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The Impact of Applying Floor Area Ratio (FAR) and Building's Height Diversity on Urban Air Temperature

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Abstract: Building height and Floor Area Ratio (FAR) are recognized as crucial design elements in urban environments, prior research has examined the effects of Floor Area Ratio (FAR) on thermal performance, explores the relationship between FAR and building coverage ratio (BCR). The combined influence of FAR and building height remains understudied. Recent policy changes in Egypt have increased the permissible FAR, potentially leading to a rise in buildings heights. These changes have prompted concerns regarding the combined effect of FAR and building height on thermal environment. However, a comprehensive understanding of this intricate relationship within urban blocks remains elusive. This study addresses this knowledge gap by investigating the impact of varying building heights on air temperature, with a focus on pedestrian thermal comfort in hot, arid climates. Employing computational simulations using ENVI-met software, the research evaluates different urban design scenarios. A base case urban block is established based on Egyptian regulations, followed by twelve additional scenarios with identical FAR and Building Coverage Ratio (BCR) but varying building heights (8-72 meters). Simulations compare potential air temperature for each scenario to the base case. Results reveal a significant influence of building height variation on air temperature. Notably, one scenario achieved a 1.5°C reduction during peak hours compared to the base case, suggesting potential for mitigating thermal discomfort. This study demonstrates that incorporating building height diversity within urban design strategies can be a valuable tool for managing air temperature and enhancing pedestrian thermal comfort in hot, arid regions.

Keywords: Floor area ratio (FAR), height diversity, air temperature, thermal comfort.

1. Introduction and literature Review

Building height, along with building setbacks, significantly influences urban form and consequently, outdoor thermal performance [1] .Previous studies have emphasized the role of building height and aspect ratio (H/W) in shaping thermal environments, with Salameh et al. [2] highlighting the impact of building height on outdoor air temperature and Urban Heat Island (UHI) intensity. Abd Elraouf et al. [3] further underscored the importance of street orientation, aspect ratio, and building typology in optimizing thermal comfort within hot-humid climates. Abdollahzadeh et al. [4] and Taleghani et al. [5] also contributed to this body of knowledge by emphasizing the influence of these urban form parameters on outdoor thermal conditions. Building codes serve as a crucial tool for regulating building heights and guiding urban development. European countries often employ direct regulations through form-based standards. These standards consider building setbacks and their relationship to street width, directly influencing building heights [6].USA and Japan, in contrast, building heights in the USA and Japan are indirectly controlled through Floor Area Ratio (FAR). FAR is a function of a building's coverage area (Building Coverage Ratio - BCR) and the number of stories, allowing flexibility in building design [7]. In Egypt, the New Urban Communities Authority has adopted the use of FAR [8] for developing communities and projects. FAR is calculated as the Gross Floor Area divided by the Plot Area. For instance, a 20-story building occupying the entire plot would have a FAR of 20, as would a 40-story building occupying half the plot. This approach provides flexibility in building heights. Extensive research has investigated the impact of FAR regulations on various urban environmental aspects. These studies have explored the influence of FAR on factors such as: Energy consumption [9], Particulate matter and air temperature [10] , Wind velocity [11], Indoor thermal comfort [12]. Existing research on the correlation between Floor Area Ratio (FAR) and thermal comfort can be categorized into three primary approaches. The first group of studies investigates the impact of varying FAR configurations on thermal comfort. The second group explores the relationship between FAR and either building height or building coverage ratio while maintaining the other constant. A significant research gap persists in understanding the combined influence of FAR and building height variability on thermal environments. Table 1 shows FAR studies.

Table 1 FAR and thermal environment studies, (source: Author).

Ref.	City	Study parameter	Main Findings
[13]	Bandung, China	BCR, FAR, Ta, Ws, Tmrt, solar radiation Comparing an existing block typology scenario with five new block typology scenarios in an area of 350*350*150meters.	The relative humidity rises dramatically as the FAR is raised while the air temperature and solar radiation decrease. The relative humidity and wind speed will decrease as the BCR rises.
[2]	Ajman, UAE	Building height (unified & diversified), UHI, SVF	Building height is a key factor in determining outdoor air temperature, UHI phenomena. Place the highest masses in the direction of the hot prevailing wind in various building heights.
[11]	China	FAR (increased from 0.63 to 2.32), Ws	FAR is negatively correlated with wind speed ratio (WSR), affecting outdoor comfort.
[14]	Kathmandu, Nepal	FAR (various FAR 1.75,2.5 and 3.5), energy load. (Different height for different FAR and ground coverage are kept constant)	clear correlation between FAR, energy production, and consumption.
[12]	Singapore	building height, density, and FAR, Density variables with same height. Height variables with same density. FAR fixed with variable height and density.	The indoor temperature was most impacted by building density. The most complicated effect of FAR is on the temperature of indoor air.
[15]	Tehran	FAR, BCR, SVF, Fixed FAR (variable BCR and height).	SVF decreases as the BSC rises at a constant FAR.

