Impact of Urban Density on the Outdoor Thermal Comfort
Case Study: Yogyakarta Tugu Station Area, TOD Based
Planning

Efrita Nur Widiyannita¹, Agus Hariyadi², Nedyomukti Imam Syafii³

¹²³Department of Architecture and Planning Engineering, Faculty of Engineering, Universitas Gadjah Mada, Jl. Graﬁka No. 2, Yogyakarta 55281, Indonesia

E-mail: efrita.widiyannita@gmail.com, agus@ugm.ac.id, nedyomukti@ugm.ac.id

Abstract. TOD neighborhood actually experiences a signiﬁcantly higher UHI increase compared to the non-TOD area. One of the factors that affect is high density where it has an impact on the outdoor thermal discomfort. Yogyakarta Tugu Station area which has outdoor thermal discomfort will be planned to be a TOD neighborhood. An increase in density according to the TOD principle will allow the thermal comfort condition to decrease. The purpose of this study is to ﬁnd the optimal urban density value for the outdoor thermal comfort.

This research method uses simulation with Envi MET 3.1 software that aims to test the effect of urban density with variables such as BCR, FAR, and urban morphology on climatic factors (air temperature $T_a$, mean radiation temperature $T_{mrt}$, relative humidity $RH$). A parametric study was conducted on interactions between urban density and microclimate.

The results of this study will find the optimal value of each building density variable that increases the value of outdoor thermal comfort. These values can be used by the Yogyakarta City Government as a reference for the development of TOD in the Yogyakarta Tugu Station area.

1. Introduction
TOD (Transit Oriented Development) has been identiﬁed as one of the regional planning tools, developed as part of the smart growth movement, that intend to limit sprawl development in urban area. Development of a compact-based TOD area is done by increasing the residential and employment density, land use diversity, urban function diversity, etc. [1]. TOD concept emphasizes the morphology of compact cities that is supported by reliable transportation system. However, several studies have shown that TOD areas actually experience a signiﬁcantly higher UHI (Urban Heat Island) level compared to non-TOD areas [1]. It is a paradox of TOD neighborhood which should be able to reduce UHI by reducing gas emissions, but UHI actually increases from the density. The UHI effect which increased by 2 °C in high density areas also occurred in commercial areas and CBD (Commercial Business District) in Singapore [2,3]. Thus, it conﬁrms the theory that high-density areas are vulnerable to increase UHI effect where UHI effect tends to have an impact on decreasing the outdoor thermal comfort.

Preliminary observation was conducted to gain users personal perceptions of outdoor thermal comfort in Yogyakarta Tugu Station area. The result is that 53% of respondents said they were uncomfortable, 30% could still tolerate thermal conditions, and only 17% said they were comfortable
with the microclimate in the region. According to Fawzi N.I. [4], the intensity of UHI in Yogyakarta increased by around +/- 2.5 °C. According to Brontowiyono et al. [5], temperature in Malioboro area can reach 38 °C. It can be concluded that the perception of outdoor thermal discomfort felt by the majority of respondents due to micro-climate conditions that are less tolerable.

Nevertheless, the Government of Special Region of Yogyakarta plans the Tugu Station area to be developed based on TOD. According to Widyastuti [6], the development of this station will be Urban TOD-based with Building Coverage Ratio (BCR) criteria of 80% and Floor Area Ratio (FAR) is > 5. On the other hand, the density of existing buildings has not met the urban TOD criteria, namely BCR 41.08% and FAR 0.72. The hypothesis is that if the building density of the area needs to be increased along with Urban TOD criteria, the thermal comfort conditions will decrease further. The purpose of this study is to find the optimal value of the building density that affects the outdoor thermal comfort in Yogyakarta Tugu Station area with TOD based planning. In addition, it is aimed to find the most optimal urban morphology to increase the outdoor thermal comfort in this future TOD area.

### Table 1. Building Density Variables (Indonesian Ministry of Public Works and Public Housing),

| Density Variable | Density Value |
|------------------|---------------|
| • The number of residential units for residential function | • High density (>60 units/ha; FAR>2; BCR>70%) |
| • Footprint area and gross floor area of commercial and office buildings | • Medium density (>30-60 units/ha, FAR 1-2; BCR 50-70%) |
| • Area of open space | • Low density (<30 units/ha; FAR<1; BCR<50%) |
|                   | • The proportion of green open space in an urban area is at least 30% (20% of public open space, 10% of private green open space) |

1.1. Building Density Variables that Affect Micro Climate

According to Wei et al. [7], building density variables form the character of urban morphology, which can describe the condition of the urban environment. Building density variables (FAR, BCR, aspect ratio, and open space ratio) have a significant relation with the outdoor thermal comfort variables (Table 2). It can be said that the density of buildings that form urban morphology has a strong influence on the microclimate.

