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Measuring effects of building orientation and vegetation on thermal comfort by ENVI-met (Case study: Maslak area, Istanbul)

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Abstract

Urban design and morphology are one of the most important factors affecting outdoor thermal comfort that should be given special attention. Optimal orientation would improve the quality of the building's thermal comfort as well as its urban area, considering the geography and climate of the area. Conversely, orientation and physical form of the buildings (particularly high-rise buildings) which are incompatible with climate could create a phenomenon called "urban heat island" and disrupt their thermal comfort. Moreover, vegetation as one of the outdoor affecting factors, through creating air movement and shading can help in enhancing the thermal comfort sensation. This paper, through a descriptive-analytical method, firstly explored the theoretical foundations around thermal comfort and the effects of morphology and vegetation on that. Secondly, a high-rise building complex located in Maslak district of Istanbul, a modern and developing region with the Mediterranean climate, was chosen as a case study. Three design alternatives, including the current design and two hypothetical design alternatives for building orientation and vegetation parameters, have been analyzed and the thermal comfort indicators, PMV and PPD have been calculated by Envi-met software. By evaluating and comparing the outputs, it can be concluded that controlling these two parameters (building orientation and vegetation) could have a positive impact on outdoor thermal comfort.

Keywords
Building orientation, Envi-met, High-rise buildings, Outdoor thermal comfort, Urban vegetation.

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1. Introduction

Achieving the human thermal comfort, in a recent high urban density, would be a challenge due to controlling the environments' micro-climate. Hasty and randomized urban design can lead to creating outdoor thermal discomfort between city blocks (Nouri, 2015).

Accordingly, urban design and morphology play an important role in providing thermal comfort, for instance, buildings form and orientation could create a phenomenon known as "urban heat islands" which could have negative impacts on urban areas like thermal discomfort. There are numerous design strategies to improve thermal comfort. In this study; two influential thermal comfort variables, building orientation and vegetation are investigated. First, with the descriptive method, definitions and theoretical foundations are presented. Then, related recent studies are presented in the form of a table to provide the theoretical framework for the analysis section of the case study.

2. Theoretical background

2.1. Thermal comfort

"Thermal comfort is defined as a state where no driving impulses exist so as to modify the environments by the behavior" (Hensen, 1991). The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) define thermal comfort as "the mental condition in which satisfaction with the thermal environment is expressed" (Ashrae, 2004).

Variety in variables and interactions can make thermal sensation to be more complicated. (Ogbonna & Harris, 2008). "To put it in another way, it is argued that thermal comfort has no absolute standard. Generally speaking, comfort takes place when body temperatures are within narrow ranges, the moisture of skin is low, and the physiological exertion of regulation is diminished. Comfort is also dependent on behavioral actions like changing clothing, changing activity, altering posture or position, changing the thermostat setting, complaining, opening a window, or leaving a space" (Djongyang et al, 2010). Thermal comfort can help sustainability through estimating energy usage of the building systems (Yao et al, 2009).

Table 1. *PMV ranges and physiological equivalent for different grades of thermal perception and physiological stress (Matzarakis, 1997) (Barakat et al, 2017).*

PMV	Thermal perception	Grade of physiological stress
<-3	Very cold	Extreme cold stress
-3	Cold	Strong cold stress
-2	Cool	Moderate cold stress
-1	Slightly cool	Slight cold stress
0	Comfortable	No thermal stress
1	Slightly warm	Slight heat stress
2	Warm	Moderate heat stress
3	Hot	Strong heat stress
>3	Very hot	Extreme heat stress

"Predicted mean vote (PMV) was developed for assessing thermal comfort. The PMV calculations consider four environmental parameters: air temperature, mean radiant temperature, wind speed and relative humidity; and two personal variables: clothing insulation and metabolic rate, as the inputs and predict thermal sensation. The Predicted Mean Vote (PMV) refers to a thermal scale that runs from Cold (-3) to Hot (+3)" as illustrated in Table 1 (Beizaee, 2012).

Despite showing the values in this table, PMV is not considering the acceptability of thermal comfort for most people and just expresses their opinion.