1.1 Problem Statement

Applying Floor Area Ratio (FAR) concept by enabling increased building heights, has encountered significant public resistance due to concerns over potential negative impacts on urban environments. While the New Urban Communities Authority has recently adopted legislation promoting FAR utilization, public apprehension persists regarding its implications for human comfort in urban spaces. **Therefore**, enough investigations should be applied on the effect of applying FAR and building height diversity on urban outdoor space thermal comfort.

1.2 Research Aim

Limited research has explored the influence of FAR on urban thermal environment. Therefore, this study aims to address this gap in knowledge by investigating the relationship between FAR and building height diversity impact on urban air temperature.

1.3 Research Method

Outdoor air temperature can be affected harshly by its surrounding urban configuration. One important factor of these urban configurations is the diversity of buildings height. To investigate the effect of building height diversity on outdoor air temperature, a mixed-research method will be employed. In this paper, **the first part** will explore the present Egyptian Urban Design Regulations using inductive approach. Where the relation between Floor Area Ratio (FAR), building height diversity, and their potential impact on outdoor thermal comfort will be investigated. **The second part** will use the analytical approach to design several hypothetical urban configurations and buildings heights diversity scenarios to be investigated for later evaluation by simulation. **Finally,** a controlled simulation approach will be utilized using simulation tool “ENVI-met” software for the best urban configuration regarding outdoor air temperature and space thermal comfort.

2. Materials and simulation

2.1 The Base Case Configuration

Numerical study is adopted to simulate the conditions of a typical residential block, which is set to be a typical precinct size of 220*220 m, street width is 15m, building area will be 225 m^2, each building dimension in base case configuration will be (15*15*20 m) [13].

(according to Egyptian building code residential block length don't exceed to 250m, street width not less than to 10m, plot length not less than 10m).

Table 2: Base case configuration (source: Author).

FAR	BCR (Building Coverage Ratio)	No. of buildings in each row	Building height	H/w Ratio	Number of floors	Gross area of All floors	Ground floor area of each building.
180%	15*15*8*8*100/220*220=**30%**	**8**	**20**	**1.3**	**5**	**1125** m^2	**225** m^2

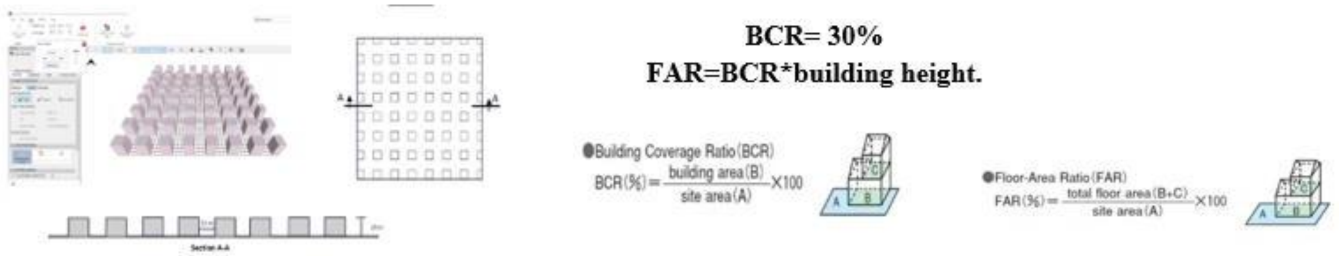


Figure 1: base case configuration and FAR and BCR (source: Author).