### Table 2. Building Density Variables that Affect Micro Climate.

| Element         | Density Variable | Indicator                      | Affected Outdoor Thermal Comfort |
|-----------------|------------------|--------------------------------|---------------------------------|
| Urban Morphology| BCR              | Ratio of footprint area to site plan area | Ta, RH                          |
|                 | Building planning configuration |                               | WS, Tmrt                       |
| FAR             | Ratio of gross floor area to site plan area |                               | Tmrt, WS                       |
| Aspect Ratio    | Number of floors (L) |                               | Ta, Tmrt, WS                   |
| Ratio           | H/W Ratio         |                               | Tmrt, WS                       |
|                 | SVF               |                               | Ta, Tmrt                       |
| Open Space      | OSR               | Ratio of open space area to site plan area | Ta, Tmrt |

1.2. Study Location

The research takes place in Yogyakarta Tugu Station area as far as 400m radius, as an area that will be developed based on TOD. Tugu Station is located in Yogyakarta City with an average air temperature of 26.4 °C -27.5 °C in 2019. Topographical conditions are relatively flat and 114 meters above the sea level. The average relative humidity is 83%, and reached the maximum at 88%, while the average highest wind speed reached 1.9 m / s [8].

2. Methodology

Parametric study was conducted to determine the interaction between building density and microclimate with ENVI-Met 3.1 software simulation by Michael Bruse [9]. The parametric study experiment was designed as follows: creating building plots model as physical geometry of the area, adjusted to the
built-up area and site area. The building plots represent building located in the Yogyakarta Tugu Station area (Fig. 1). The plots are assumed to be buildings with an area of 18mx18m. The impact of plants on microclimate is excluded. Therefore, there is no vegetation in the model.

This experiment is looking for optimal density values (BCR and FAR) to increase the outdoor thermal comfort. Therefore, 10 different models were made with varying BCR and FAR values. The scenarios for BCR and FAR values are adjusted to the level of density and local regulations (Table 3). Although the plots share the same BCR value, their urban morphological characteristics could have many variations. For instance, their building site coverage, footprint area, number of floors, and the building layout can vary dramatically. So, it will be attained the most optimal urban morphology.

Figure 1. Modelling Scenarios.

Table 3. Modelling Scenarios.

| BCR  | A  | B  | C  | D  | E  | F  | G  | H  | I  | J  |
|------|----|----|----|----|----|----|----|----|----|----|
| FAR  | 30%| 50%| 50%| 50%| 70%| 70%| 70%| 90%| 90%| 90%|
| FAR  | 2  | 2  | 3  | 4  | 3  | 4  | 5  | 4  | 5  | 6  |
| FAR  | 6  | 4  | 6  | 8  | 6  | 7  | 4  | 6  | 7  |    |
| FAR  | 684| 684| 972| 1296| 972| 1296| 1620| 1296| 1620| 1944|
| FAR  | 100| 169| 169| 169| 225| 225| 225| 289| 289| 289|
| FAR  | 0.352| 0.278| 0.216| 0.179| 0.272| 0.21| 0.191| 0.272| 0.21| 0.185|

3. Result

3.1. Optimal Value of Building Density

In this section, the average value of microclimate is taken from 9:00 to 17:00, which is found more activity at that time (active hours).

3.1.1. Average Air Temperature (Ta). The average Ta on the BCR 50%-model decreases from 28.77 °C to 27.68 °C as the FAR value increases from 2 to 4. This also applies to the BCR 70% -model, the average Ta decreases from 28.25 °C to 27.82 °C. However, this does not apply to the BCR 90%-model, where the average Ta fluctuates from 29.64 °C and drops to 29.25 °C, then rise to 29.3 °C. From Fig. 2a, it can be seen that an increase in FAR tends to decrease the average Ta value.

