

Assessment of the impact of spatial development changes on thermal comfort experienced by man in the external environment

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Abstract. Progressive urbanization has a direct influence on both the local and consequently global climate. The spatial development methods of the area require the use of modern computer technologies that support planning decisions by key decision makers. Evaluation of the prevailing microclimate conditions in the external environment is possible using CFD software. In this paper were presented scenarios of the impact of changes in spatial development of the area covered by revitalization process in the most urbanized zone of Lodz. The changes proposed by the authors included two types of simulation input data, i.e. values determined for a typical meteorological year and values of meteorological parameters from the nearest measuring station – Lodz-Lublinek. PMV index enabled to evaluate the thermal comfort of human in an external environment. Conducted research has shown that the more effective solutions were scenarios based on a growth of the green area rather than introduction of water elements within the analyzed public space.

1. Introduction

Dynamically progressing urbanization process contributes to disadvantageous changes in spatial development. The creation of new buildings, increase in land cover with impermeable materials and decrease in the share of green areas result in emergence of urban heat island phenomenon in urban areas. As a result, there is an increase in energy consumption necessary to cool buildings, water is used to lower the temperature in external environment (e.g. in a form of water curtains), air quality deteriorates, thermal discomfort is created, as well as morbidity and mortality caused by thermal stress are increased [1].

One of possibilities to limit the negative effects of phenomena caused by transformations of the spatial development method is to undertake mitigation actions. The collection of mitigation strategies was published by the Environmental Protection Agency (EPA) in 2008. The compendium describes, among others the use of traditional and vertical forms of vegetation. High greenery enables to reduce the amount of sunlight reaching the earth's surface (70-90%). It provides a shadow and contributes to reduce the air temperature in the vicinity of trees. It also modifies the airflow in cities. Green roofs and walls, limiting the amount of radiation reaching the surface of building partitions, are responsible for temperature reduction inside the buildings. By capturing rainwater, they contribute to the increase of relative air humidity. The next steps concern the use of building materials characterized by high albedo values, absorbing less heat during the daytime and reflecting a significant amount of solar radiation back



into the atmosphere [2]. However, these are only selected mitigation strategies. According to empirical research, the introduction of water elements into the environment causes modification of microclimatic parameters. This is confirmed by research carried out by Chatzidimitriou and Bruse. The use of water elements in a form of fountains and water curtains reduces the air temperature [3]. According to Barakat et al., water resources cause a cooling effect (they modify the value of temperature and relative humidity) [4]. Tests performed by Chan et al. confirm that the presence of water surfaces increases the acceptance of prevailing microclimatic conditions in the external environment [5].

The authors took into account only the summer period due to the fact that the highest temperature values occur during this period (overheating conditions), and thus the most uncomfortable conditions prevailing in the external environment. In addition, it was associated with the highest intensity of use of public spaces in the city. Nine scenarios of the impact of changes in spatial development on perceived thermal comfort were considered in this work. They concerned transformations of selected public space in terms of vegetation and water elements. Simulations were conducted using the Envi-met program. The input parameters of models were data of Typical Meteorological Year obtained from databases of the European Commission and information obtained from the Lodz-Lublinek meteorological station. Finally, the assessment of thermal comfort was carried out by comparing the values of thermal comfort index – PMV determined for individual scenarios with its value for the baseline scenario (determined on the basis of current state of spatial development of the area).

2. Area of research

One of the oldest public spaces in the city, located in so-called Greater City Zone of Lodz, has been selected as a research area. This area – The Old Market was indicated as a priority area for the revitalization process. Multi-family residential building is the dominant type of development. The objects constituting the frontage of square have been entered into the municipal register of monuments in Lodz. As a result, the potential change in land development related to the geometry of objects has been significantly hampered. All transformations require arrangements with the monument conservator, urban planners and municipal officials. However, modifications within the public space may occur by changing the surface types, introduction of additional plantings and water elements.

3. Thermal comfort

Thermal comfort is defined as a state of mind expressing satisfaction from the thermal environment (ASHRAE 55) [6]. It is dependent on physical condition of the man, resulting from the pace of metabolism, clothing and physical activity. What is more, it is felt in a subjective way. Its assessment is related to psychological factors, i.e. expectations, experiences, acceptance of external conditions, mobility and thermal adaptation by changing the exposure to microclimate parameters [7].