To investigate the impact of building height diversity on thermal comfort, the study proposes twelve scenarios categorized into four distinct groups based on building height variations, its percentage and aspect ratio within each group. This categorization allows for a focused analysis of different height diversity patterns. Buildings height in the block classified into low rise (up to 12m), midrise (up to 32m), Highrise buildings (up to 72 m). Each group will comprise several scenarios with varying building heights. The simulations for these scenarios will be compared among themselves relative to the base case scenario. This approach allows us to identify how specific building height configurations within each group influence air temperature compared to the uniform building heights of the base case. The research will explore height diversity through four separate groups:

1- Stratified configuration.
2- Stratified configuration started from inner loop (**case 6**) or outer loop (**case 5).**
3- Random configuration of height variation (**case 7**).
4- High rise building configuration of height variation (case 9 -10-11-12)

2.2 Simulation Software.

To comprehensively assess the microclimatic conditions and thermal comfort within an urban environment, this study employed a coupled modeling approach utilizing ENVI-met and RayMan software. ENVI-met V4.0, a well-established simulation tool for the urban built environment, replicates the climate of a specific metropolitan region, considering the intricate physical interactions between soil, vegetation, buildings, and the atmosphere, thereby enabling a detailed analysis of microclimatic variations. RayMan V3.1 serves as a complementary tool, capable of computing a wide range of thermal indices relevant to human comfort, including physiologically equivalent temperature (PET) and predicted mean vote (PMV). Like ENVI-met, RayMan has found application in numerous studies [14], [15], [16].

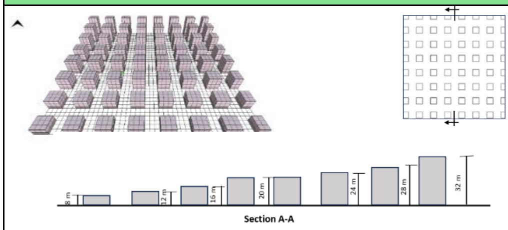
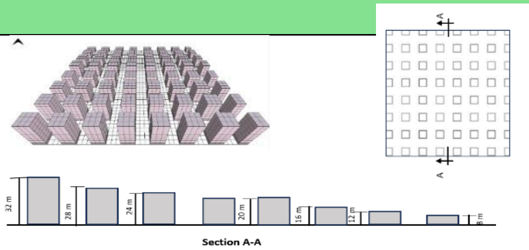
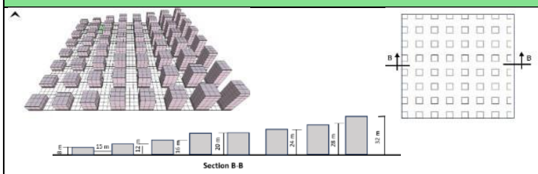
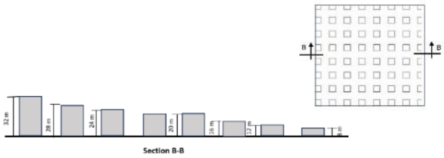
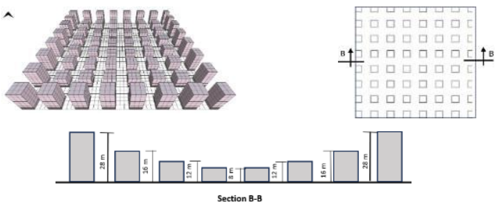
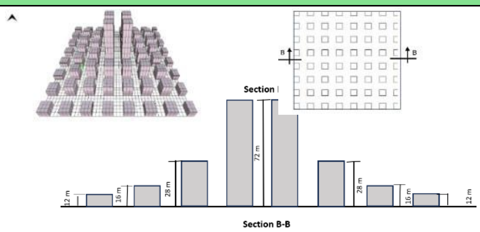
2.3 Simulation Settings