Fig. 3a shows that model H has the highest average air temperature of 29.64 °C, with BCR of 90%, FAR 4, and height of 4 floors (assuming 1 floor is equivalent to 4 m). Meanwhile, the lowest average Ta (27.58 °C) occurs in model A with BCR of 30%, FAR 2, and height of 6 floors. The significant difference between the two is the excessively far BCR value, which building coverage in model H is higher than model A so that the mass of the model H is wider (Fig. 1).

3.1.2. Average Relative Humidity (RH). Simulated urban morphological models show an increase in FAR along with an increase in average RH (Fig. 2b). The average relative humidity of the BCR 50%-model increases from 68.49% to 71.49% along with an increase in the FAR value. This is directly proportional to the BCR 70%-model and the BCR 90%-model.

The lowest average RH occurs in model B that is 68.49% with BCR of 50%, while the highest occurs in model J with BCR of 90%. Fig. 3b shows that the higher the value of BCR, the higher the RH is resulted. However, the RH model tends to be moderate at 79.4% whereas the BCR value is only 30%.
3.1.3. Average Mean Radiant Temperature (Tmrt). The average Tmrt tends to decrease when FAR is getting higher. The BCR 50%-model and the BCR 70%-model have a graph that tends to be the same, when the Tmrt value drops dramatically as FAR is raised from 2 to 5. However, this is inversely proportional to the BCR 90%-model, where the increase in FAR actually raises Tmrt value.

The highest average score is achieved by model B with FAR 2, BCR 50%, and height of 4 floors. Meanwhile, model F with FAR 4, BCR 70%, and height of 6 floors has the lowest radiation compared to all simulation models. Model B and model E have significant high value of 33.37 °C and 32.8 °C, whereas the Tmrt of other models range from 29.84 °C to 30.35 °C (Fig. 2c).

3.2. PMV
Predicted Mean Vote (PMV) is an index of thermal comfort that has been standardized in ISO 7730. This index indicates the sensation of cold and warmth felt by humans in a scale of -3.5 to +3 [10]. PMV values generated from the simulation of model A-model J ranged from 1.75 to 2.25 (Fig.4). This explains that the most optimal building density value compared to other models is model D with BCR 50%, FAR 4, and height of 8 floors. The density value results in an urban morphological configuration with SKV 0.179 and building masses which tend to be lean and tall. The higher PMV values tend to have lower FAR values. Meanwhile, the higher the value of BCR, the higher the value of PMV.

Figure 2. Effect of Increasing FAR on Outdoor Thermal Comfort Variable.

Figure 3. The graph above describes the model with optimal Ta, RH, and Tmrt variable results.
4. Discussion
There is a correlation between Tmrt and Ta when FAR is constant. The lower SVF is inversely proportional to the higher FAR with a constant BCR [7]. Fig. 2a and 2c show that the increase in FAR actually affects the decrease in Ta and Tmrt. It is because the building coverage area in each model with the same BCR value (BCR 50%-model, BCR 70%-model, BCR 90%-model) has a constant value. When the BCR value is constant while the FAR value is getting higher, it will result in a higher building height and number of floors. As a result, the sky view is obstructed, so that the SVF value tends to decrease and the building shade effect is higher.

BCR is a ratio of built-up area to site plan area. This ratio aims to determine the effect of radiation that exists in an area, and also to identify the availability of humidity or heat absorbed [11]. Fig. 2c shows that when BCR increases with a constant FAR, the Tmrt will also increase. It is due to the lower building height that received more sunlight. The increase in Tmrt is directly proportional to the increase in Ta and RH.

Building density that meets the outdoor thermal comfort based on the lowest PMV value (1.79) is model D with a BCR of 50% and FAR 4 although the value is still relatively hot and uncomfortable [12]. However, when compared to the outdoor thermal comfort standard by ASHRAE 55 [12], the outdoor thermal comfort variable of model D almost meets the thermal comfort standard. The Ta of model D is 27.68 °C where the standard ranges from 16 °C to 27 °C. The standard of Tmrt is 16 °C - 28 °C, whereas the Tmrt of model D is 29.75 °C. Therefore, Ta and Tmrt value indicate worse condition as compare to comfort standard. The RH standard is 20% - 90%. Model D results 71.49% of RH which is still categorized as comfortable.