Thermal conditions can be estimated using the Predicted Mean Vote (PMV) index, which is the average rating of a group of people who determine their thermal impressions. At first, it was used to determine indoor conditions. Modification of the Fanger's thermal balance equation by Jendritzky and Nubler enabled to use it in external environment research. The PMV index can be calculated for any combination of metabolism, clothing, air temperature, average temperature radiation, air-flow velocity and humidity. The evaluation of thermal sensations is carried out on a seven-stage scale from [-3] to [+3]. The conditions described as comfortable are for the range [-0.5, +0.5] [8].

The PMV index is commonly used in studies of highly urbanized areas, including public spaces. This fact is confirmed by the research of Coisson et al. (assessment of thermal comfort in urban areas in Italy), Djekic et al. (assessment of thermal comfort in public spaces – Serbia), Wang et al. (assessment of thermal comfort depending on spatial development method – Netherlands).

4. Simulation of thermal comfort

The assessment of thermal comfort was conducted with the use of CFD type software, i.e. Envi-met program. This tool enables creation of three-dimensional, non-hydrostatic microclimatic models for urbanized areas. Simulations of meteorological parameters take into account the air-flows between

buildings, processes of vertical and horizontal heat exchange of surfaces, turbulence, transpiration, vegetation parameters, as well as dispersion of pollutants [9]. The program enables to carry out simulate of the relation between substrate – vegetation – air in the twenty-four hour cycle (from 24 to 48 hours) [10-11]. In order to estimate meteorological parameters, it is necessary to define the initial conditions in the external environment. One way to determine them is to adopt data of Typical Meteorological Year. Finally, there is an option to calculate the basic thermal comfort indicators, i.e. PMV (Predicted Mean Vote), PET (Physiological Equivalent Temperature) and UTCI (Universal Thermal Climate Index) [12-13].

In work, the assessment of thermal comfort was conducted for the warmest day of Typical Meteorological Year, determined on the basis of data from a 10-year period (from 2006 to 2015). In order to estimate the PMV index, it was necessary to determine the individual characteristics of the man, his clothing and type of performed physical activity. The thermal comfort was estimated for a 35-year-old man with a height of 1.75 m and weight of 75 kg, with a clothing insulation of 0.50 clo [14]. The authors considered two cases, i.e. for a person not performing physical activity and moving at a speed of 1.21 m/s (average speed of the man's movement – walk). In the latter case it should be expected that PMV values will be lower due to the formula of the index.

5. Typical meteorological year

Over the past decades, methods have been developed to determine average meteorological conditions. The most commonly used are: Weather Year for Energy Calculation (WYEC2) developed for ASHRAE by Watson Simulation Laboratory, Typical Meteorological Year (TMY2) updated by the National Renewable Energy Laboratory, the Canadian Weather for Energy Calculation (CWEC) established by the WATSUN Simulation Laboratory and the Test Reference Year (TRY) proposed by the Technical University of Denmark. Usually, climate data are developed from actual measurements of at least 30 years of observation per location. They concern parameters such as: dry bulb temperature, incident radiation, wind direction and speed, as well as dew point temperature [15].

The data set for selected weather parameters for Poland is defined by EN ISO 15927-4:2005 – Hygrothermal performance of buildings – Calculation and presentation of climatic data – Part 4: Hourly data for assessing the annual energy use for heating and cooling. Typical Meteorological Year is created on the basis of hourly values of weather parameters, i.e. dry bulb temperature, incident radiation and relative humidity over a period of at least 10 years.

Standardized data – Typical Meteorological Year reflect long-term conditions ruling in the external environment. Therefore, they can be used as input data of the simulation for atmospheric processes.