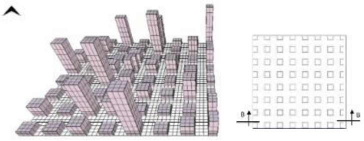
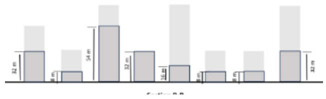
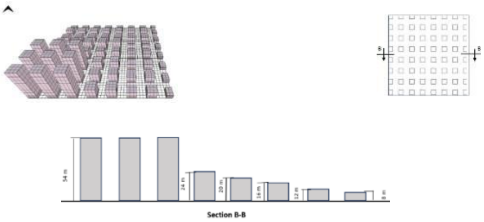
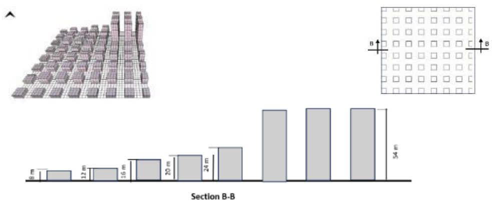
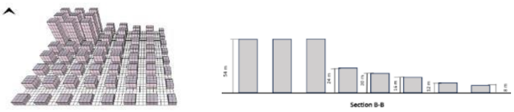
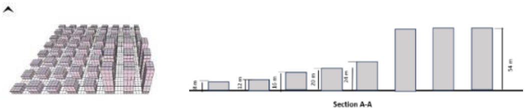
To evaluate the impact of building height diversity on thermal performance across various urban design scenarios, 14-hour simulations were conducted. The chosen period, May 29th from 5:00 to 19:00, represents a typical summer day. ECOTECT5.6 software was used to analyze an extreme summer day with high radiant interaction values. While this selection provides insights into heat extremes, the specific date (May 29th) holds less significance for this comparative study between base and alternative design cases. Pedestrian comfort was the primary focus; therefore, results were collected at 1.6 meters above the model area, corresponding to a typical pedestrian eye level. The climatic data used for these simulations is presented in **Table 4**. This study utilized two primary subprograms within ENVI-met for thermal comfort evaluation:

- **SPACE:** This subprogram serves as the model creation tool. A separate model was created for each scenario being investigated.
- **Envi-guide:** Within Envi-guide, the simulation settings were defined, including Simulation starts time and duration, Initial meteorological conditions, Air temperature, Relative humidity (extracted from the Cairo EPw file)

Following model creation and parameter definition, the simulation was executed using the core ENVI-met software (version 44×44×40, indicating the model resolution). Finally, the output data from the "**LONARDO**" subprogram was used as input for RayMan software to calculate PET, a thermal comfort index.

Table 3: Scenorios configuration (source: Author).

First group (Stratified configuration of height variation with different orientation**)** **(with H/W ratio (2.1-1.8-1.6-1.3-1-0.8-0.5)).** **25% Low rise buildings - 75% midrise buildings**	
Case 1 north	**Case 2** south
	
Case 1 height variation oriented to north (buildings height variation started from **north 32-28-24-20-20-16-12-8 m) .**	**Case 2** height variation oriented to south (buildings height variation started from **south 32-28-24-20-20-16-12-8 m).**
Case 3 east	**Case 4** west
	
Case 3 height variation oriented to east (buildings height variation started from **east 32-28-24-20-20-16-12-8 m).**	**Case 4** height variation oriented to west (buildings height variation started from **west 32-28-24-20-20-16-12-8 m).**
Case 8 diagonal	
	
height variation-oriented diagonal (**Mid diagonal line with highest buildings 33 m and other height 32-16-12-8 m**).	
Second group (Stratified configuration of height variation started from inner loop or outer loop).	
Case 5 **with H/W ratio (1.8-1-0.8-0.5).** **25% Low rise buildings - 75% midrise buildings**	**Case 6** **with H/W ratio (4.8-1.8-1-0.8).** **44% Low rise buildings - 50% midrise buildings – 6% high rise buildings**
	

(buildings height variation from the outer loop **28-16-12-8)**	buildings height variation from the inner loop **72-28-16-12).**
Third group (Random configuration of height variation**) (with H/W ratio (4.8-3.6-2.1-1.6-1-0.8-0.5)).**	
Case 7 random variation (**55% Low rise - 33% midrise– 12% high rise buildings**)	
  Random buildings height variation **8-12-16-24-32-54-72 m).**	
Fourth group (High rise building configuration of height variation with different orientation**)** **(with H/W ratio (3.6-2.3-1.3 -1-0.8-0.5)). 43% Low rise - 42% midrise– 15% high rise buildings**	
Case 9	**Case 10**
 High rise buildings oriented to **the south-west.** Building height variation (54-24-20-16-12-8) m.	 High rise buildings oriented to **north-east.** Building height variation (54-24-20-16-12-8) m.
Case 11	**Case 12**
 High rise buildings oriented to **north-west.** Building height variation (54-24-20-16-12-8) m.	 High rise buildings oriented to **the south-east.** Building height variation (54-24-20-16-12-8) m.

