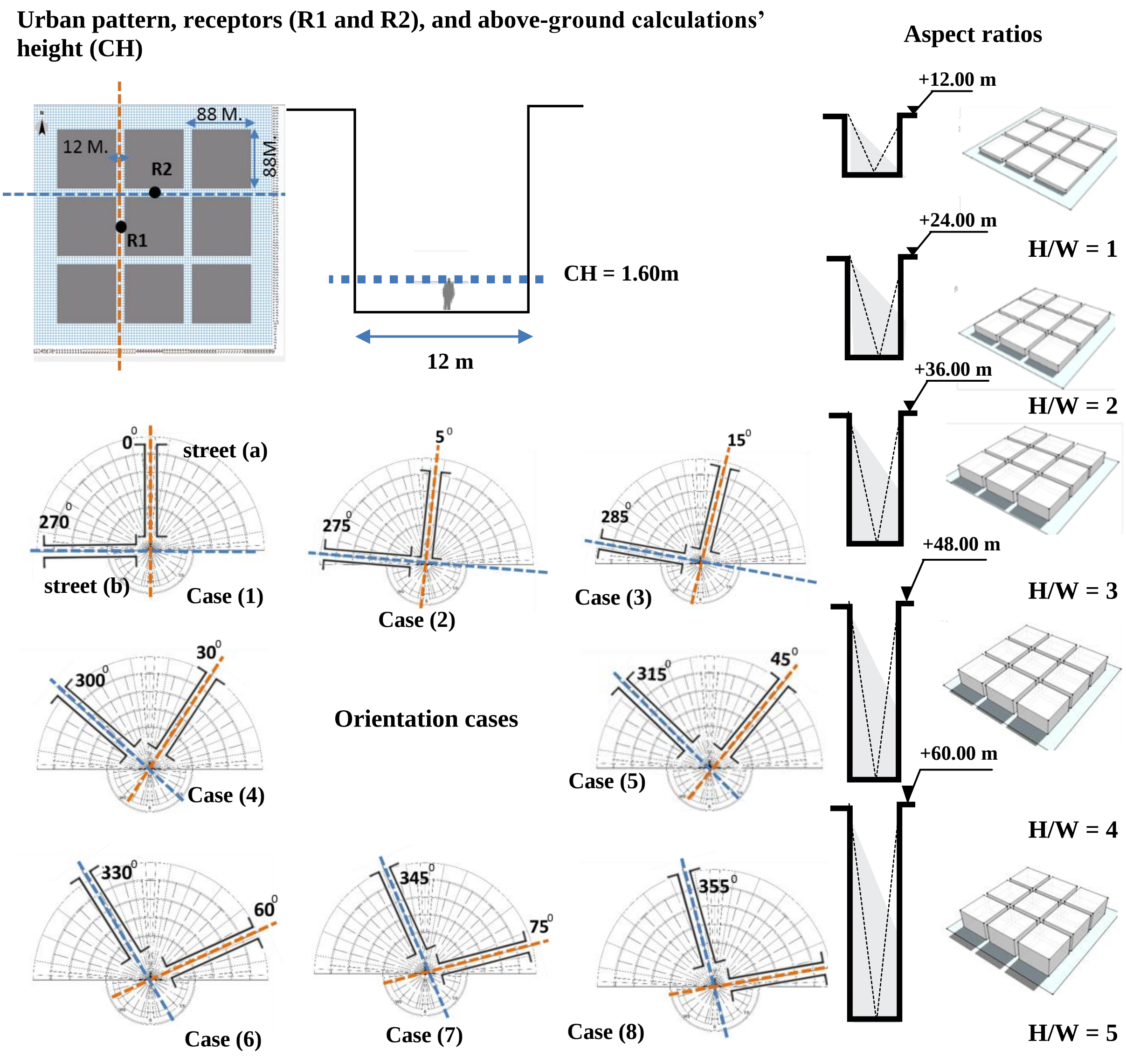

Fig 2. Simulated urban pattern, aspect ratios and orientations. R1 and R2 are the receptors used for microclimate data generation in ENVI-met, and CH is the above-ground calculations' height.

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Numerical calculations were first made for a north-south east-west oriented urban pattern given street canyons' aspect ratios of 1:1, 1:2, 1:3, 1:4 and, then, 1:5. Then, based on the analysis of the generated data (out of which aspect ratios 1:4 and 1:5 were excluded), readings were taken to different orientations of the same urban pattern given different aspect ratios of 1:1, 1:2, and 1:3 only. A clockwise rotating shift every 15° is applied to the urban pattern departing from the north-south/east-west direction. In addition, a 5° rotating shift from the north direction to east and to west directions were also tested following ASHRAE[53] which indicated that these are the best orientations possible for urban masses (based on Meteorological data of Cairo Airport Station). A total of 26 simulations were conducted on a total of 8 different orientations. All urban form scenarios were tested for continuous 19 hours starting at 12:00 am on July 1st and ended at 19:00 pm the same day.

D.Simulation Data

Table 1 illustrates the input data for the 1st of July, the hottest summer day (similar to, e.g.,[24,39]), including urban data, building information (from: [31]), PMV data (from: [63]), climate data, soil data (from: [53]) and model area. The 3D grid resolution used is 4m horizontally, and 1.6 m vertically for the first grid box above ground with telescoping factors starting after an additional 1.6 m for the following boxes upward (table 1). This study used telescoping grid as it tested high objects but with less interest in the processes at the upper parts of the model.