6. Input data

The analysis of thermal comfort in the external environment was carried out on the basis of average atmospheric conditions characterized by the warmest day of Typical Meteorological Year. At first, information on hourly values of selected meteorological parameters was obtained from archival databases of the European Commission for a period of 10 years (from 2006 to 2015). The warmest day of Typical Meteorological Year is July 2, 2012. Information on relative humidity and wind direction has been used as an input data to simulate atmospheric processes. The specificity of used software required to determine hourly values of the air temperature, wind speed, atmospheric pressure, dew point temperature and specific humidity at a height of 2.500 m. The data necessary for their calculation were collected from databases of the Lodz-Lublinek measurement station located in the suburban zone, in the south-western part of the city. Parameter values measured in an open area do not fully correspond to conditions prevailing in the city centre. Therefore, it was necessary to calculate the wind speed for the centre area of Lodz. For this purpose, a modified version of the logarithmic equation (1) was used [16], i.e.:

$$\bar{U}_{(z)} = \frac{u_*}{K} * \ln \frac{(z-z_d)}{z_0} \quad (1)$$

where:

$\bar{U}_{(z)}$ – average wind speed at a height of 10 m [m/s],

u_* – friction speed [m/s],

K – Von Kármán constant (0.4),

z – altitude above the area level [m],

$(z - z_d)$ – effective height [m],

z_d – displacement of zero plane [m],

z_0 – roughness coefficient (also called the roughness parameter or surface roughness level) [m].

At first, the friction speed was calculated for an open area, where the Lodz-Lublinek meteorological station was located.

$$u_* = \frac{\bar{U}_{(z)}}{\ln \frac{(z-z_d)}{z_0}} * K \quad (2)$$

The use of modified version of the logarithmic formula is justified from a level of $z \cong (z_d + 10)$, below the value of wind speed should be considered as constant and equal to $\bar{U}_{(z_d + 10)}$ [17]. In this study, the friction speed was calculated using a simplified form of equation (3), because the test was carried out at a height not exceeding 10 m.

$$u_* = \frac{\bar{U}_{(z)}}{\ln \frac{10}{z_0}} * K \quad (3)$$

Then it was necessary to determine the friction speed for an area of the city centre of Lodz. The relation proposed by Simiu provides a link between the speed profiles of an open area and inner city [18], i.e.:

$$\frac{u_*}{u_{*1}} = \left(\frac{z_0}{z_{01}} \right)^{0,0706} \quad (4)$$

where:

u_* – friction speed on the Lublinek area [m/s],

u_{*1} – friction speed in the central zone of Lodz [m/s],

z_0 – roughness coefficient for the Lublinek area [m],

z_{01} – roughness coefficient for the central zone of Lodz [m].

$$q = q_1 + (25 * \Delta q_{100}) \quad (5)$$

where:

q – specific air humidity at a height of 2500 m [g/kg],

q_1 – specific humidity by ground surface [g/kg],

Δq_{100} – vertical gradient of specific humidity at a height of 100 m.

Table 1. Values of the simulation input parameters.

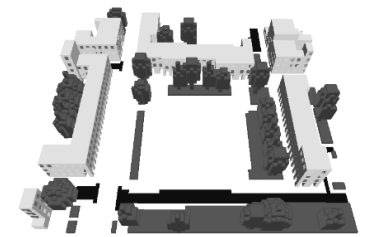
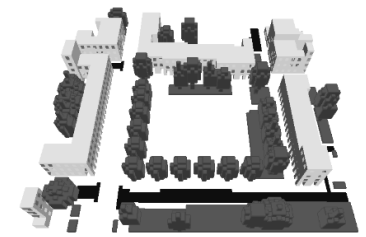
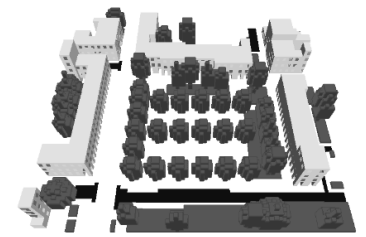
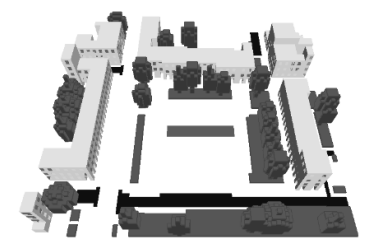
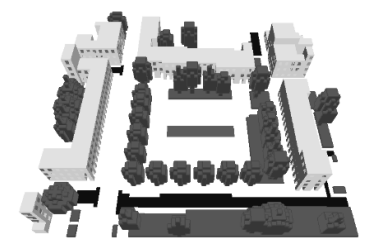
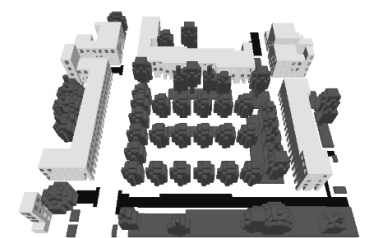
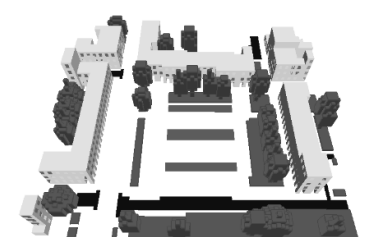
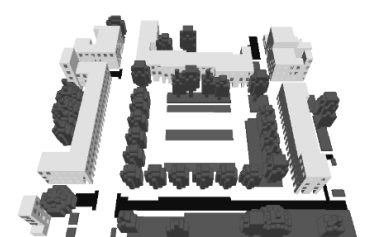
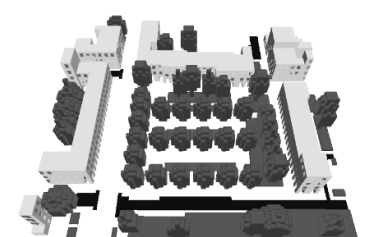
Input parameters	User input during simulation	Input parameters	User input during simulation
Simulation days	2 July 2012 – 3 July 2012	Dew point [°C]	18.5
Simulation time [h]	25 hours	Specific humidity	7.14
Wind speed [m/s]	1.79	Temperature [°C]	20.55 – 32.27
Wind direction [°]	234.10	Relative humidity [%]	39.04 – 84.64
Air pressure [hPa]	989		