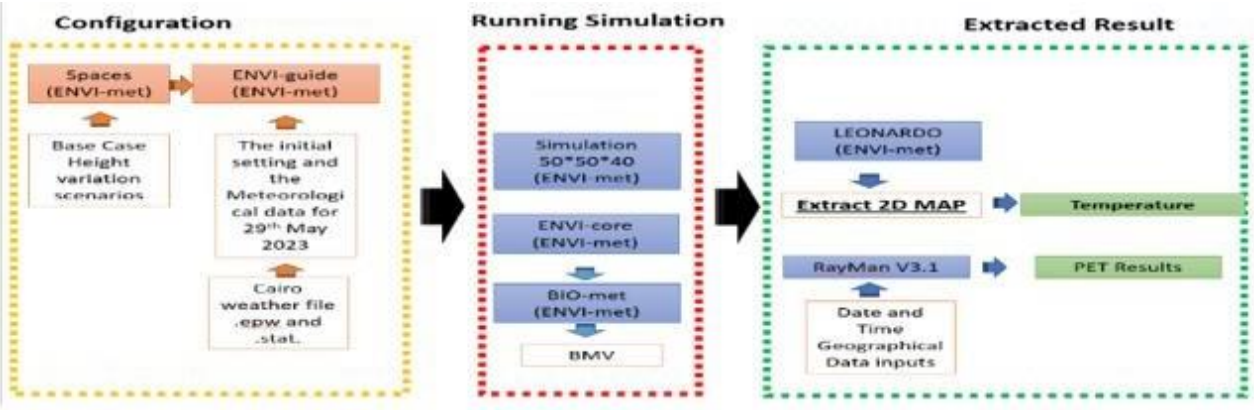


Figure 2: Simulation method with ENVI-met and RayMan in outdoor simulations (source: Author).

2.4 Validation for Simulation Software

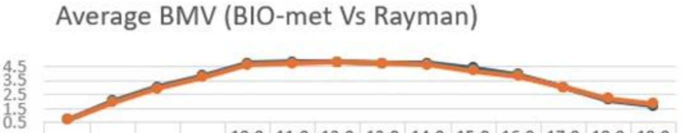
Investigating the impact of Floor Area Ratio (FAR) on microclimate parameters requires robust methodologies. The three primary approaches include: **Field Measurements:** This method involves directly measuring relevant microclimate parameters (e.g., air temperature, humidity, wind speed) at a site. While providing real-world data, it may not always be feasible due to space limitations in existing urban environments. **Weather Station Data Simulations**: This approach utilizes existing weather station data to simulate microclimate conditions for different FAR scenarios. However, it may not fully capture the site-specific complexities that influence microclimates. **Validated Simulations** [14] This method is considered the most rigorous. It involves creating computer models of the urban environment and validating them with actual field measurements. This validated model can then be used to simulate microclimate conditions for various FAR scenarios, offering a balance between real-world accuracy and scenario testing capabilities.

2.5 Predicted Mean Vote (PMV) PMV BIO-met Vs PMV Rayman

In this phase, two parameters will be calculated. The BMV will be validated using Rayman and Envi-met BIOmet. The simulated PMV values in the base case scenario reportedly ranged from 0.7 to 4.8. This range suggests variations in thermal comfort perception across the simulated environment. The minimum PMV coincided with the minimum air temperature, indicating a positive relationship between air temperature and PMV in the base case configuration.

Table 4: main input data used in Simulation cases (source: Author).

Parameter	Value
Model data	
Walls material	Concrete (absorption: 0.5, transmission: 0.00; reflection: 0.50; emissivity: 0.90; specific heat: 850 J/kgK; thermal conductivity: 1.6 W/mK; density: 2220 kg/m3) and insulation (absorption: 0.5, transmission: 0.00; reflection: 0.50; emissivity: 0.90; specific heat: 1500 J/kgK; thermal conductivity: 0.07 W/mK; density: 400 kg/m3)
Roofs material	Concrete (absorption: 0.5, transmission: 0.00; reflection: 0.50; emissivity: 0.90; specific heat: 850 J/kgK; thermal conductivity: 1.6 W/mK; density: 2220 kg/m3) and insulation (absorption: 0.5, transmission: 0.00; reflection: 0.50; emissivity: 0.90; specific heat: 1500 J/kgK; thermal conductivity: 0.07 W/mK; density: 400 kg/m3)
Streets	Asphalt (albedo: 0.20; emissivity: 0.90)
Soil type	Loamy (emissivity: 0.98)
Simulation	
Location	Cairo (latitude 30.1- longitude31.4)
Simulation day	29/5/2023
Simulation duration	14 h from 05:00 AM
Relative humidity	Rh_{min} 10 - RH_{max} 24
Wind speed (10 m)	5.7 m/s - Cloud coverage = 0%
Reveling Wind direction	350
Specific humidity at 2500 m (g/kg)	0.04
Air Temperature (T_A)	$T_{A\text{-}min}$ 25 and $T_{A\text{-}max}$ 40
Building indoor temperature	26



