Journal of Urban Management and Energy Sustainability (JUMES)

Homepage: http://www.ijumes.com

ORIGINAL RESEARCH PAPER

Improving the urban heat island (UHI) phenomenon by converting the simulated urban space into a linear model

Amir Masoud Salehi*, Hamed Naeemayi

Department of Engineering, Construction Engineering and Management, Civil Engineering, Kharazmi University, Tehran, Iran.

ARTICLE INFO

Article History:
Received 2021-06-28
Revised 2021-09-30
Accepted 2021-11-23

Keywords:
Artificial lakes
Building height
Urban heat island
Experimental design
Green space
Linear model

DOI: 10.22034/JUMES.2021.556727.1078

ABSTRACT

The urban heat island (UHI) is one of the most important phenomena related to urbanization, which indicates an increase in temperature of urban areas compared to the surrounding rural environment. The main goal of this study is a process for urban designing in order to improve air quality (in terms of temperature). To develop the proposed process, three factors affecting the temperature of urban areas including the area of green space, the area of artificial lakes and the ratio of building height to street width (H/W) in a region of Tehran city were examined. Then, instead of performing multiple simulations, a process was developed to convert the simulation space into a mathematical model. Thus, by using Taguchi method (a method of experiment design), targeted scenarios were designed and by resulting temperature from Envi simulation software, the average values of ambient temperature were determined. Based on the obtained results, in the area investigated in this research, the optimal levels of factors, plants and artificial lake area ratio and H/W equal to 0.22, 0.4 and 0.5 respectively.

Running Title: Improving UHI by converting the simulated urban space into a linear model

NUMBER OF REFERENCES
23

NUMBER OF FIGURES
6

NUMBER OF TABLES
3

*Corresponding Author:
Email: *am_salehi@khu.ac.ir*
Phone: +98-21-88329220
ORCID: https://orcid.org/0000-0003-2991-4044

1. Introduction

The development process over the past 50 years has had many positive and negative effects on urban communities around the world. One of the significant concerns is the continuous increase of urban temperature as an urban heat island (Tran et al., 2006). Urban Heat Islands (UHI) are the experience of higher temperatures than outlying areas in urbanized areas. This phenomenon is, like an umbrella of air that the temperature inside of it, is warmer than the air around of it (Tan et al., 2010).

The UHI phenomenon occurs when a large percentage of natural surface cover disappears and is replaced by buildings, roads, and other facilities (Susca et al., 2011; Tan et al., 2010; Unger, 2004). Variety of urban and building occupancy and impermeable surfaces cause more absorption of solar energy in the city and UHI intensify with the increase in the population density ratio per unit area (Magee et al., 1999). In addition, the heat emitted from homes and car fuels also affects the city's climate change. In general, thermal islands act as a barrier to the passage of air flow and increase the concentration of pollutants (Tran et al., 2006; Unger, 2004).

UHI directly and indirectly affects various human factors such as mental turmoil and increased stress, and socio-economic factors such as reduced water quality and increased energy consumption (Guhathakurta and Gober, 2007; Kim and Baik, 2005; Rosenzweig et al., 2005). Clean air, clean water, less noise and more vegetation in cities areas represent the most important objectives goal in the development of cities (Liu and Zhang, 2011). Cities are at risk from industrial hazards, natural disasters, and global warming (Imhoff et al., 2010; Kleerekoper et al., 2012). The negative effects of global warming include increased flooding, drought, and the destruction of some ecosystems (Kusaka and Kimura, 2004; Tan et al., 2010).

Many UHI with different dimensions and extent have been seen in most urban areas of the world. Heat islands are usually not formed during rainy and stormy nights. Also, winds with speeds of more than 25 km/h can eliminate the effect of thermal islands (Streutker, 2003).

Implementation of urban green infrastructure (GI) programs will increase urban sustainability and reduce urban temperature. Quantitative indicators of GI are green space networks, including natural areas such as waterways and forests, and built-up areas such as local parks and gardens. Examples of Green Engineered infrastructure include green roofs, porous pavements, rainforests and rain tanks. These are the types of green infrastructure that are most associated with GI applications (Alshuhail and Taleb, 2020).