Table 1. General conditions for the simulations

Urban Data		**Building Information**	
The applied site location	(30.0, 31.56) Egypt	Indoor air temp.	20 ˚C
Applied model area	312 x 312 = 97344 m^2 (23.18 F)	Heat Transmission- Walls	1.7 W/m²K
Built up ratio	48%	Heat Transmission -Roofs	2.2 W/m²K
Model cases floor levels	4,8,12,16,20	Albedo- walls	0.3
Building area	88 x 88 =7744 m^2	Albedo- roofs	0.15
Street canyon width	12 m	Building heights	12 ,24 ,36 ,48 ,60 m
Street canyon paving	Concrete		
Model area data		**Climate Data**	
Model area x, y, z	89 x 89 x 25	Simulation day	1st July
Size of grid in meter	$\Delta x=4$, $\Delta y=4$, $\Delta z=25$	Average air temp.	35.09 ˚C
Number of nesting area	5	Air velocity at 10m height	2.8 m/s
Telescoping factor (%)	4% for H/W=1, 10% for H/W=2, 13% for H/W=3, and 16% for H/W=4 and 5	Average Relative Humidity	24.75%
Start telescoping after height	1.6 m	Wind orientation	315˚ NW
PMV (predicted mean vote) **calculation**		**Soil data**	
Walking speed	0.3 m/s	Initial Temperature Upper Layer	30.91 ˚C
Energy-Exchange (Col. 2 M/A)	116 w/m2	Relative Humidity Upper Layer	20%
Heat transfer resistance- cloths	0.50 clo.		

III. RESULTS AND DISCUSSION

This section shows the best H/W ratio of street canyons in a north-south, east-west oriented urban pattern that would optimize thermal performance day and night. Then it shows the most suitable aspect ratios for other different orientations given to this urban pattern, and chooses the best performing urban form among them. Finally, it develops a thermal comfort wheel showing the thermal performances of different aspect ratios and orientations to help designers make the most climatically-responsive geometrical decisions possible.

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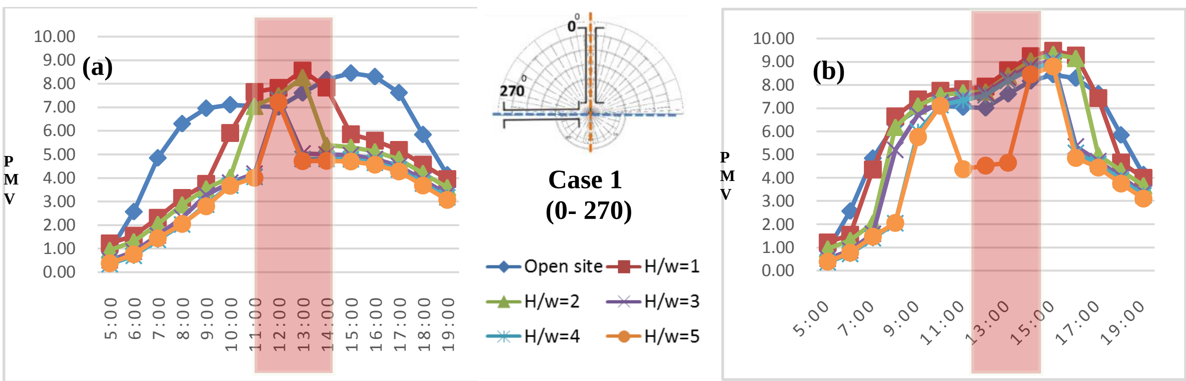
A.Optimizing The Street Canyon's Aspect Ratio in a N-S/E-W Located Model

Fig 3 (a & b) shows the diurnal evolution of the PMV values in urban streets with the different selected ratios for N–S and E–W orientations respectively. The thermal comfort perception in these two orientations is similar at sunrise (5:00 LST) with PMV readings from 0 to 1.5, and at sunset (19:00 LST) with PMV readings from 3 to 4. Also, the thermal comfort level of most of the aspect ratios of urban streets (excluding the 1:5 proportion) is similar at 12:00 noon with PMV readings from 7 to 8. Otherwise, PMV readings tend to get significantly higher in the E-W oriented street canyon than in the N-S oriented one. The highest recorded PMV values in E-W direction range from *8 to around 10* at 15:00 LST, while those in N-S direction are *around 7* for deeper canyons (1:3 to 1:5) at 12:00 noon and are *slightly higher than 8* for shallower canyons at 13:00 LST.



	1	2	3	4	5	H/W	1	2	3	4	5	
NS Street	7.52	6.62	5.59	5.43	5.34	**PT Avg. PMV**	8.82	8.62	8.47	8.35	6.61	EW Street
	0	-0.9	-1.93	-2.09	-2.18	**PT Avg. Diff.**	0	-0.21	-0.36	-0.48	-2.21	

Fig 3. Temporal variation of PMV (predicted mean vote) values at 1.6 m above the ground within: (a) N-S and (b) E-W oriented street canyons in a simple urban form with aspect ratios H/W of 1, 2, 3, 4, and 5. Peak time (PT) is set from 12:00 to 15:00 LST. PT Avg. PMV is the average PMV for peak time. PT Avg. Diff. is the difference between the PT avg. PMV for a street with an aspect ratio and another.

Overall, these readings show that the thermal performance of the N-S oriented street canyon is better than that of the E-W oriented street canyon, receiving less overall heat accumulation in its cavity along the daytime, and recoding therefore better PMV values, regardless of the aspect ratio. Fig 4 best illustrates this. This comes in tune with, for instance, Ali-Toudert[31], Alznafer[13] and Bourbia and Awbi[17]. The PMV evolution of the two streets also assures what was already concluded from previous research (see, e.g., [31,48]) that, in subtropical regions, the impact of increasing the aspect ratio of an E-W orientation is limited, contrary to that of a N-S orientation. Apparently, orientation matters in the attempt to reach the best thermal performance (in tune with, e.g., [44,52]).This finding would influence the aspect ratio choices for both street orientations.