	6:00	7:00	8:00	9:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00
PMV (BIO-met)	0.7	2	3	3.8	4.7	4.8	4.8	4.7	4.7	4.4	3.9	3	2.1	1.7
PMV (Rayman)	0.7	1.9	2.9	3.7	4.6	4.7	4.8	4.7	4.6	4.2	3.8	3	2.2	1.8

Figure 3: Base Case Hourly profile of the average PMV on 29 May (source: Author).

3. Results and discussion

3.1 effect of height variation on air temperature. First group

An analysis of air temperature within the first group configurations, compared to the base case scenario, reveals several key observations:

- **Peak Temperature Timing:** Across all five configurations and the base case, the average maximum air temperature consistently occurs at midday (12:00 PM).
- **Case 1 Demonstrates Potential:** Among the configurations, Case 1 exhibits the most significant impact on air temperature. It achieves a maximum air temperature approximately 1°C lower than both the other configurations and the base case scenario. This substantial reduction suggests that Case 1 has the potential to create a more favorable thermal environment compared to the other options.

- **Second group configuration (Temperature)**
  - **Case 6 Demonstrates Lower Peak Temperature:** Among the two configurations, Case 6 exhibits a lower maximum air temperature compared to Case 5.
  - Comparison case 6 with base case found that air temperature in all the block decrease by 1 ^{0}c than base case especially in the middle where high rise buildings are (72 m), this air temperature difference appears.
- **Third group configuration (Temperature)**

The analysis of air temperature within the third group configurations, compared to the base case scenario, reveals interesting trends:

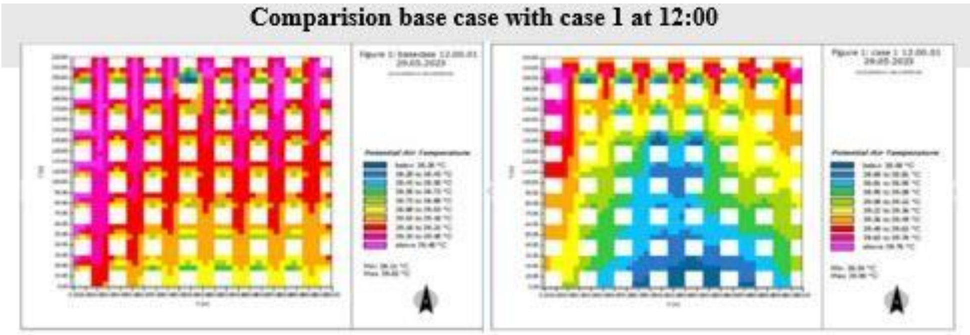
Case 7 demonstrates the most significant impact on air temperature. It achieves a maximum air temperature nearly 1°C lower than the base case scenario across the time of 10 AM to 4 PM. This suggests that Case 7 has the potential to create a more favorable thermal environment compared to the base case. While Case 7 appears promising, a more comprehensive evaluation is recommended for a definitive conclusion.

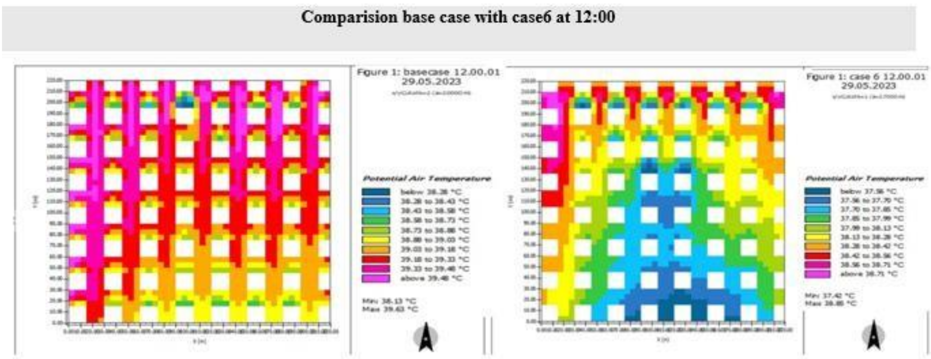
- **Fourth group configuration (Temperature)**