"Following these considerations, Fanger (1972) proposes an index for the evaluation of the conditions of

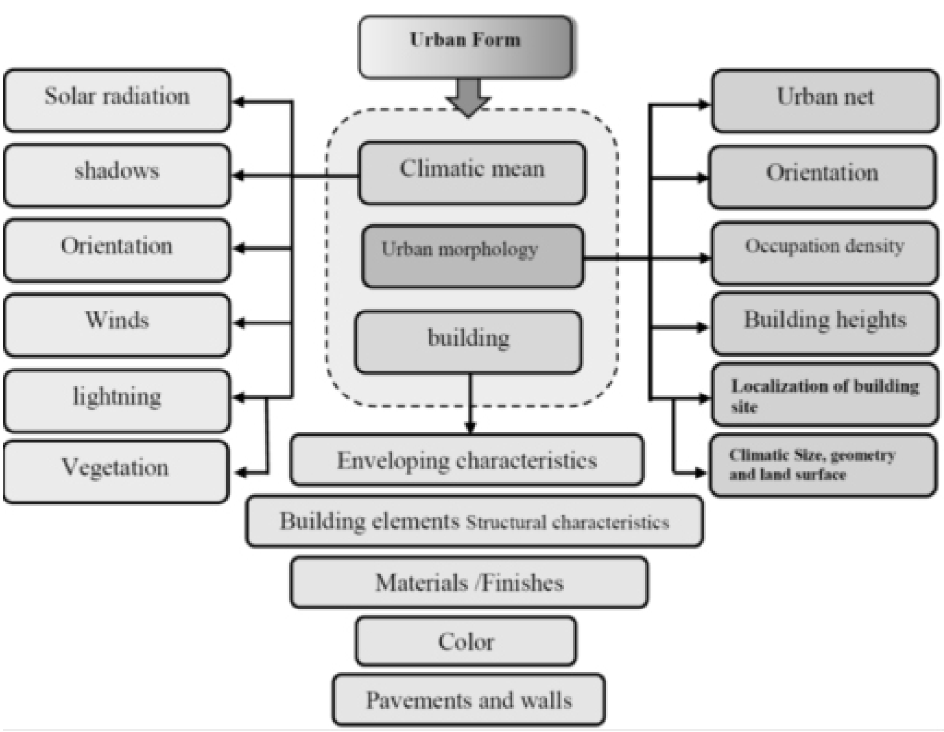


Figure 1. *Categories of constant intervening variables in outer space (Makvandi & Li, 2016).*

non-comfort (or discomfort) to an environment, expressed as a Predicted Percentage of Dissatisfied (PPD). The PPD index expresses the percentage of people in those conditions of metabolism, clothing and physical parameters of the environment, expressing, however, a negative judgment, in fact, complain; even when an environment is assessed by most people as neutral, it is believed that there are however 5 % of people who consider this condition as unsatisfactory" (Fabbri, k, 2015).

2.2. Outdoor thermal comfort variables

Mahvandi and Li (2016) classified outdoor thermal comfort variables into three categories. The first one included climatic characteristics like wind, humidity, temperature, solar radiation, vegetation and etc. The second category consists of morphological features, such as building geometry and orientation. The third one considers building elements, such as façade, finishes and materials. These variables must be simultaneously taken into account in a way that both climate and morphological features would be linked (Mahvandi & Li, 2016). Some of these thermal comfort variables also have been sorted in figure 1.

2.2.1. Building orientation

Building's angle can have a great impact on thermal comfort. Exposing building facades to the exterior environment, their form, orientation, and material properties could control the natural ventilation and solar radiation by evaporative cooling (Susie, 2011) (Iyendo et al, 2016).

Commonly, northern elevations are exposed to minimum solar rays versus southern elevations that are hit maximum amounts. Therefore, building orientation is one of the important factors that determine the received solar radiation of a building (Gupta & Ralegaonkar, 2004) (Omrany & Marsono, 2016).

2.2.2. Thermal comfort and vegetation in high-rise buildings

Being surrounded by vegetation is one of the key factors that help low-rise buildings mitigate uncomfortable climate conditions. In contrast, high-rise buildings are exposed to more solar radiation due to their larger surface area. Also, a high concentration of this type of building can cause environmental problems such as urban heat island (UHI), an effect that leads to thermal discomfort. As a result, providing thermal comfort requires more consideration in high-rise buildings. (Chia Sok Ling et al. 2007) (Taib et al, 2010).