For the N-S orientation, from 9:00 to 15:00 LST in which sun radiation is relatively intense, one can notice the variations in comfort level among 1:1, 1:2 and 1:3 aspect ratios where PMV differences reach as high as more than 3 degrees (Fig 3). For higher aspect ratios (1:4 and 1:5), there are no significant differences between their comfort levels and that of the 1:3 proportion. Specifically during the peak time (PT) from 12:00 to 15:00 LST, the difference in PMV value between the 1:1, and that of 1:2 and 1:3 proportions is significant, recording 0.9 and 1.93 degrees respectively. On the contrary, the difference in PMV value between the 1:1 and 1:4 proportions increases only to 2.09 degree. Therefore, one can conclude that the best choice to achieve relatively good comfort level during daytime while elevating the chance to secure relatively better ambient conditions during night time is the 1:3 aspect ratio.

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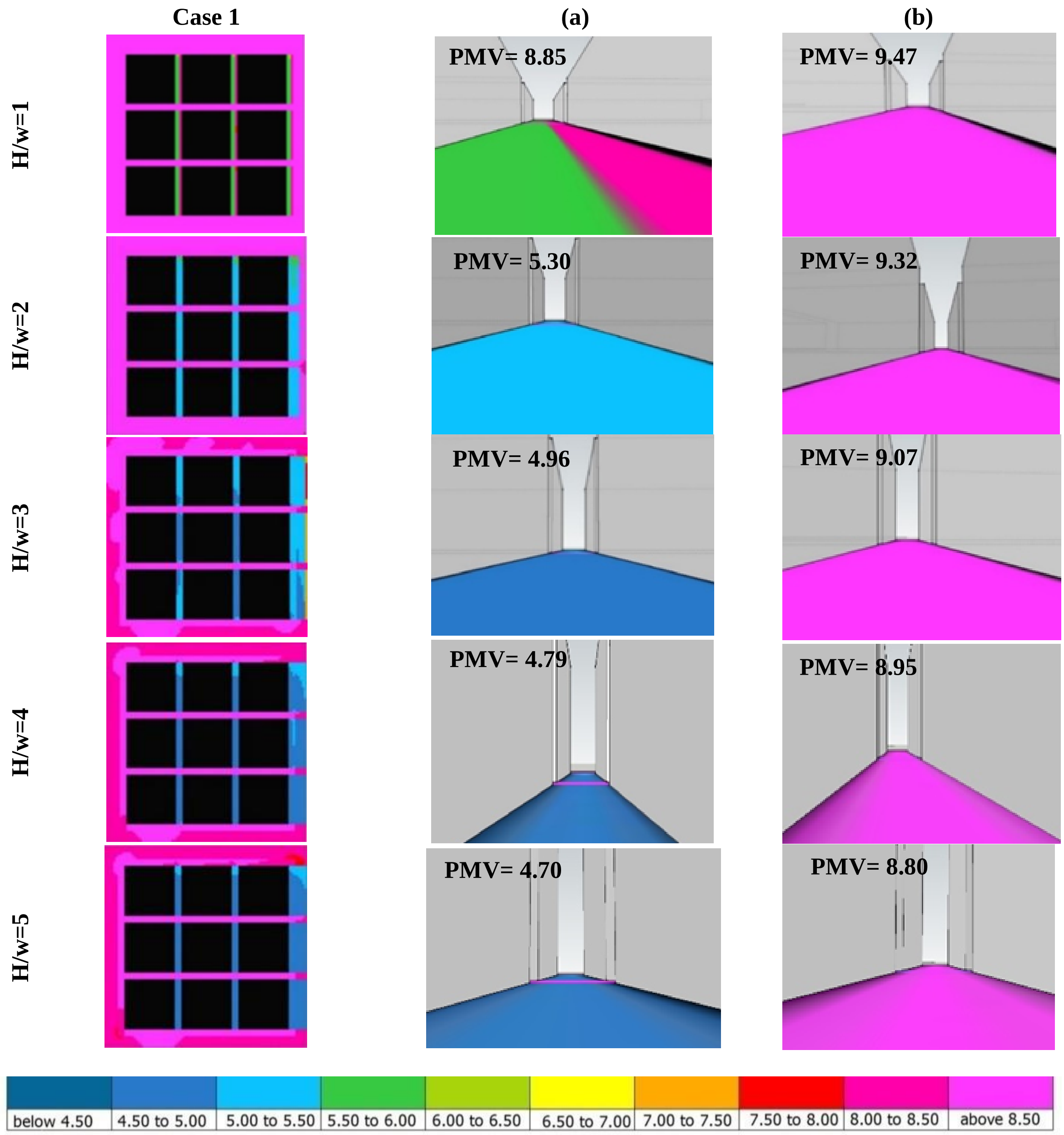

Fig 4.3D illustration of PMV values at 1.6 m above the ground at 15:00 LST within: (a) N-S and (b) E-W oriented street canyons with aspect ratios H/W of 1, 2, 3, 4 and 5 (color should be used in print).

For the E-W orientation, during the same time span (from 9:00 to 15:00 LST), it is noticeable that moderate variations exist among the comfort levels of different aspect ratios where PMV differences reach a maximum value of 0.5 only (with the exception of the 1:5 aspect ratio in which PMV decreases significantly but only for two hours). With these generally modest PMV differences, giving a 1:1 aspect ratio (with SVF of 0.51) to its E-W oriented street canyons seems reasonable for better night-time thermal comfort. This is especially needed to increase the SVF in this N-S/E-W oriented urban form which has been preferably recommended a deep 1:3 aspect ratio for its N-S oriented street canyons (with SVF of only 0.22). Add to this the fact that, in hot-arid subtropical regions, *deep* street canyons with N-S orientation still permit preferable solar access in winter while those with E-W orientation do not [31,48]. So, in this regard, while it is possible to go for deeper aspect ratios in N-S orientation, doing the same with E-W orientation means blocking solar access. No wonder, then, to exclude the 1:5 proportion despite that its PMV value significantly differs

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from that of the 1:1 proportion at peak time (with 2.21 difference). This tendency to include shallow streets for better winter solar access comes opposite to what Ratti et al.[33] recommends but partially in harmony with what Johansson[30] concludes.