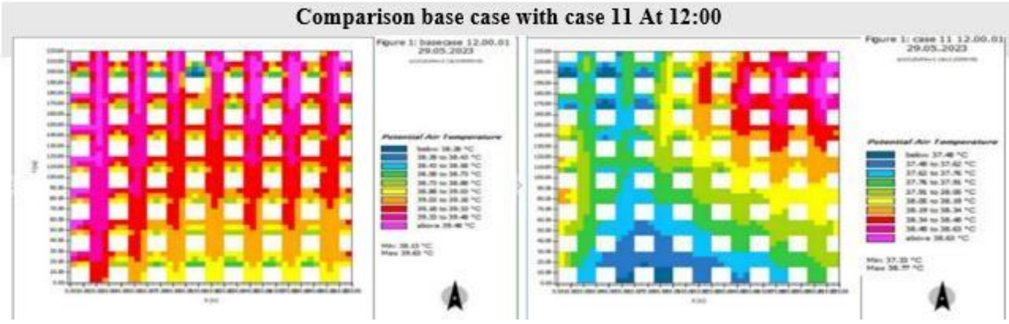
The analysis of air temperature within the fourth group configurations, compared to the base case scenario, reveals:

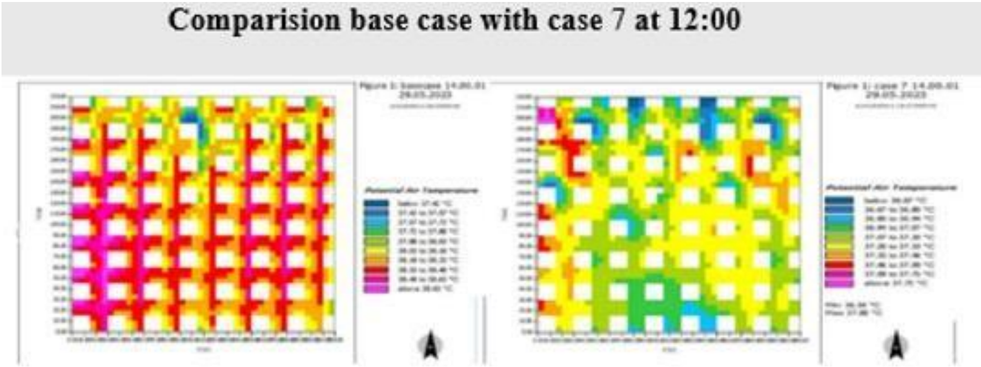
- **Case 11** Demonstrates Significant Improvement: Among the configurations in Group 4, Case 11 exhibits the most significant impact on air temperature. It achieves a maximum air temperature nearly 1.5°C lower than the base case scenario across the time of 10 AM to 4 PM. While Case 11 appears to be the most promising configuration based on its lower peak temperature, a more comprehensive evaluation is recommended for a definitive conclusion.

  Figure 4 and table 5 indicate that air temperature rises through the morning hours until 12:00 when it started to decrease and Case 6, case 10, and case 7 recorded almost 1 0c difference than base case configuration at this time 10 – 11 -12 -13 -14 -15, and Case 11 recorded almost 1.5 0c difference than base case configuration at same hours.









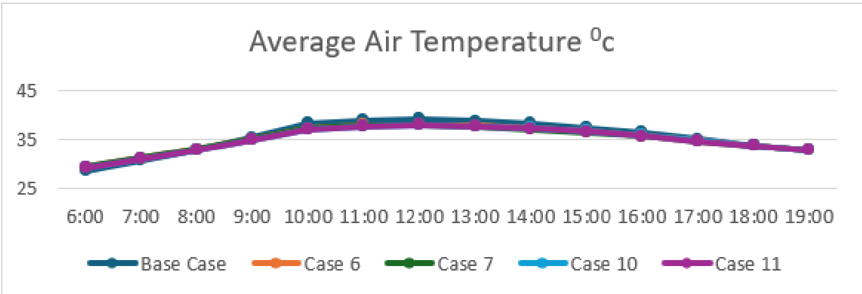


Figure4: Hourly profile of the average Air Temperature case 6-7-10-11 on 29 May(source: Author).