One of the methods for improving thermal comfort around high-rise buildings is introducing landscapes. This improvement is achieved through vegetation qualities such as evaporation, provided shade and air movement. Akbari (2002) found that "urban tree planting can account for a 25% reduction in net cooling and heating energy usage in an urban landscape". In addition to the outdoor thermal comfort benefits, the aesthetic of vegetation around the building blocks can have positive psychological effects (Iyendo et al, 2016) (Taib et al, 2010).

As mentioned above, the morphology of urban spaces and building form has a great impact on the micro-climates, and therefore on thermal comfort. Several studies have been conducted in recent decades and examined the impact of both variables on thermal comfort. Table 2 surveyed 14 of these studies from 2001 to 2017, which have been done in different locations and climates. In this table, the studies are classified according to the climate, and their dependent and independent variables are identified and categorized.

3. Case Study: Maslak area Istanbul

3.1. Research methodology

The method of research is descriptive-analytical. The theoretical framework has been developed using the literature review on the assessment of the various morphologies of urban high-rise buildings on thermal comfort. Therefore, one of the main administrative-commercial zones of Istanbul, Maslak area has been opted for quantitative and spatial estimation and evaluating the effects of high-rise buildings. This neighborhood is one of the main business districts in Istanbul, which is located in the European part of the city (Figure 2). Currently, one of the tallest buildings in this area is the 47-story spin tower, with a height of 202 meters. The other high-rise buildings in this area are the 53 and 54-tier towers that are between 261 to 270 meters high. Most of the towers built in this area are made of steel structures.

Table 2. *Key indicators regarding the "Urban Heat Island" (UHI) effect in the Adriatic settlements (Suau, C. et al, 2015).*

Climate	Research Title	Author(s)	Year	Dependent variables	Independent variables	Methods	Area of Study
Hot-dry	Numerical study on the effects of aspect ratio and orientation of an urban street canyon on outdoor thermal comfort in hot and dry climate	Ali-Toudert F. , Mayer H.	2006	Air temperature	Height to wide ratio (H/W), Orientation	Simulation (with ENVI-met)	Ghar-daia, Algeria
	Outdoor Thermal Comfort in the Hot Arid Climate	Aljawabral, F., Nikolopoulou M.	2009	Outdoor activities, Predicted Mean Vote (PMV)	Solar radiation	Survey	Marrakech in North Africa and Phoenix in North America.
	Impact of street design on urban microclimate for semi-arid climate (Constantine)	Bourbia F. , Boucheriba F.	2010	Physiological Equivalent Temperature (PET)	Sky view factors (SVF), wind speed	Quantitative	Cairo, Egypt
	Urban design in favor of human thermal comfort for hot arid climate using advanced simulation methods	Barakat A. et al.	2017	PMV,PET	Air temperature, relative humidity, MRT and PMV	Simulation (with ENVI-met)	New Borg El-Arab, Dubai, Emirate
Warm-humid	Urban shading (a design option for the tropics) A study in Colombo, Sri Lanka	Emmanuel R. et al.	2007	MRT, PET	Height to wide ratio (H/W)	Simulation (with ENVI-met)	Colombo, Sri Lanka
	Thermal perception, adaption and attendance in a public square in hot and humid regions	Lin T.	2009	PET, Thermal Sensation (Perception & attendance)	Air Temperatures, mean relative Humidity	Quantitative/ Survey	Taiwan
	Thermal Comfort Investigation in Three Hot-Humid Climate Theme Parks in Jakarta	Koerniawan M. D. and Gao W.	2015	PET	Solar radiation, Vegetation	Literature Review	Theme parks in Jakarta
	Effect of urban design on microclimate and thermal comfort outdoors in warm-humid Dar es Salaam, Tanzania	Yahia M.W. et al.	2017	Air temperature, wind speed, mean radiant temperature (MRT) //the physiologically equivalent temperature (PET)	Building Height, Vegetation// Wind speed, MRT	Simulation (with ENVI-met)	Dar es Salaam, Tanzania
Subtropical	Influence of Building Orientation on the Indoor Climate of Buildings	Januário M., Rodrigues A. L.	2012	Indoor temperature, Absorbed solar radiation	Orientation, Opened & closed windows	Simulation (with DEROB-LTH)	Maputo, Mozambique
	Thermal Comfort Zone for Outdoor Areas in Subtropical Climate	Moreno M. M. et al.	2008	Thermal Sensation	Air and globe temperatures, relative humidity, wind speed and temperature/ Vegetation	Survey	Campinas, Brazil
Temperate	Thermal Comfort and Outdoor Activity in Japanese Urban Public Places	Thorsson S. et al.	2007	Air temperature, globe temperature, surface temperature, relative humidity, wind speed, incoming short wave radiation, and incoming long-wave radiation// Thermal Sensation	Height// Stage of human Stress	Quantitative/ Survey	Matsudo, Japan
Cold	Climate and behavior in a Nordic city	Eliasson I. et al.	2007	Thermal Sensation (Human emotion, Attendance)	Height// Clearness index, Air temperature , Wind speed	Quantitative/ Survey	Gothenburg, Sweden
	Thermal Comfort in Outdoor Urban spaces: Understanding the human parameters	Nikolopoulo M. et al.	2001	Globe temperature	Number of people outdoors	Quantitative/ Survey	City-center of Cambridge, England
	Studies of Outdoor Thermal Comfort in Northern China	Lai D. et al.	2014	solar radiation, wind speed, and relative humidity //PMV, PET, UTCI	Air temperature	Quantitative/ Survey	Tianjin, China