As a result, the value of air-flow velocity was determined at a height of 10 m in the central part of Lodz. Another necessary input data of simulation is the value of specific humidity at 2500 m. Knowing its value at the ground level and vertical humidity gradient, it is possible to determine it using the equation (5) [19].

The values of model input parameters determined on the basis of data from the Typical Meteorological Year and calculated on the basis of information obtained from the Lodz-Lublinek meteorological station were presented in table 1.

7. Scenarios of spatial development changes

The way of spatial development affects the microclimate parameters, i.e. air temperature, solar radiation reaching the ground atmospheric layers, air-flow and relative humidity. Through appropriate modifications within the public space, it is possible to provide thermal comfort to people living in the external environment.

		
Figure 1. Base Case (BC). Green cover – 16%	Figure 2. Additional Trees (AT). Green cover – 22%	Figure 3. Additional Plantings (AP). Green cover – 30%
		
Figure 4. Additional Water (AW). Green cover – 16% Water surface – 3%	Figure 5. Water – Trees (WT). Green cover – 22% Water surface – 3%	Figure 6. Water – Plantings (WP). Green cover – 30% Water surface – 3%
		
Figure 7. Water Surface (WS). Green cover – 16% Water surface – 8%	Figure 8. Water Surface – Trees (WST). Green cover – 22% Water surface – 8%	Figure 9. Water Surface – Plantings (WSP). Green cover – 30% Water surface – 8%

The impact of spatial development changes on thermal comfort was estimated by comparing the PMV index value calculated on the basis of nine scenarios related to introduction of greenery and water elements within the main square plate.

Three-dimensional model of public space – Base Case (BC) – shows the current state of land development. The size of area is 80 x 80 x 30 cells with a resolution of $dx, dy = 2\text{m}$ and $dz = 1\text{m}$. The

basic materials used in this model are: concrete (building structures – 20%), impermeable surface (concrete cube – 63.94%, asphalt – 0.06%), natural surface (land with grass – 16%). In addition, high greenery was included, which is the native species occurring in the area of study, i.e.: acer pseudoplatanus, ash (fraxinus excelsior), lime tree (tilia).

Simulations take into account two scenarios based on introduction of additional vegetation in the square. Additional Trees (AT) assumes addition of two tree frontages along the communication routes (south and west). The plantings were provided at a distance of 10 m. In this case, the rate of green cover of the square was increased from 16% to 22%. Additional Plantings (AP) include maintenance of plantings along communication routes and the addition of plant cover on the main square plate. Percentage of greenery on the land has increased to 30%. The study uses native tree species, i.e. acer pseudoplatanus, as new plantings.