Table 5: Minimum and maximum Air Temperature case 6-7-10-11 on 29 May (source: Author).

Name		**06:00**	**07:00**	**08:00**	**09:00**	**10:00**	**11:00**	**12:00**	**13:00**	**14:00**	**15:00**	**16:00**	**17:00**	**18:00**	**19:00**
Base case	**min**	27	29.5	32	34.7	37.5	38.3	38.2	37.7	37.2	36.8	36	34.7	33.5	32.5
	max	29	31	33.5	36	39.3	39.7	39.6	39.5	38.8	38	37	35.5	34	33
Case 6	**min**	28.6	30.5	32.5	34.5	36.4	37	37.4	37	36.7	36.3	35.5	34.5	33.5	32.5
	max	29.6	31.6	33.8	36	38.5	38.8	38.8	38.5	37.8	37.2	36.2	35	34	33
Case 7	**min**	28.5	30.5	32.5	34.5	36.5	37	37.2	37	36.5	36	35.3	34.5	33.5	32.6
	max	29	31.5	33.5	36	38.5	38.7	38.7	38.5	37.8	37	36	35	34	33
Case10	**min**	28.4	30	32	34.3	36.3	37	37	36.8	36.5	36	35	34.5	33.5	32.5
	max	29.5	31	33.5	36	38.5	39	39	38.5	38	37.5	36.5	35.2	34	33
Case 11	**min**	28	30	32.2	34.5	36.3	37	37.3	36.9	36.5	36	35.3	34.5	33.5	32.5
	max	29.5	31.5	33.6	36	38.3	38.7	38.7	38.5	37.9	37	36	35	33.9	33

4. Conclusion and Recommendations

This study investigates the impact of building height diversity on the urban temperature in hot, arid regions like Egypt. A 220m x 220m urban block was modeled and simulated using ENVI-met software. The simulations revealed significant variations in thermal performance among the four groups configuration compared to the base case, particularly at peak sun hours (12:00 PM and 2:00 PM). These peak hours experience high ambient air temperature and strong solar radiation. The results suggest that a higher Height-to-Width (H/W) ratio leads to improved thermal performance. This is because a larger H/W ratio translates to increased shaded areas outdoors, leading to a decrease in absorbed solar radiation. These findings align with previous studies that have demonstrated the effectiveness of building height diversity in reducing daytime air temperatures [17], [12]. The four groups of building height configurations exhibited varying degrees of success in influencing outdoor thermal comfort parameters. Among the configurations studied, Cases 6, 7, 10, and 11 emerged as the most promising options for achieving thermal comfort. The study highlights the crucial role of building heights in shaping urban air temperature.

The following conclusions can be generated from the findings:

1) The study revealed a positive correlation between building height variation, aspect ratio variation, and urban temperature levels. Increased variability in both building height and aspect ratio contributed to enhanced thermal performance.
2) Case with building height variation (55% lowrise-33%midrise-12%highrise), demonstrated a notable reduction in both air temperature and thermal comfort compared to the base case scenario.
3) The increase of aspect ratio variation seems to be an effective strategy in improving urban temperature level (cases with H/W = 4.8 and 3.6 are better than those with H/W =1.3 ,0.5, 0.8 and 1).
4) Buildings with high aspect ratio (4.8 and 3.6) enhanced shading potential and consequently, decrease urban air temperature **therefore**, placing the tallest buildings within the center of the urban block, as demonstrated in Case 6, Moreover, randomizing the placement of buildings within the urban block, as demonstrated in Case 7, further increased shading coverage, resulting in additional decreases in air temperature.

The findings offer valuable insights for urban planners and policymakers working to improve outdoor thermal comfort. Building code regulations concerning building heights, particularly those with a significant impact on air temperature and pedestrian comfort, can be re-evaluated based on these results.

5. Study Limitations and Future Research

The geographic scope of the study was limited to Cairo, Egypt, which exhibits a hot and dry climate. To comprehensively assess the advantages of building heights diversity on thermal performance across diverse climatic conditions, future research should encompass additional locations within Egypt. Moreover, as the current study focused on a single summer day, expanding the analysis to include various days throughout the year would provide a more robust dataset and enable a deeper understanding of the phenomenon. In addition, future research should consider height diversity and FAR and its impact on parameters such as wind velocity and its direction, as well as humidity.

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