Figure 2. *Maslak Mashattan area.*

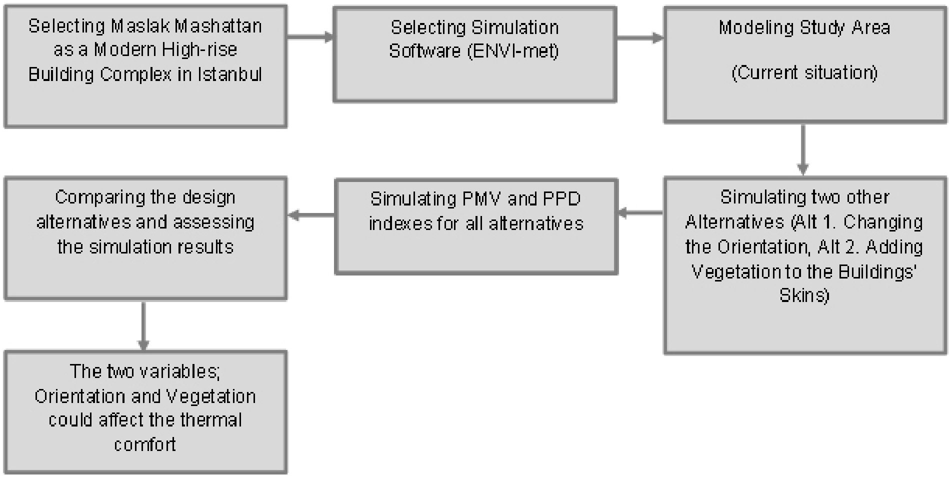


Figure 3. *Research process diagram.*

3.2. Research process

Maslak district due to having high-rise and modern buildings has been chosen for the study area and Mashattan Maslak building blocks for modeling and analyzing. After choosing the case study, the existing status of the neighborhood and building complex was simulated with the ENVI-met software (which has been identified as an appropriate tool for the simulation and evaluation of the thermal comfort indexes.). In order to measure the effects of vegetation and orientation on outdoor thermal comfort, two hypothetical alternative designs were proposed. Afterward, PMV and PPD variables as two thermal comfort indicators simulated with the software. Comparing the results, the effect of two variables (vegetation and orientation) on outdoor thermal comfort has been analyzed and demonstrated (Figure 3).