The most important factors influencing the creation of urban heat islands can be air pollution, the ratio of building height to street width, the area and type of vegetation and materials used in buildings etc. (Mirzaei and Haghighat, 2010; Nuruzzaman, 2015).

Today, one of the biggest challenges for engineers is how to reduce the harmful effects of this phenomenon in sustainable cities. Large-scale thermal islands are more concerned with urban planning, but on a smaller scale, there are principles and rules that can be effective in controlling them. Green space is one of the parameters that influence the reduction of ambient temperature and humidity, and as a result, reduce the effects of UHI (Corburn, 2009; Weng, 2003).

In hot and dry areas, it is very important to evaluate and determine the best direction of buildings. In a study by Alshuhail and Taleb (2020), the thermal performance of buildings in the UAE was investigated. In order to assess the thermal comfort of buildings in the city of Sharjah, a sample laboratory-scale house was built to the north as well as to the south direction. The required information in the building was recorded using an infrared camera, thermograph from all directions and the average temperature over 5 months. The results show that the building temperature in the south direction is 9.4% higher than the north direction. Also, the building in the south direction has 3% more moisture than the building in the north direction.

One of the most important ways to improve the quality of urban climate is to use green roofs and good insulation for it. In a study by Kazemi and Courard (2021), green roofs with pozzolans materials were modeled as a drainage layer and in winter and summer climates, humidity and temperature changes were evaluated in the depth of the systems. The results of this study show that pozzolans are effective in maintaining the quantity of moisture and temperature of the building in winter and summer.

The results of a study by Litardo et al. (2020) show that the UHI intensity is zero or negative at noon and increases in the afternoon and evening; early in the morning, the effect of thermal inertia is maximized when combined with the heat released from traffic. Aboelata and Sodoud (2019) examined the effect of vegetation on the island of urban heat in a dense part of Cairo. Wang and Akbari (2016) also studied the phenomenon of urban heat in Montreal, Canada. The focus of this study was on the type, size and space between the trees. Finally, it was found that the size of the tree canopy is directly related to the shade level and the amount of transpiration, and can affect the temperature in this way.

Alavipanah et al. (2018) in addition to the effect of vegetation on the temperature of Yazd, have considered the role of urban geometry height, street width, volume and lateral area of buildings and the effects of shade. After the analysis conducted in this study, the role of three-dimensional indices was recognized as more important than two-dimensional indices.

Based on the research, each of the known effective parameters can have a different effect in the desired area. Therefore, in this research, a process has been developed to optimize urban design in reducing heat island effects. Once, three factors were selected from the urban index that have the greatest impact on environmental conditions. Since determining the simultaneous effect of three parameters requires multiple simulations that lead to spending a lot of time and cost, a linear model was created based on the simulation results, which can be used to design the factors and urban design.

2. Materials and Methods

To study the effect of urban environmental factors on air temperature in this study, Landsat 8 satellite data, prepared from a joint database of NASA and the United States Geological Survey, was used to calculate and extract the baseline data. Landsat 8 satellite data is available at 30 m and 15 m resolution levels. The image used in this research was taken from the earth in May 2019 and atmospheric and thermal corrections were applied to it.

Urban environment simulation and temperature analysis of this research has been done by using Envi software and using tools to convert the simulation into a linear model.

2.1. Study area

The study area considered in this study is a region in Tehran. The capital of Iran has an area of 751 km^2 and a population density of 12,200 people per km^2 and geographical coordinates of 51.4 east longitude and 35.7 north latitude. The case study that has shown in Figure 1, is a region in Tehran municipal district of 11 and 12 with an area of 90,000 m^2.

2.2. Input data

Maps

Based on preliminary research, three important factors affecting thermal island including vegetation, water areas and urban geometry were considered. Landsat-8 images were taken from earthexplorer.usgs.gov to determine the effect of factors on temperature of urban areas and modifying them to achieve greater temperature comfort. To simulate the urban space based on the images of the study area by using Envi 5.3 software, first the radius of the thermal band and its correction was done.