Next variants are related to change of the type of existing surface. Additional Water (AW) assumes introduction of water elements in the central part of square. Its area is 8 m x 40 m – 3% of the land cover. As a result, the impermeable part of surface – concrete slab – is eliminated. Water Surface (WS) consists in adding three water elements with dimensions of 6 m x 40 m (reservoir in the northern and southern part of the square) and 8 m x 40 m (reservoir in the central part of the square).

Subsequent scenarios take into account the addition of both greenery and water elements. An overview of individual variants was presented in Figure 1-9.

8. Analysis of obtained results

Comparison of the average value of PMV index for a typical warmest day of the year, depending on the spatial development method, was presented in Figure 10-11.

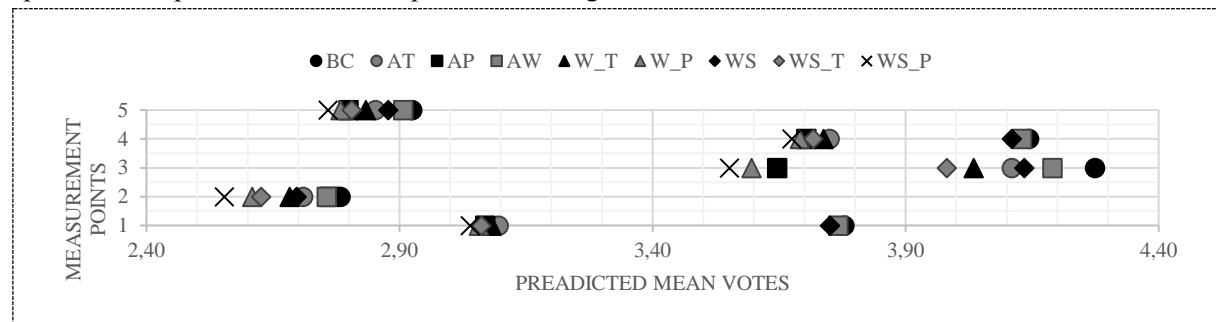


Figure 10. PMV values depending on the spatial changes scenario (standing person).

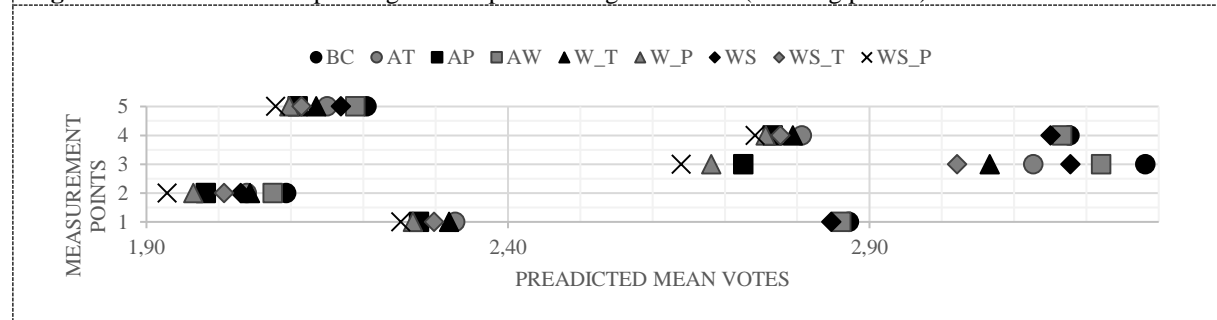


Figure 11. PMV values depending on the spatial changes scenario (walking person).

The analysis showed that regardless of the type of performed physical activity, the nature of changes in PMV index is analogous. Variants related to physical activity (slow walking) are characterized by lower PMV values. It results from the fact that PMV value is dependent on the relative air velocity. The research conducted by Sugiono and Hardiningtyas confirmed that the higher relative air velocity the lower PMV value [20]. In all the measurement points, the WSP scenario proved to be the best, consisting in introduction of additional plantings (30%) and water elements (8%) within the main square plate. The value of index has been reduced from 3.54 to 3.08 (sitting person) and from 2.72 to 2.33 (walking

person). This means that thermal sensations of people staying in the public space for a long period of time have changed from “extreme heat stress” to “hot”. In case of people performing physical activity, they were reduced to “warm” level.