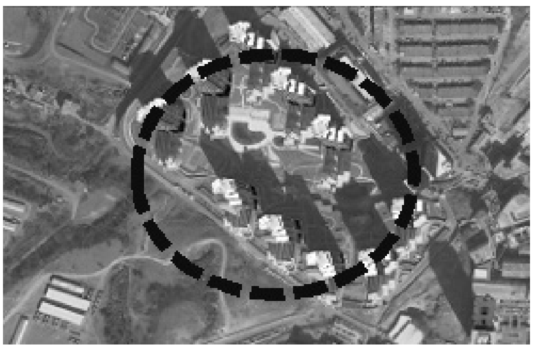


Figure 4. *Site location: Aerial photograph, 2018.*

3.3. Study area: Maslak area in Istanbul, Turkey

"The site is located between latitude 41°06' 26"N and 41°06'05"N, and longitude 29°01'45"E and 29°01'56"E. The area is bordered by the Bosphorus to the east, Belgrade Forest to the north and Kemerburgaz to the west. Densely populated residential areas, namely Levent and Etiler, are to the south. Moreover, an artificial lake and a stream (Kanlıkavak) are in the neighborhood. The altitude of the area ranges between 90 and 110 meters. Northern parts of both Asian and European sides of Istanbul are covered with Euro-Siberian flora that is deciduous forest vegetation. In the southern parts, which are under the Mediterranean effect, maquis vegetation dominates. The natural flora of the region has been changing for years because of the rapid increase in population and construction" (Çobanoglu, 2007) (Figure 4).

3.4. Simulation with ENVI-met

In this study, three alternatives have been evaluated using Envi-met 3D software. In several studies, this software has been used to simulate the microclimate factors in urban areas. This software is designed by Michael Bruse at the University of Mainz in Germany to simulate the interactions between surfaces, plants and urban environments (Bruse and Fleer, 1998). The effects of small-scale changes in urban design (construction patterns, vegetation, buildings morphology, etc.) could be analyzed through this software, as well as the micro-climate factors of the intermediate scale patterns in the urban environment (Tumini et al, 2014).

Physical components such as green spaces, watercourses, accesses, and the location of 6 blocks in modeling the design alternatives have been considered the same. Asphalt material has been used for paving the streets floor and soil and concrete for the courtyards, in accordance with the type of paving pattern. The space between these streets is filled with grass and building façade is a combination of glass and stone. The vegetation type inserted for alternative 3 is 4.5-meter trees. Also, the site is a rectangular shape, with 420 meters long and 240 meters wide, approximately. Figure 5 shows the input physical components of the simulation model for design alternatives.

The preliminary data for the modeling process has been entered at this stage. This data is based on geographic location (Istanbul), including latitude and longitude, air temperature, wind velocity and direction, relative and

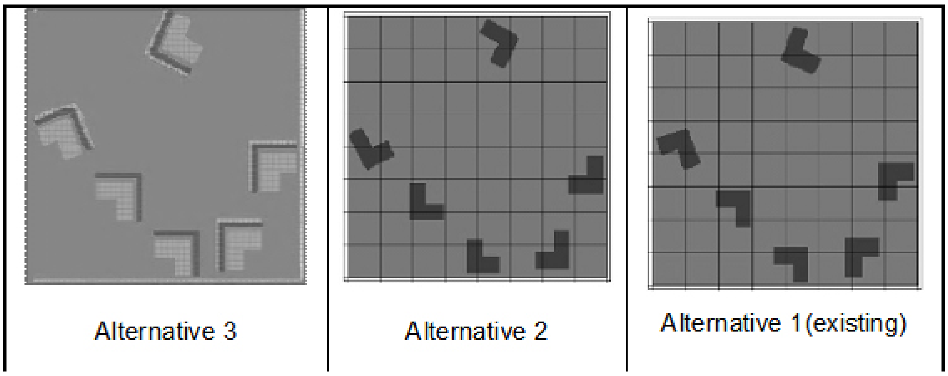


Figure 5. *Three options of modeling physical inputs (Authors, 2018).*

```
Total Simulation Time in Hours:                  =00.25
Save Model State each ? min                      =15
Wind Speed in 10 m ab. Ground [m/s]              =3.52
Wind Direction (0:N..90:E..180:S..270:W..)       =45
Roughness Length z0 at Reference Point           =0.1
Initial Temperature Atmosphere [K]               =303
Specific Humidity in 2500 m [g Water/kg air]     =7
Relative Humidity in 2m [%]                      =50
Database Plants                                  =[input]\Plants.dat

         ( -- End of Basic Data --)
         ( -- Following: Optional data. The order of sections is free. --)
         ( -- Missing Sections will keep default data. --)
         ( Use "Add Section" in ConfigEditor to add more sections )
         ( Only use "=" in front of the final value, not in the description)
         ( This file is created for ENVI-met V3.0 or better )
[PMV] ______________________________________ Settings for PMV-Calculation
Walking Speed (m/s)                              =0.3
Energy-Exchange (Col. 2 M/A)                     =116
Mech. Factor                                     =0.0
Heattransfer resistance cloths                   =0.5

[SOURCES] ______________________________________ Type of emitted gas/particle
Name of component                                 =PM10
Type of component                                 =PM
Particle Diameter in [µm] (0 for gas)             =20
Particle Density [g/cm³]                          =1
Update interval for emission rate [s]             =600
```

Figure 6. *Basic microclimate input data for simulation software (Istanbul weather station, 2017).*

Table 3. Reviewing 14 researches on urban microclimates and thermal comfort (2001-2017) (Authors).