To investigate the effect of selected factors on global warming, shape files of a case study with the desired layers were used. These shape files were first processed by ArcGis10.5 and then filtered by the relevant tables. Then, the corrected shape file was matched with the Landsat file in Envi software. The surface temperature in the Envi software extracted the output file of the thermal temperature of different regions. Thus, the desired output, which is land surface temperature (LST), was taken from Envi software (Figure 2).

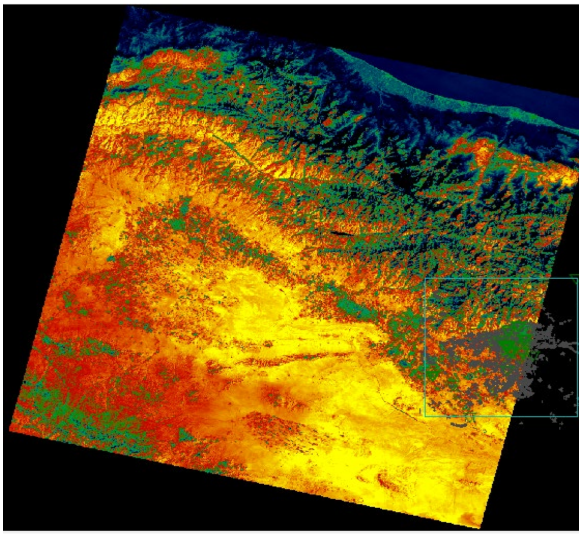
2.3. Ambient temperature data

Since the temperature varies at different days of the year, in this study, two days were selected as a sample for research development. As samples

(a)

(b)

Fig. 1: The study area map; a) Tehran city; b) A region of city for case study in 11 and 12 Tehran municipal district (map from Google map)


(a)

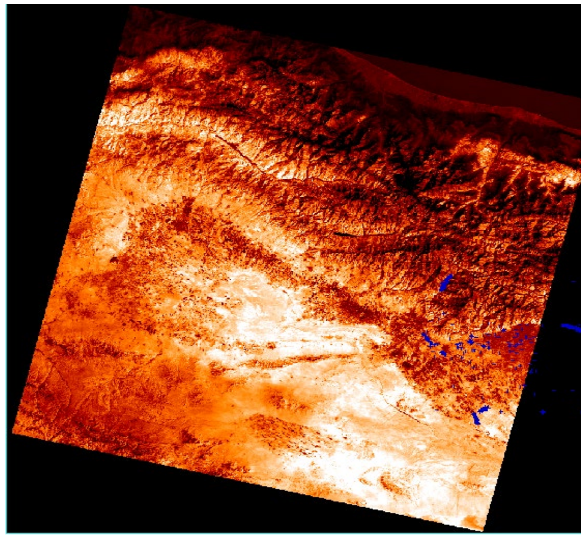

(b)

Fig. 2: Execute scenarios in Envi software space

of hot and cold days of the year, two days, June and January 1st, were considered and numerical data of these days were extracted. The meteorological data was taken from www.wunderground.com The weather conditions of the days are given in Table 1. These data have been studied from 07:00 PM to 19:00 AM.

2.4. Modeling

One of the objectives of the present study is to develop a linear model based on information obtained from the simulation (from Envi software) according to dependent variables. The dependent variable is considered to be the temperature of the urban environment and three independent variables including the ratio of the area of plants to the area of the region, the ratio of the water and lakes area to the area of the region and the ratio of building height to street width.

2.5. Experimental design

By using experimental design (DOE) the effect of factors affecting the process can be expressed in the form of an equation. Experimental design can be defined as "making purposeful changes in characteristics and influencing factors to observe changes in output or response characteristics." Applying this technique will improve the process of designing and producing for existing or new products.

One of the most widely used and important methods of designing experiments is full and partial factorial design. Based on the full factorial design, all possible scenarios are examined and therefore in most cases it is not justifiable in terms of cost and time. In partial factorial and Taguchi methods, orthogonal arrays reduce the number of scenarios required and can provide a suitable relationship with a suitable approximation by performing finite scenarios (or experiments). In this study, by using Taguchi method with Minitab software, a linear model is developed.

At least two levels must be studied to obtain the effect of each factor, and at least three levels must be considered based on the orthogonal array. In this study, three factors have been investigated at three levels (Table 2). Therefore, the total number of compounds for model development is the implementation of 3 (number of factors) to the power of 3 (number of levels), i.e. 27 simulations. By using the Taguchi method, instead of performing 27 simulations based on the complete factorial simulation method, it has been reduced to 9 scenarios.