In brief, the daytime thermal performance of the N-S oriented street canyon is better than that of the E-W oriented street canyon regardless of their aspect ratios. In hot arid subtropical regions, the impact of increasing the aspect ratio of an E-W orientation is limited, contrary to that of a N-S orientation. Hence, in a north-south/east-west oriented urban form, which is located in New Cairo city extension into the Egyptian eastern desert, the most preferable aspect ratio of a N-S orientation is 1:3, and that of an E-W orientation is 1:1 in order to increase comfort level during daytime while mitigating nocturnal UHI, and additionally better allow solar access in winter. Indeed, orientation matters.

B.Optimizing the Street Canyon's Orientation and Aspect Ratio

This section examines the thermal performance of the same urban pattern but with street network orientations other than the N-S/E-W orientation. It also identifies for each orientation case the most suitable two aspect ratios (of its two perpendicular streets) which increase the thermal comfort daytime and mitigate the nocturnal UHI. Then, it puts these optimized urban forms in order in terms of its achieved comfort level.

Fig 5 shows the diurnal evolution of the PMV values in urban streets with aspect ratios of 1, 2 and 3 and with orientations as detailed in this research methodology. Generally, as street (a) starts to rotate from N-S orientation towards E-W one, PMV readings unsurprisingly increase and the differences in PMV among different aspect ratios decrease. The opposite takes place but in different course as street (b) starts to rotate from E-W orientation towards N-S one.

In identifying the most suitable aspect ratios for each orientation case, this section follows the same logic followed in the previous section. That is, evaluating the comfort performance of each aspect ratio and, then, excluding the deeper one(s) which does not have a *significant* difference in PMV value from that of the shallower one. The aim of this exclusion is to secure the highest possible SVF for better night-time thermal comfort (which is, in this case, accompanied by minimum loss in comfort daytime). The *significant* difference in PMV values has been identified in this research to be equal to or greater than 0.5 (as stated in section 2.2).

Table 2 (illustrated in Fig 6) presents the average PMV values during the peak time (from 12:00 to 15:00LST) inside each of the two perpendicular street canyons (streets a & b) of the tested urban pattern, given different aspect ratios (from 1 to 3) and orientations. Based on the comparison of PMV net differences among different aspect ratios for each orientation case, each case is allocated the best possible aspect ratios for its two perpendicular streets that increase daytime comfort while mitigating nocturnal UHI. For example, for orientation case (5), street (a) records peak time average PMV readings of 8, 6.64 and 6.25 for aspect ratios of 1, 2 and 3 respectively. When considering a significant difference of 1.36 in PMV readings between aspect ratios 1 and 2, but of only 0.39 between aspect ratios 2 and 3, then the recommended aspect ratio to apply to this street is 2. This preferred ratio increases the SVF (reaching 0.35) for significantly better thermal comfort during night time accompanied by insignificant loss of thermal comfort daytime. For street (b) of the same orientation case, a significant difference of 1.41 between aspect ratios 1 and 2, and another of 0.71 between aspect ratios 2 and 3 lead to the adoption of an aspect ratio of 3. This recommended aspect ratio secures significantly better thermal comfort during daytime which is considered more important to achieve than that of the night time in hot arid environments. Aspect ratios 2 and 3 for streets (a) and (b) of the urban form orientation case (5) represent together the best combination that would increase daytime thermal comfort while mitigating nocturnal UHI for this orientation.

After identifying the most suitable proportions for each urban pattern orientation case, the resulting urban form cases are, then, put in order in terms of their ability to increase daytime thermal comfort while mitigating nocturnal UHI. This was accomplished, first, by calculating the peak time average PMV and the average SVF of each urban form orientation case, i.e. the average PMV and the average SVF of its two perpendicular street canyons (as shown in table 2). For example, urban form orientation case (5) has a *collective* average of 6.11 and 0.29 for its PMV and SVF values respectively. Second, a comparison is conducted among these calculated average PMV and SVF values of different urban form cases observing the priority given to achieving significant increase in daytime thermal comfort. The priority