The greatest variation of PMV values was recorded within the third site. It was located in the middle of square's main plate. Thus, prevailing there conditions were not affected by the land developed method. This enabled the assessment of extreme thermal conditions within analyzed space. In this case, the maximum change in PMV was 0.72 for a person not performing physical activity and 0.64 for a person with moderate physical activity (walk). Strategies to mitigate thermal discomfort enabled to reduce the average PMV up to 3.09, which meant that there were “hot” conditions in the third site. The lower daily variations in PMV values were observed in points 2 and 5. Measurement sites were located along the main facades of buildings (point 2 – northern and point 5 – western frontage). Therefore, the objects contributed to reduction of the amount of solar radiation reaching the earth surface. Thus, lower PMV values were observed in their vicinity. Difference between the extreme values of PMV for a person not performing physical activity was 0.23 (point 2), 0.17 (point 5) and for moving person 0.16 (point 2) and 0.13 (point 5). Thermal conditions within buildings have been reduced to “warm” conditions (PMV from 2.47 to 2.33).

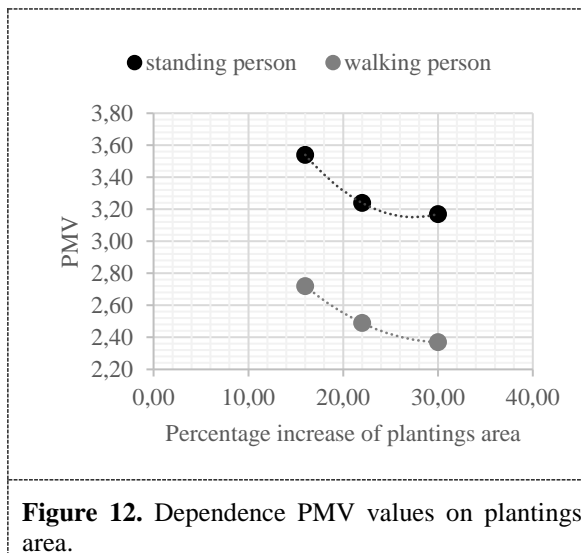


Figure 12. Dependence PMV values on plantings area.

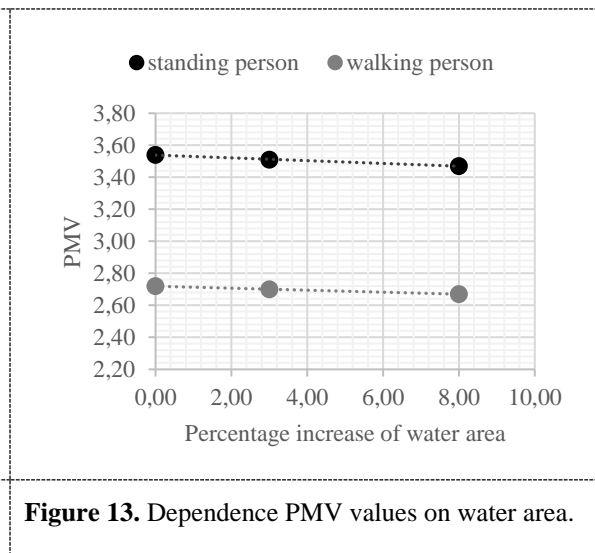


Figure 13. Dependence PMV values on water area.

Variants of changes related to introduction of greenery proved to be more effective in reducing the thermal discomfort experienced by man compared to scenarios assuming the change of surface type through introduction of water elements (Fig. 12-13). Studies show that an increase in the planting surface by 1% reduces thermal discomfort by an average of 0.038 (person not performing physical activity), 0.033 (moving person). Also, the removal of impermeable (concrete) surfaces for introduction of water elements contributes to reduction of PMV index. An increase of 1% in the natural surface (water) results in an average decrease of 0.009 (person not performing physical activity), 0.007 (walk).

9. Conclusions

The prevailing climate in highly urbanized areas depends on the land developed method. Persons responsible for spatial planning have the opportunity to transform the urban tissue through modification of the buildings, introduction and liquidation of construction works. However, transformation of historical areas of cities requires agreement with the conservators of monuments. Sometimes it is not possible to modify the structure of buildings, in particular those entered in the register of monuments. Then, the only solutions are transformations within the existing surface (their replacement), as well as creation of plantings in vertical and horizontal form. Changes in the way of spatial development translate into the modification of microclimatic parameters. The result is formation of thermal environment.