Table 1: Climatic characteristics of the selected days

Day	Temperature (C)			relative humidity (%)		wind speed (mph)
	Average	Max temp.	Min temp.	Max	Min	
1 June	23.8	28.8	16.6	55	17	7
1 January	4.9	10	2.7	60	3	14

Table 2: Factors examined and their levels

Factors (independent variables)	Level 1	Level 2	Level 3
The ratio of the area of plants to the area of the region	0.12	0.22	0.36
the ratio of the water and lakes area to the area of region	0.1	0.2	0.4
the ratio of building height to street width	0.5	1	2

Table 3: Scenarios from Taguchi experimental design and simulation results in ENVI

Scenario	Ratio			Temperature (C)	
	Plants	Artificial lake	H/W	June	January
1	0.12	0.1	0.5	28.132	6.953
2	0.12	0.2	1	27.853	6.946
3	0.12	0.4	2	27.521	6.938
4	0.22	0.1	1	27.502	6.937
5	0.22	0.2	2	28.146	7.001
6	0.22	0.4	0.5	27.769	6.998
7	0.36	0.1	2	27.811	6.951
8	0.36	0.2	0.5	27.495	6.936
9	0.36	0.4	1	28.136	6.959

3. Results and Discussion

3.1. Scenarios

In order to achieve the effect of factors in changing the ambient temperature caused by the urban environment, three factors, including the ratio of trees, the ratio of artificial lakes and the ratio of height of buildings to the width of street, were determined by using Taguchi method (DOE method). Table 3 shows the variables and levels of factors. This table also shows the results obtained from the simulated scenarios and results of temperature in two different days of year.

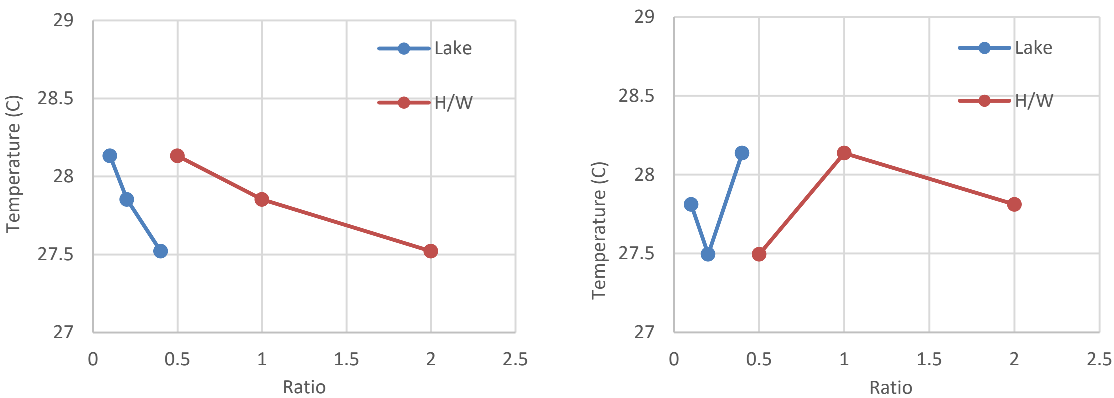
The results obtained from 9 scenarios show that the temperature changes due to urban design within the considered levels are significant. The average temperature measured at the meteorological station in June is 23.8C, which according to the results, the urban environment changes the temperature from 23.49 to 28.15 Celsius. In January, the temperature of the meteorological station is 4.9C, which the environment of Tehran city causes the temperature to increase to 6.9 to 7C.

According to the obtained results, different environmental conditions in the city in the hot season have caused an average temperature of 27.82 C with a variance of 0.067 C. These values in the cold season of the year have caused the average and standard deviation of 6.96 and 0.0005 C respectively. These results show that the heat island is more effective in hot weather than cold weather.

The values of covariance and correlation coefficient between temperature changes in 9 scenarios in June and January are 0.0037 and 0.55, respectively. Therefore, it can be concluded that urban geometry in cold weather and hot weather do not have the same effect on the heat island.