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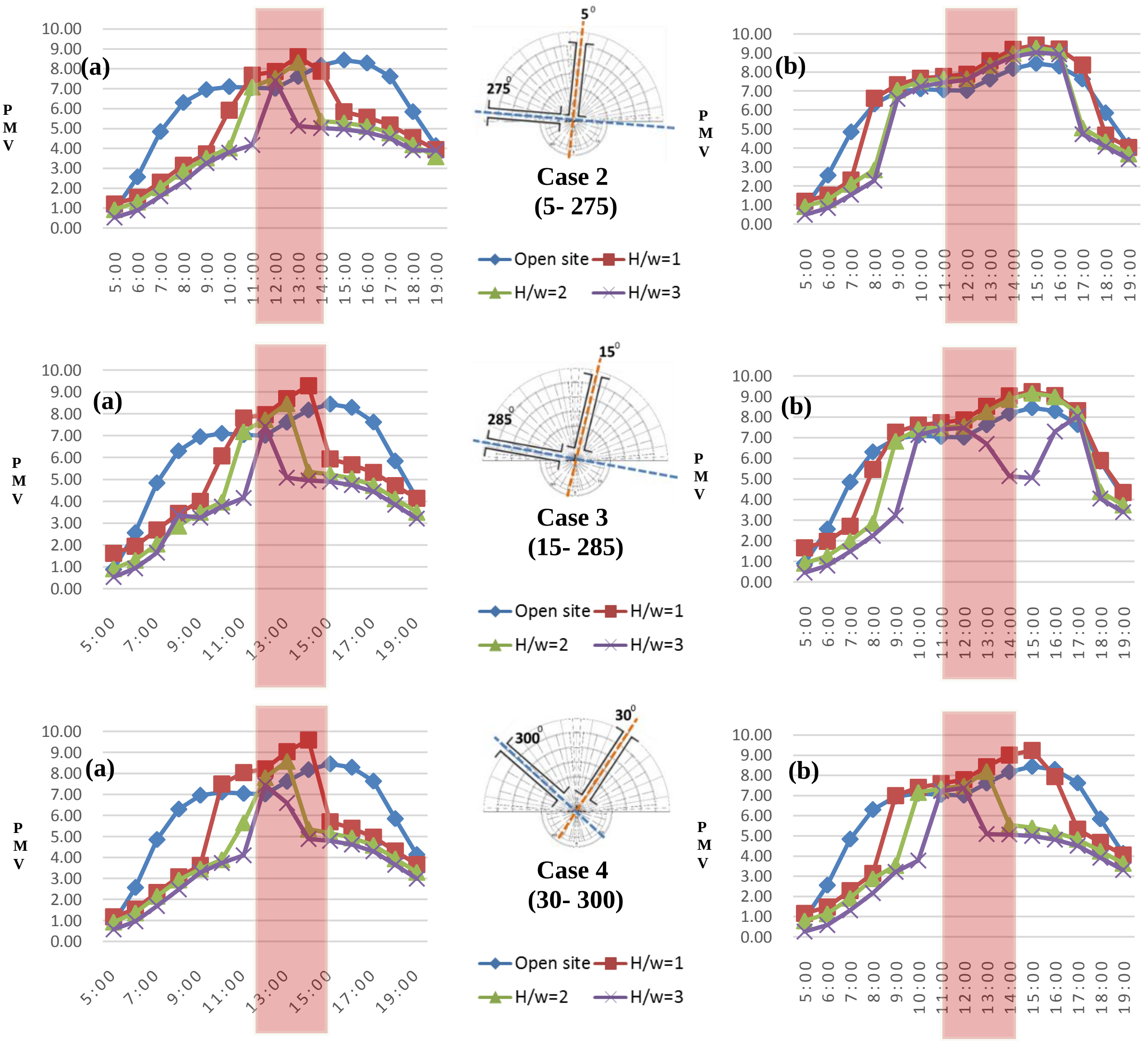
was given to night-time thermal comfort when an insignificant increase in daytime thermal comfort is recorded. Based on this comparison among the average PMV and SVF values of different urban form cases, these cases were sorted in a descending order from the best performing case to the worst.

On top of the list comes case (5), which is the urban form with NE-SW/NW-SE orientation and with 1:2 and 1:3 aspect ratios given to its two streets (a) and (b) respectively (Fig 7). This finding, specifically in relation to orientation, matches with those of previous research (see, e.g., [48]). Case (5) has been preferred over case (6), which comes next in order, as the difference between them in average PMV values is not significant, to the advantage of the latter, while case (5) enjoys a relatively better SVF. Yet, still, the overall advantage of case (5) over case (6) is negligible if compared to that of, for example, case (6) over case (7), or case (7) over case (4). Further, case (1) with the N-S/E-W orientation and cases (8) and (2) (with the 5^{o} rotating shift from the north direction), which are almost similar in performance, rank really low down the list. This interestingly comes at odds with what was indicated by ASHRAE[53] to be the best orientations for the study area.

In brief, the best urban form which increases daytime thermal comfort while mitigating nocturnal UHI is the one with a NE-SW and NW-SE orientations given to its two perpendicular streets with 1:2 and 1:3 aspect ratios respectively.



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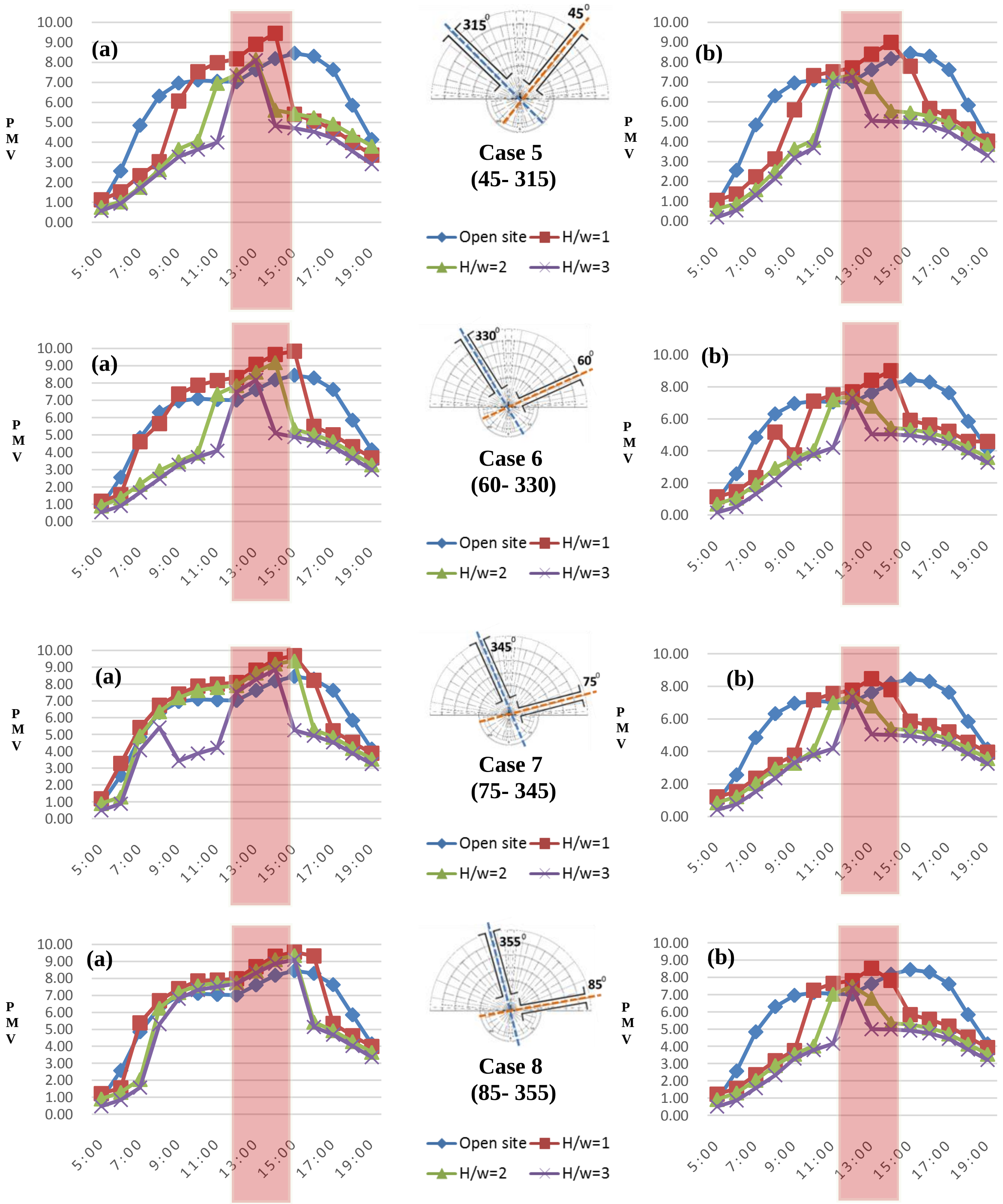