Metabolic Rate	Clothing	Building height
1.2 met	0.9 Clo	180 m

specific humidity, and the number of gaseous pollutants and suspended particles at a height of 2 meters. The calculation time for this simulation model is 3 pm on July 22nd, 2018. The atmospheric input data are extracted from the nearest airborne station in Maslak district. The basic data and initial inputs can be found in figure 6.

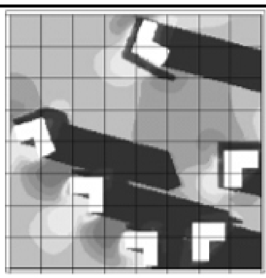
Also, Table 3 shows the clothing information, physiological and physical characteristics used to simulate in the software.

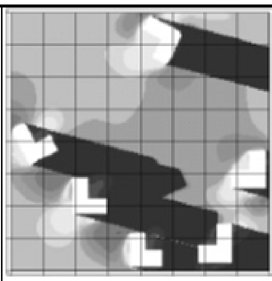
4. Analysis results

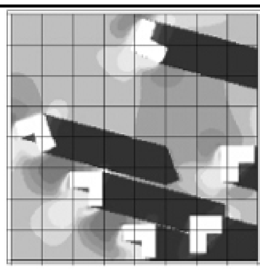
To assess the thermal comfort variations in different alternative morphologies, the indexes of Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD) have been calculated, and the indexes have been simulated for all alternatives with the Envi-met. The first alternative simulation shows the existing situation and alternative 2 and 3 demonstrates the effects of orientation and vegetation, respectively. Figure 7 depicts the PMV index simulation for these three alternatives, moving from the darker shades to the lighter ones, the thermal comfort becomes closer to the ideal condition.

The results indicate that the minimum and maximum of the PMV in alternative 1 are -0.38 and 1.56, respectively. These values are also estimated for alternative 2; -0.36 and 1.59, and for alternative 3; -0.37 and 1.55, respectively. It is clear that the purpose of this study is to assess the changes in outdoor thermal comfort in the high-rise urban complexes. The criterion of assessments should be the rate of changes in the indexes for the outdoor condition of the site's center. As a result, according to the above outputs, the average PMV index for all three alternatives can be seen in Table 4.

The maximum value of PMV is 1.59 and belongs to Alternative 2, which is less favorable in terms of thermal comfort compared to other alternatives. Through examining the building





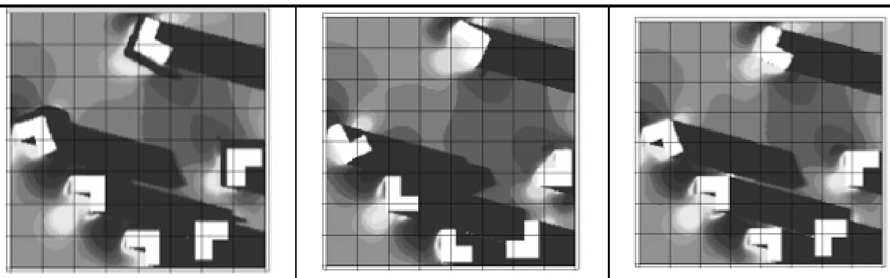


Alternative 3	Alternative 2	Alternative 1 (extant)
Min:-0.37 Max:1.55	Min:-0.36 Max:1.59	Min:-0.38 Max:1.56

Figure 7. *The results of simulated Predicted Mean Vote (PMV) in the three research's alternatives.*

Table 4. *Basic information of input variables for simulation (Authors, 2018).*

Alternatives	Average PMV in the middle of the open spaces	PMV min	PMV max
Alternative 1 (extant)	-2.56	-0.38	1.56
Alternative 2	-2.51	-0.36	1.59
Alternative 3	-1.84	-0.37	1.55