Model D results tall buildings configuration but there is still a large open space. Maximum building height can provide shade effect on the surrounding environment so Ta can be reduced. H/W ratio of model D (4.57) is the optimal ratio. A deep urban canyon gives shade effect to achieve lower Tmrt, one thing should be anticipated is the overshadowing in order to increase RH [13]. Deep urban canyon is a media to cool down an area in tropical climates [14].

TOD concept has to meet certain building density criteria in order to achieve sustainability and success in the area [6]. According to Indonesian Ministry of Agrarian Affairs and Spatial Planning, urban TOD has criteria of 80% BCR and FAR > 5. Building density consideration certainly has to be adjusted to the carrying capacity of the environment of Yogyakarta. The local government said that Yogyakarta Tugu Station area can support building intensities with 20-90% BCR and 0.4-6.4 FAR with a maximum building height of 32m. Model D (with building density of BCR 50%, FAR 4, and building height 8 floors / 32 m) does not meet urban TOD criteria yet. It means that the building density has not been achieved. However, according to the Public Works Agency of Yogyakarta, model D has met the high density in terms of FAR (Table 1).
5. Conclusion

- Building density affects the outdoor thermal comfort. When the FAR increases and the BCR remains constant, it is resulting Ta and Tmrt to get higher. Another case, when the BCR increases and the FAR is constant, Ta, Tmrt, and RH will also increase.
- Building density values that are close to the optimal values to be applied in TOD-based planning in Yogyakarta Tugu Station area are BCR 50% and FAR 4. Building configuration should be a high building with sufficient width and has 4.57 of H/W ratio. It is also necessary to design a green open space and to select appropriate pavement material in order to achieve outdoor thermal comfort.
- Although model D does not meet the density value for the TOD-based area of Yogyakarta Tugu Station, this model has the most optimal result compared to other models in increasing outdoor thermal comfort.

Acknowledgements

The author would like to thank the master student of MDKB UGM for guidance and Department of Architecture and Planning, Universitas Gadjah Mada to support the research.

References

[1] Kamruzzaman, M., Deilami, K., and Yigitcanlar, T 2018 Investigating the urban heat island effect of Transit Oriented Development in Brisbane Journal of Transport Geography 66 pp116-124
[2] Rajagopulan, Priyadarsini and Wong, N 2007 An investigation of the urban heat island of Singapore ANZASCA 2007: 41st annual conference (Queensland) pp 191-198
[3] Rajagopulan, Priyadarsini, et al. 2008 Microclimatic modeling of the urban thermal environment of Singapore to mitigate urban heat island Solar Energy 82 pp 727-745
[4] Fawzi, N. I 2017 Mengukur urban heat island menggunakan penginderaan jauh, kasus di kota Yogyakarta Majalah Ilmiah Globe pp 195
[5] Brontowiyono, W., Lupiyanto, R., Wijaya, D., and Hamidin, J 2011 Urban heat islands mitigation by Green Open Space (GOS) canopy improvement: A case of Yogyakarta Urban Area (YUA), Indonesia International Journal of Technology 2 pp 207-214
[6] Widyastuti, Dyah Titisari 2017 Konsep pengembangan kawasan stasiun kereta api: model rail-transit oriented development di indonesia (Universitas Gadjah Mada, Fakultas Teknik)
[7] Wei, R., Song, D., Wong, N. H., and Martin, M 2016 Impact of urban morphology parameters on microclimate Procedia Engineering 169 pp 142-149
[8] BPS Kota Yogyakarta, 2019. Kota Yogyakarta dalam Angka. Yogyakarta: BPS Kota Yogyakarta
[9] Bruse M 2004 ENVI-met 3.0: Updated Model Overview (University of Bochum)
[10] Honjo, Tsuyoshi 2009 Thermal comfort in outdoor environment Global Environmental Research Japan pp 13
[11] Koch-Nielsen, Holger 2002 Stay Cool - A design guide for the built environment in hot climates (United Kingdom: The Cromwell Press)
[12] ASHRAE/ANSI Standard 55 2010 Thermal environmental conditions for human occupancy (Atlanta, GA: American Society of Heating, Refrigerating, and Air-Conditioning Engineers)
[13] Paramita, B., & Fukuda, H 2013 Building groups design strategies in hot-humid climate: a dense residential planning in bandung, Indonesia PLEA Passive and Low Energy Architecture volume 28 (Munich)
[14] Brown, Robert D 2010 Design with microclimate: the secret to comfortable outdoor space (Washington DC: Island Press)