Fig 5. Temporal variation of PMV (predicted mean vote) values at 1.6 m above the ground within street canyons (a and b) in a simple urban form of 7 different orientations and with aspect ratios H/W of 1, 2, and 3. Peak time (PT) is set from 12:00 to 15:00 LST.

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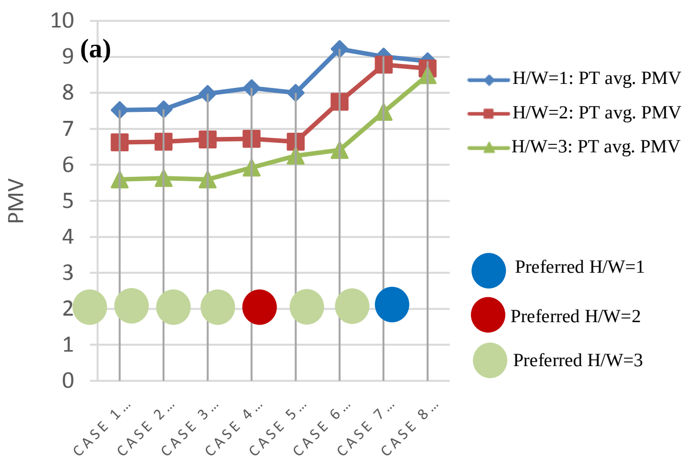
Table 2. Recommended aspect ratios and ranks given to different orientations of a simple urban pattern. PMV stands for predicted mean vote, and SVF for sky view factor. PT Avg. PMV is the average PMV for peak time (PT). PT is set from 12:00 to 15:00 LST. Diff. bet. H/W=1&2 or 2&3 stands for the difference between the PT avg. PMV for a street with an aspect ratio and another.

Urban form orientation cases	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Street (a)	**0_360**	**5**	**15**	**30**	**45**	**60**	**75**	**85**
H/W=1: PT avg. PMV	7.52	7.54	7.97	8.13	8	9.22	9.01	8.88
H/W=2: PT avg. PMV	6.62	6.64	6.7	6.72	6.64	7.75	8.78	8.67
H/W=3: PT avg. PMV	5.59	5.63	5.59	5.92	6.25	6.41	7.47	8.49
Diff. bet. H/W=1&2	**0.9**	**0.9**	**1.27**	**1.41**	**1.36**	**1.47**	**0.23**	**0.21**
Diff. bet. H/W=2&3	**1.03**	**1.01**	**1.11**	**0.8**	**0.39**	**1.34**	**1.31**	**0.18**
Recommended Aspect Ratio	**1_3**	**1_3**	**1_3**	**1_3**	**1_2**	**1_3**	**1_3**	**1_1**
SVF	0.22	0.22	0.22	0.22	0.35	0.22	0.22	0.51
Street (b)	**270**	**275**	**285**	**300**	**315**	**330**	**345**	**355**
H/W=1: PT avg. PMV	8.82	8.77	8.65	8.61	8.22	7.67	7.47	7.49
H/W=2: PT avg. PMV	8.62	8.56	8.46	6.65	6.28	6.26	6.24	6.22
H/W=3: PT avg. PMV	8.46	8.43	6.09	5.64	5.57	5.58	5.6	5.57
Diff. bet. H/W=1&2	**0.2**	**0.21**	**0.19**	**1.96**	**1.94**	**1.41**	**1.23**	**1.27**
Diff. bet. H/W=2&3	**0.16**	**0.13**	**2.37**	**1.01**	**0.71**	**0.68**	**0.64**	**0.65**
Recommended Aspect Ratio	**1_1**	**1_1**	**1_3**	**1_3**	**1_3**	**1_3**	**1_3**	**1_3**
SVF	0.51	0.51	0.22	0.22	0.22	0.22	0.22	0.22
Average PMV for each case	**7.21**	**7.2**	**5.84**	**5.78**	**6.11**	**6.00**	**6.54**	**7.23**
Average SVF for each case	**0.37**	**0.37**	**0.22**	**0.22**	**0.29**	**0.22**	**0.22**	**0.37**
Order	**6**	**6**	**3**	**2**	**1**	**4**	**5**	**6**



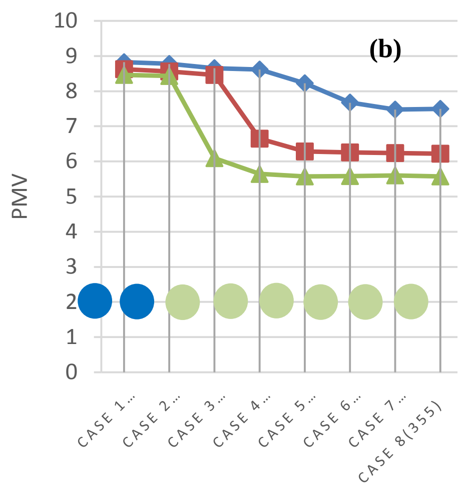


Fig 6. The comparison of average PMV (predicted mean vote) readings at peak time (PT) of aspect ratios 1, 2 and 3 given to streets (a) and (b) for each orientation, and the identification of the preferred aspect ratio of each street in each orientation case. PT Avg. PMV is the average PMV for peak time. Peak time (PT) is set from 12:00 to 15:00 LST (color should be used in print).