Alternative3	Alternative 2	Alternative 1 (extant)
Min:5% Max:53.83%	Min:5% Max:55.59%	Min:5% Max:54.09%

Figure 8. *Results of predicted percentage of dissatisfied (PPD) simulation in the three research's alternatives (Authors, 2018).*

Table 5. *The average PMV index for the three research's alternatives (Authors, 2018).*

Alternatives	Average PPD in the middle of the open spaces	PPD min	PPD max
Alternative 1 (extant)	83.1%	5%	54.09%
Alternative 2	81.7%	5%	55.59%
Alternative 3	72.4%	5%	53.83%

locations in the site for all three alternatives, it can be seen that the differences in buildings orientation in relation to each other result in having the lowest thermal comfort in Alternative 2. The lowest minimum is for the existing layout (-0.38). Having the highest average value in alternative 3 (-1.84) comparing to existing situation (alternative 1) proves the importance of vegetation in improving thermal comfort perception.

In Figure 8, the outputs of the PPD index simulation are shown for three design alternatives. Changing from the lighter shades to darker represents an increase in the amount of dissatisfaction predicted by the residents, consequently away from the ideal thermal comfort.

The simulation shows that the maximum of PPD index has been estimated at 54.09% for alternative 1, 55.59% for alternative 2, and 53.83% for alternative 3. The maximum PPD value for alternative two is more than the other alternatives that predict the highest percentage of thermal dissatisfaction for this alternative. Therefore, by simulating both indicators for all alternatives, it can be found that alternative 2 has the lowest degree of thermal comfort. In contrast, alternative 3 with vegetation on the building complex has the lowest percentage, which demonstrates the better thermal comfort in PPD index simulation (Table 5).

Simulating PMV and PPD indexes, the closer the PMV value to zero, and the lower the PPD percentage, the better thermal comfort. Therefore, by comparing the PPD and PMV values in all three alternatives, it can be deduced that the third alternative is the most optimal proposal among the other study alternatives, with the average PMV and the average PPD, -1.84 and 72.4%, respectively. Conversely, in alternative 2, the highest percentage of PPD and the least value of PMV results in not being the optimal design alternative compared to others. As can be seen from the analysis, the differences between outputs are not very remarkable. However, on the larger scale of an urban area, it can show a significant result, eventually. Therefore, it is critical to consider building orientation in plans before construction in order to provide better outdoor thermal comfort in urban complexes.

Obviously, relocating the building projects that have been already implemented is impracticable; nonetheless, for the future designs, the optimal building location should be identified and put into practice. Moreover, for the current built projects, other solutions such as adding vegetation to the building facades could affect the thermal comfort positively.

5. Conclusion

3D simulation of the PMV and PPD indexes in alternative 3 shows that this alternative provides the most optimal condition in terms of thermal comfort than other alternatives. Moreover, alternative 2 (changing the blocks' orientation) has the lowest thermal comfort compared to the others. Clearly, in addition to these alternatives, there are various types of design options, yet the purpose of this study is to prove that the way of placing the buildings in the site without relocating and merely by rotating them, would affect the thermal comfort. Furthermore, it proves the effect of vegetation on improving thermal comfort.

The data analysis shows that the PMV / PPD space model can predict the thermal comfort in different urban design patterns. In some ways, it can be admitted that the values of PMV / PPD indexes change by the morphology of urban buildings. Changes in building morphology, especially high-rises, alter the sky view factor, and also the microclimate parameters, which will eventually affect the outdoor thermal comfort. On the other hand, rapid population growth, urbanization, and industrialization of the cities have a significant changing role in some meteorological quantities. Since there is a strong relationship between urban morphology and sky view factor, variations in sky view factor will change the air temperature inside the city. As a result, changing the urban buildings form and urban morphology will alter the parameters affecting thermal comfort and other environmental factors, as well as the formation of the urban heat islands.

Consequently, the plan, shape, and morphology of the urban buildings, should be considered in development plans, based on different climate conditions. As well as considering the building regulations' clause of urban development projects, such as a detailed urban plan, with emphasis on improving the human thermal comfort. In order to achieve sustainable development, designers, architects, and urban planners should contemplate the above considerations.

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