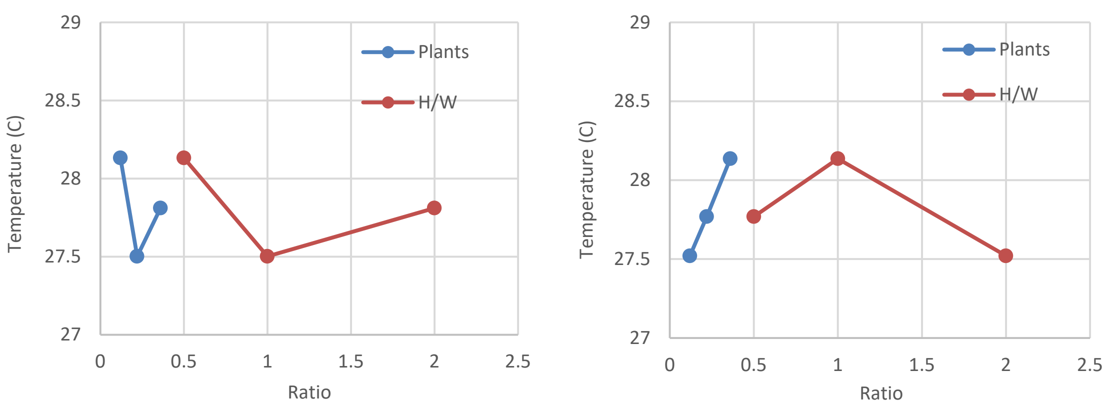
Another investigation is related to the effect of independent variables on temperature in the same conditions. In Figure 3, it shows the change of ambient temperature in plant ratio of 0.12 (Figure 3-a) and 0.22 (Figure 3-b). According to fig. 3-a, in plant ratio of 0.12, the effect of building height on the width of the street is more than the area of artificial lakes. However, in the plant ratio of 0.22, the effect of the area of the artificial lake does not have the same trend and in the value of 0.2, it causes the greatest decrease in temperature. Also in this case, height to width ratio of 0.5 is optimal.

Figure 4 shows the effect of the amount of plants and the ratio of building height to street width in constant ratio of artificial lake. In the artificial lake area ratio of 0.1 (Figure 4-A), the area ratio of plants and the height ratio do not have a uniform effect, and the optimal value in the ratio of plants is 0.22 and the height ratio is 1. The results are different in the artificial lake area ratio of 0.4 (Figure 4-b) and increasing the plant area increases the temperature. In this case, the optimal temperature value is obtained at a height ratio of 1.



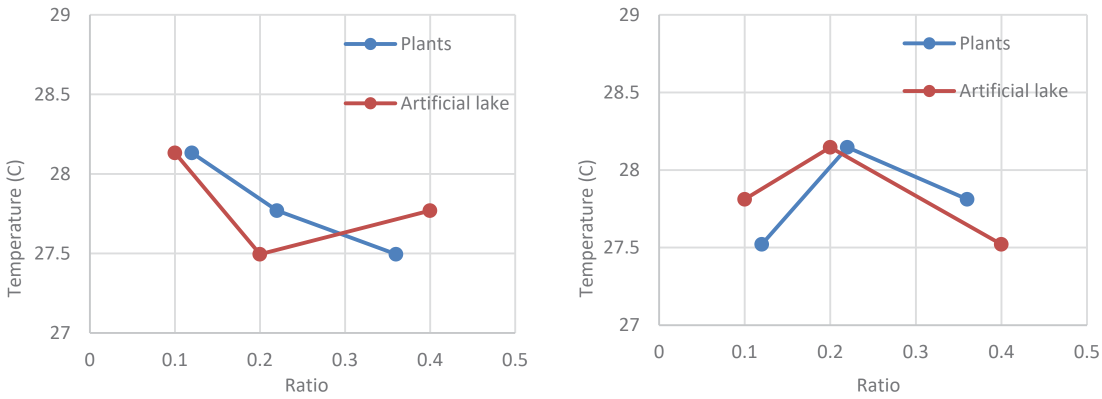
(a) (b)