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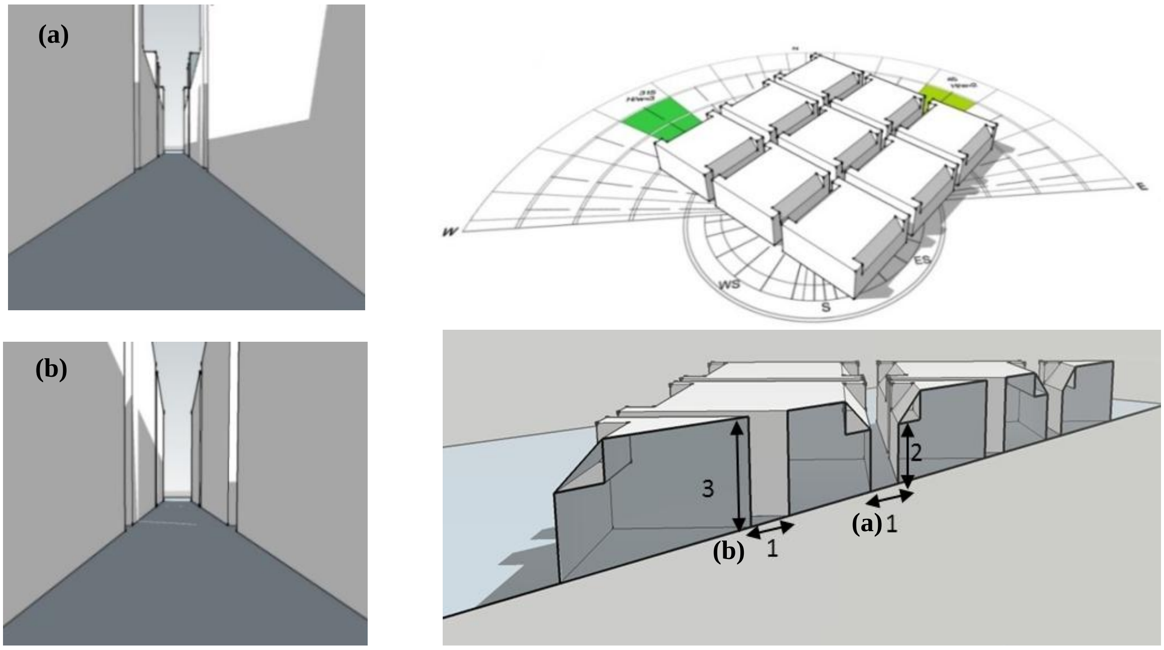

Fig 7. The best performing combination between orientations and aspect ratios given to a simple gridiron urban form: a diagonal one with aspect ratios of 1:2 and 1:3 given to its two perpendicular streets (a) and (b) respectively.

C.The Thermal Comfort Wheel

In reality, urban practices are the outcome of a complex societal process, one aspect of which is the way through which climate is allowed to influence urban geometry. A complex web of interactions/processes (be it political, economic, social, cultural, environmental and technical) function simultaneously, and are collectively responsible for shaping the built environment. It is illogical, therefore, to assume that one of these active processes, that is, the climatic consideration in our case, would solely influence the built environment, nor is it possible to expect that it would be able to *totally* achieve its goals in the presence of other active processes/forces.

Hence, this section lays down to urban designers, working on the extension of New Cairo city into the Egyptian eastern desert, a plain chart of thermal performances of street canyons orientations and ratios to use in their designs for the best possible thermal performance. Fig 8 shows the thermal comfort wheel developed for this purpose. The first three concentric strips from the inside out represent the comfort level, indicated by averaged peak time PMV values, of different aspect ratios (H/W=1, 2 and 3) given to street canyons when directed to different orientations represented by radial slices. The fourth outer strip recommends the best street ratio for each orientation with the consideration of not only daytime comfort level but also the night-time one by discarding the deep canyon that has no significant difference from the shallower one.

Observing the wheel, one can easily notice that the best orientation of a 1:3 street canyon proportion is in the range of 300° northwest to 30° northeast with a range of 5.57 to 5.64 PMV values; the best orientation of a 1:2 street canyon proportion is from 315° to 355° northwest with a PMV range of 6.22 to 6.28; and the best orientation of a 1:1 street canyon proportion is from 345° to 355° northwest, indicating a wider range of orientation to deeper canyons, centred around 345° northwest. It is also noticeable that the thermal performances for all street profiles get worse as their orientation gets close from the E-W direction.