Nine scenarios of changes in the development of one of the oldest squares in the city – the Old Market Square – were considered in this work. The possibility of transforming urban structure has been limited to changing the surface types (introduction of water elements) and increasing the surface area of plantations. This was due to the fact that objects forming the frontage of square were entered in the municipal register of monuments.

Conducted research has shown that the more effective solutions were scenarios based on a growth of the green area rather than introduction of water elements within the analyzed public space. The authors showed that increase in the planting area by 1% contributed to a decrease in PMV index by an average of 0.036. The difference in case of water elements was 0.008. Scenarios consisting in introduction of both greenery and water elements resulted in the resultant of above mentioned variants.

Change of the land development method can have a positive impact on the thermal sensations of people in the external environment. Introduction of new plantings and water elements into the strongly urbanized environment modifies microclimatic parameters. In this way, it has an impact on thermal comfort. However, these strategies do not significantly reduce thermal discomfort. They can only be a part of mitigation strategies. Adaptation of urban spaces to changing climatic conditions should primarily take into account changes in the geometry of construction works and in their arrangement in relation to each other. In areas where the historical urban tissue is present, such activities are significantly hampered. An increase in the planting surface and change in the type of surface can only have so-called cooling effect.

10. References

- [1] Middel A, Chhetri N and Quay R 2015 *Urban Forestry and Urban Greening* **14** 178-186
- [2] United States Environmental Protection Agency 2008 *Reducing Urban Heat Islands: Compendium of Strategies* **1-6**
- [3] Chatzidimitriou A, Liveris P, Bruse M and Topli L 2013 *Proc. 29th Int. Con. Of the Passive and Low Energy Architecture. Sustainable Architecture for a Renewable Future (Munich)*
- [4] Barakat A, Ayad H and El-Sayed Z 2017 *Alexandria Engineering Journal* **56** 533-543
- [5] Chan S Y, Chau T M and Leung T M 2017 *Building and Environment* **122** 171-183
- [6] American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) 2010 *Thermal environment conditions for human occupancy (America)* p 62
- [7] Thorsson S, Lindqvist M and Lindqvist S 2004 *International Journal of Biometeorology* **48** 149-156
- [8] Bohořlo A 2010 *Budownictwo i Inżynieria Środowiska* **1** 11-16
- [9] Elnabawi M H, Hamza N and Dudek S 2015 *HBRC Journal* **11** 246-251
- [10] Huttner S, Bruse M and Dostal P 2008 Using ENVI-met to simulate the impact of global warming on the microclimate in central European cities *5th Japanese-German Meeting on Urban Climatology (Freiburg, Germany)* ed H Mayer and A Matzarakis p 307-312
- [11] Srivanit M and Hokao K 2013 *Building and Environment* **66** 158-172
- [12] Salata F, Golasi I and De Lieto Vollaro R 2016 *Sustainable City and Society* **26** 318-343
- [13] Huang Q, Meng X, Yang X, Jin L, Liu X and Hu W 2016 *Energy Procedia* **104** 177-182
- [14] Gaspari J and Fabbri K 2017 *Energy Procedia* **111** 500-509
- [15] Crawley D B 1998 *ASHRAE Transactions* **104** 498-515
- [16] Żurański J A 2005 Wpływ warunków klimatycznych i terenowych na obciążenie wiatrem konstrukcji budowlanych. *Prace Naukowe Instytutu Techniki Budowlanej* (Warszawa) p 128
- [17] Flaga A 2008 Inżynieria wiatrowa. Podstawy i zastosowania. *Arkady* p 720
- [18] Simiu E 1975 *Proc. of the 4-th International Conference on Wind Effects on Buildings and Structures* (Heathrow) p 721-735
- [19] Stopa-Boryczka M and Boryczka J 2016 Atlas współzależności parametrów meteorologicznych i geograficznych w Polsce *Uniwersytet Warszawski* p 416
- [20] Sugiono S and Hardiningtyas D 2014 *International Science Index* **8** 612-618