Fig. 3: The area of the artificial lake and the ratio of the height of the buildings to the width of the street (H/W) in constant area of the plant a) 0.12; b) 0.22



(a) (b)

Fig. 4: The area of the plants and the ratio of the height of the buildings to the width of the street (H/W) in constant area of artificial lake a) 0.1; b) 0.4



(a) (b)

Fig. 5: The area of the plants and artificial lake in constant ratio of the height of the buildings to the width of the street (H/W) a) 0.5; b) 2

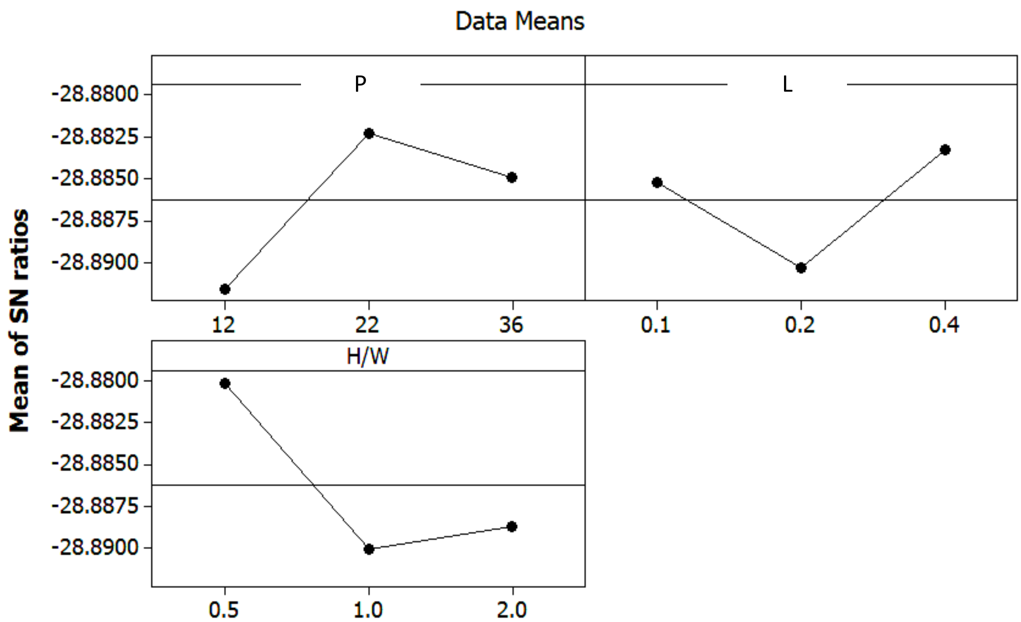


Fig. 6: Effect of independent factors on ambient temperature using signal-to-noise analysis

Figure 5 shows the effect of plants and artificial lake area in the constant ratio of the height of the building to the width of street. At the lowest height ratio (Figure 5-a), the effect of the plant area is uniform, and increasing the ratio causes a decrease in temperature. But in this case, the maximum temperature reduction is obtained in the artificial lake area ratio of 0.2. In the highest height ratio (2) which is shown in Figure 5-b, the effect of both parameters (plant and artificial lake area) is not uniform and the maximum temperature decrease occurs in plant ratio of 0.12 and lake ratio of 0.4.

3.2. Linear Model

The effect of each factor that considered in the present study, including the ratio of plants, the ratio of artificial lakes and the ratio of building height to street width on temperature and thermal island is almost predictable.

But the combined effect of all three factors is complex. Therefore, based on the results of 9 scenarios designed based on Taguchi (DOE), the linear model of temperature to three factors has been developed. This relationship helps to understand the effectiveness of each factor in the hot and cold days of the year. Equation 1 is a linear model based on January 1 temperature data and Equation 2 is developed based on June 1 temperature data:

$$T_{cold} = -0.002.P + 0.0543.L + 0.0029H / W + 6.94 \quad (1)$$

$$T_{warm} = -0.08.P + 0.034.L + 0.015H / W + 27.8 \quad (2)$$

P: ratio of plants to region area
L: ratio of artificial lakes to region area
H/W: ratio of building height to street width

3.3. Influencing factors

In order to compare the results and achieve the optimal combination of independent variables, the analysis was performed based on signal-to-noise method. Figure 6 is the output of the Minitab software, which shows the effect of changes in factor levels on the dependent variable. Based on the obtained results, the optimal levels of factors (maximum values of graphs) obtained from 9 experiments designed as P = 0.22, L= 0.4 and *H/W* = 0.5. As can be seen in Figure 6, the urban geometry factor (*H/W*) has the greatest impact among the factors.