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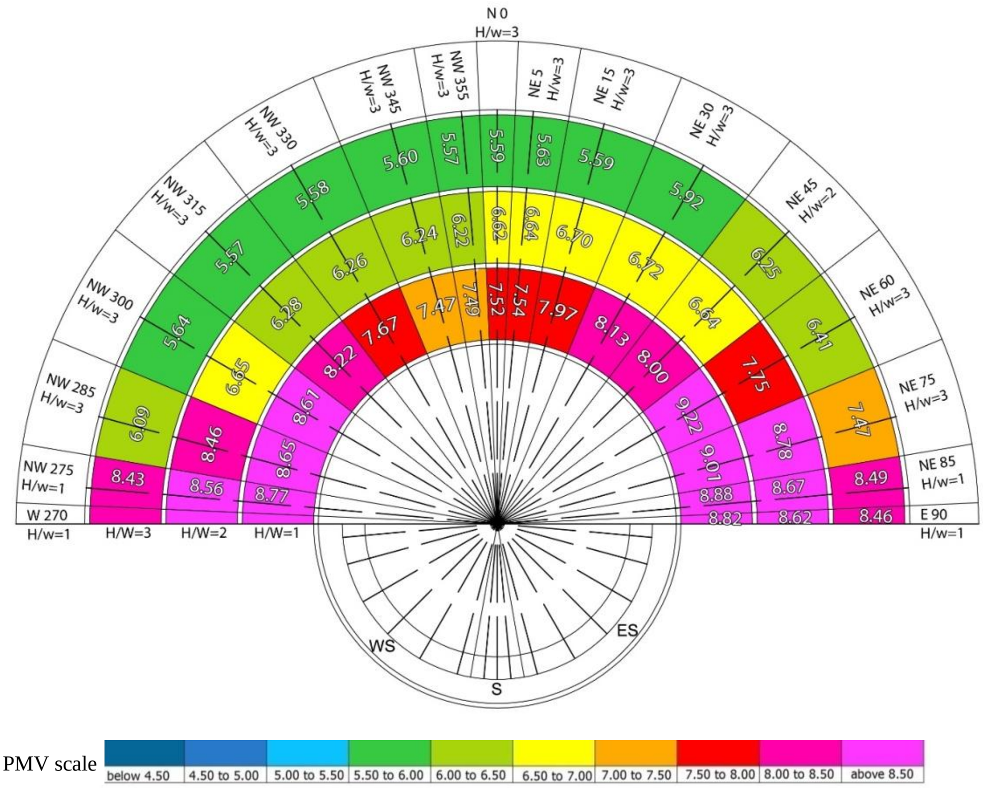

Fig 8. The thermal comfort wheel. The colored three concentric strips represent the comfort level, indicated by averaged peak time PMV values(color should be used in print).

IV. CONCLUSIONS

Attempting to optimize the orientation and aspect ratio of street canyons to increase daytime thermal comfort while mitigating nocturnal UHI, this paper studied the thermal comfort level on the hottest summer day of the street network in a simple urban pattern when given different orientations and aspect ratios, using ENVI-met v3.1 and utilising PMV and SVF readings. It eventually identified the best orientation and aspect ratio of this urban pattern which is located in New Cairo extension into the hot arid eastern desert in Egypt, and developed a thermal comfort wheel to help urban designers make the best possible thermal comfort combination of orientations and aspect ratios in their designs.

The first conclusion of this paper assures that, in hot arid regions, the daytime thermal performance of the N-S oriented street canyon is better than that of the E-W oriented street canyon regardless of their aspect ratios. In tune, the impact of increasing the aspect ratio of an E-W orientation is limited, contrary to that of a N-S orientation. Hence, orientation has a significant role to play in the thermal performance of street canyons in hot arid region. **Second**, for this research's study area, a canyon with a north-south orientation has to be given a 1:3 proportion, not less, in order to maintain a relatively better pedestrian thermal comfort daytime, and not higher to permit an acceptable amount of heat release during evening hours, mitigating therefore the nocturnal UHI phenomenon. For street canyons along the west-east axis, there is no significant difference in daytime thermal performance among different proportions, except the 1:5 proportion. A street canyon proportion of 1:1 is recommended to better mitigate nocturnal UHI, and allow solar access in winter. **Third**, the best urban form which increases daytime thermal comfort while mitigating nocturnal UHI is the one with a NE-SW and NW-SE orientations given to its two perpendicular streets with 1:2 and 1:3 aspect ratios respectively. **Fourth**, the more the street canyon gets deep the more it has a wider range of preferable orientation which is almost centred around 345^{o} northwest in this study area, maintaining relatively better good ambient conditions daytime. The more one departs from this direction towards E-W direction the more the thermal situation gets worse, which takes us back to the first conclusion.

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There are some limitations on these findings. **First**, and as stated in section 2.2, ENVI-met v3.1 does not consider the heat stored in urban masses during the day and which is reradiated during night time. Therefore, it was not possible to rely on the model in properly predicting the night-time thermal performance of different street aspect ratios and orientations. We could not use the model in weighing the losses/gains made during night time against those made during daytime to convincingly decide what would be the best balancing ratio and orientation to apply. Due to this shortage, a significant difference in PMV values was identified in this research on the basis of which aspect ratio and orientation choices were made. Despite that this has its own logic, it is still definitely hypothetical and requires further research. It is worth mentioning that we attempted to quantify UHI variation against SVF variation. Similar to [46], we set out to average field measurements taken during night time in similar/close hot desert environments, e.g. [12,15,31,49]. These measurements were to be then correlated with SVF readings to reach better quantitative understanding of nocturnal UHI variations. But, the outcome was not consistent enough to capitalise on in verifying/enhancing the findings of this research. **Second**, while the investigated site area lies on a higher sea level than that of the meteorological station from which data were obtained, sea level is not among the data entered to the ENVI-met v3.1 model. This difference in height would have had an impact, though insignificant, on the findings if considered. **Third,** the tested urban pattern was placed inside the simulated model with no adjacent urban or natural compositions that would mimic reality and help produce more accurate calculations. Also, the additional layer to urban geometry, including trees, plantation, water features and green roofs and walls, was not part of the examination neither the other seasons of the year, urging for further research.

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Conflict of Interest: The authors declare that they have no conflict of interest.

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APPENDIX: ACRONYMS INDEX

a.s.l.	Above sea level	**PT**	Peak Time
E	East	**R1&2**	Climatological data receptors
H/W	Height/Width	**S**	South
LST	Local standard time	**SE**	Southeast
N	North	**SVF**	Sky View Factor
NE	Northeast	**SW**	Southwest
NW	Northwest	**UHI**	Urban Heat Island
PMV	Predicted Mean Vote	**W**	West