4. Conclusion

Because of the large number of influencing factors, optimizing the urban design in order to improve the temperature and air quality and reduce the conditions for creating heat islands is complicated and difficult.

One of the best ways to urban design (for improving thermal comfort) is using urban environment simulation software. However, the multiplicity of effective factors causes numerous simulations to be performed to optimize and achieve the desired air quality and temperature.

A good way to target the optimization process and speed up the achievement of the desired solution is to develop a mathematical model of the simulation space.

In this research, first, a region with 90000 m^2 in Tehran city was simulated in Envi software. Then by considering three factors including the amount of green space, the area of the artificial lake and the ratio of building height to street width and change of their value, the amount of ambient temperature was determined.

In order to optimize to achieve the minimum ambient temperature of city, a linear model of simulated region developed by using of the experimental design (Taguchi method). This model can be easily used for various applications such as optimizing ambient temperature and then applying optimal values in the simulation environment.

The results of this research show that in low areas of green space, changing the height of buildings has a greater effect on reducing the ambient temperature. But increasing the area of green space has changed the effect of both parameters (artificial lake and H/W) and the optimal value is in the middle value.

The area of artificial lakes affects the effect of plants area and H/W ratio on the ambient temperature. In the upper area of the artificial lake, increasing the area of green space increases the temperature of the environment.

Also, the ratio of H/W has a considerable effect on the effect of the plants and artificial lakes area. In a low ratio, increasing the area of plants causes a decrease in temperature, and the optimal value of artificial lake area is the middle value.

To improve the evaluation and design, other statistical methods can be used for experimental design, as well as non-linear models and optimization methods. Also, by combining GIS software and building information modeling, temperature changes and energy consumption analyzes can be performed more accurately.

References

Aboelata, A., and Sodoudi, S. (2019). Evaluating urban vegetation scenarios to mitigate urban heat island and reduce buildings' energy in dense built-up areas in Cairo. Building and environment, 166, 106407. https://doi.org/10.1016/j.buildenv.2019.106407

Alavipanah, S., Schreyer, J., Haase, D., Lakes, T., and Qureshi, S. (2018). The effect of multi-dimensional indicators on urban thermal conditions. Journal of cleaner production, 177, 115-123. https://doi.org/10.1016/j.jclepro.2017.12.187
Alshuhail, K., and Taleb, H. (2020). Thermal performance and experimental assessment of building orientations in the United Arab Emirates (UAE). Science and Technology for the Built Environment, 26(10), 1461-1489. https://doi.org/10.1080/23744731.2020.1735261
Corburn, J. (2009). Cities, climate change and urban heat island mitigation: Localising global environmental science. Urban studies, 46(2), 413-427. https://doi.org/10.1177/0042098008099361
Guhathakurta, S., and Gober, P. (2007). The impact of the Phoenix urban heat island on residential water use. Journal of the American Planning Association, 73(3), 317-329. https://doi.org/10.1080/01944360708977980
Imhoff, M. L., Zhang, P., Wolfe, R. E., and Bounoua, L. (2010). Remote sensing of the urban heat island effect across biomes in the continental USA. Remote Sensing of Environment, 114(3), 504-513. https://doi.org/10.1016/j.rse.2009.10.008
Kazemi, M., and Courard, L. (2021). Simulation of humidity and temperature distribution in green roof with pozzolana as drainage layer: Influence of outdoor seasonal weather conditions and internal ceiling temperature. Science and Technology for the Built Environment, 27(4), 509-523. https://doi.org/10.1080/23744731.2021.1873658
Kim, Y.-H., and Baik, J.-J. (2005). Spatial and temporal structure of the urban heat island in Seoul. Journal of Applied Meteorology and Climatology, 44(5), 591-605. https://doi.org/10.1175/JAM2226.1
Kleerekoper, L., Van Esch, M., and Salcedo, T. B. (2012). How to make a city climate-proof, addressing the urban heat island effect. Resources, Conservation and Recycling, 64, 30-38. https://doi.org/10.1016/j.resconrec.2011.06.004
Kusaka, H., and Kimura, F. (2004). Coupling a single-layer urban canopy model with a simple atmospheric model: Impact on urban heat island simulation for an idealized case. Journal of the Meteorological Society of Japan. Ser. II, 82(1), 67-80. https://doi.org/10.2151/jmsj.82.67
Litardo, J., Palme, M., Borbor-Córdova, M., Caiza, R., Macías, J., Hidalgo-León, R., and Soriano, G. (2020). Urban Heat Island intensity and buildings' energy needs in Duran, Ecuador: Simulation studies and proposal of mitigation strategies. Sustainable cities and society, 62, 102387. https://doi.org/10.1016/j.scs.2020.102387
Liu, L., and Zhang, Y. (2011). Urban heat island analysis using the Landsat TM data and ASTER data: A case study in Hong Kong. Remote sensing, 3(7), 1535-1552. https://doi.org/10.3390/rs3071535
Magee, N., Curtis, J., and Wendler, G. (1999). The urban heat island effect at Fairbanks, Alaska. Theoretical and applied climatology, 64(1), 39-47. https://doi.org/10.1007/s007040050109
Mirzaei, P. A., and Haghighat, F. (2010). Approaches to study urban heat island-abilities and limitations. Building and environment, 45(10), 2192-2201. https://doi.org/10.1016/j.buildenv.2010.04.001
Nuruzzaman, M. (2015). Urban heat island: causes, effects and mitigation measures-a review. International Journal of Environmental Monitoring and Analysis, 3(2), 67-73. https://doi.org/10.11648/j.ijema.20150302.15
Rosenzweig, C., Solecki, W. D., Parshall, L., Chopping, M., Pope, G., and Goldberg, R. (2005). Characterizing the urban heat island in current and future climates in New Jersey. Global Environmental Change Part B: Environmental Hazards, 6(1), 51-62. https://doi.org/10.1016/j.hazards.2004.12.001
Streutker, D. R. (2003). Satellite-measured growth of the urban heat island of Houston, Texas. Remote Sensing of Environment, 85(3), 282-289. https://doi.org/10.1016/S0034-4257(03)00007-5
Susca, T., Gaffin, S. R., and Dell'Osso, G. (2011). Positive effects of vegetation: Urban heat island and green roofs. Environmental pollution, 159(8-9), 2119-2126. https://doi.org/10.1016/j.envpol.2011.03.007
Tan, J., Zheng, Y., Tang, X., Guo, C., Li, L., Song, G., Zhen, X., Yuan, D., Kalkstein, A. J., and Li, F. (2010). The urban heat island and its impact on heat waves and human health in Shanghai. International journal of biometeorology, 54(1), 75-84. https://doi.org/10.1007/s00484-009-0256-x
Tran, H., Uchihama, D., Ochi, S., and Yasuoka, Y. (2006). Assessment with satellite data of the urban heat island effects in Asian mega cities. International journal of applied Earth observation and Geoinformation, 8(1), 34-48. https://doi.org/10.1016/j.jag.2005.05.003
Unger, J. (2004). Intra-urban relationship between surface geometry and urban heat island: review and new approach. Climate research, 27(3), 253-264. https://doi.org/10.3354/cr027253
Wang, Y., and Akbari, H. (2016). The effects of street tree planting on Urban Heat Island mitigation in Montreal. Sustainable cities and society, 27, 122-128. https://doi.org/10.1016/j.scs.2016.04.013
Weng, Q. (2003). Fractal analysis of satellite-detected urban heat island effect. Photogrammetric engineering and remote sensing, 69(5), 555-566. https://doi.org/10.14358/PERS.69.5.555

HOW TO CITE THIS ARTICLE

Salehi, AM.; Naeemayi, H. (2021). Improving the urban heat island (UHI) phenomenon by converting the simulated urban space into a linear model. J Urban Manage Energy Sustainability, 3(1): 13-22.

DOI: 10.22034/JUMES.2021.556727.1078