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Orginal Article

Assessment of effectiveness of selected adaptation actions to climate change. The example of the New Centre of Lodz

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Abstract: The increase of the average annual temperature is observed in many cities around the world. Consequently, not only the Southern Europeans, but also the inhabitants of Central and Northern Europe are now exposed to thermal stress. Therefore, Nature Based Solutions (NBS) developed strategies for mitigation of this issue, i.e., the process of alleviating the negative effects of climate change in highly urbanized areas.

The main objective of this study is to answer the question whether the planned spatial activities involving the use of NBS solutions in the New Centre of Lodz can contribute to the improvement of the urban spaces' microclimate and thermal comfort of people in external environment. This research focusses on the microclimate of urban spaces, understood as climatic conditions set, and thermal conditions in particular, in a small area. The spatial scope of this research covers a 30-hectare area of the New Centre of Lodz bound within the following streets: Kilińskiego, Narutowicza, Piotrkowska, and Tuwima, which is currently undergoing a large-scale revitalization process. To determine the microclimate conditions and thermal comfort, numerical simulations conducted in the ENVI-met program were used.

Keywords: adaptation strategies in urban spaces, Nature-Based Solutions, microclimate, human thermal sensations, numerical simulations

1. Introduction

Forecasts indicate that the ongoing urbanization process[1] will affect the design of urban spaces. Transformations of settlement systems, including the structure, type of buildings functions, and natural components, will affect quality of life of residents; it will have a significant effect on health and well-being of people living in a given area. Researchers emphasize that not only the inhabitants of Southern Europe, but also Central and Northern European cities will be exposed to heat stress.

In recent years, numerous research projects were carried out, such as RUROS [2] and KLIMES [3], aimed at examining microclimatic conditions of urban spaces, such as streets, public squares, playgrounds, and parks. The research was conducted in various cities including Athens, Cambridge, Göteborg, Szeged, and Taichung City. The research emphasized the role and importance of planning activities in the study of thermal comfort [4]. When it comes to Polish cities, studies on the microclimate of urban spaces were carried out by Błażejczyk [5], Kłysik [6] (Lodz) and Lewińska [7]. Unfortunately, the obtained results were very rarely included in planning practice.

Local spatial development plans play important role in this aspect and should include matters related to urban spaces' microclimate shaping and human comfort. They are an integral part of the strategy for improving the quality of the living environment and the quality of life of those inhabiting urbanized areas. Very often, local spatial development plans do not fulfil their particularly important role. There is a pressing need to fill the gaps between urban climatology, spatial planning, urban design, and transferring microclimate knowledge to spatial planning.

This study has been limited to Lodz, the fourth largest and third most populous city in Poland. The research covered the area of the New Centre of Lodz, i.e., a 30-hectare area, which is considered to be of key importance due to the ongoing process of city revitalization. At the same time, it is the largest investment in Central Europe. For the selected area, research was carried out, which was divided into three main stages:

(1) Acquiring information on meteorological parameters in the New Centre of Lodz.

At this stage, a numerical base model was developed, covering the existing state of a 30-hectare part of the New Centre of Lodz bound within the following streets: Kilinskiego, Narutowicza, Piotrkowska, Tuwima. It was the starting point for further research.

(2) An analysis of the impact of the designed buildings on microclimatic conditions and thermal comfort of urban spaces.

An adaptive model (1) was created for a fragment of the New Centre of Lodz within which, in accordance with the city's design assumptions, new high-rise objects will be built. The construction of the Fabryczna Office complex has been considered.

(3) Assessment of the impact of the implemented passive adaptation strategies on the microclimate of urban spaces in the New Centre of Lodz. For this purpose, an adaptive model (2) was developed, considering blue-green solutions (NBS), in accordance with local spatial development plans for Lodz.

2. Urban adaptation strategies – Nature Based Solutions

The selection of optimal NBS is a key and extremely complex process. Currently, there is a very wide range of passive solutions. Every type of NBS has a significant impact – not only in terms of the environment, but also economic and social matters. This perception allows us

[1] By 2030, more than 60% of the world's population will live in cities, 70% of Europeans currently live in cities, and by 2050 it is expected to be 80% [1].

to state that the use of NBS solutions fits perfectly into the multifaceted idea of sustainable development.

It is worth emphasizing that shaping the microclimate of urban spaces should be an integral element of urban policy. NBS works well not only as an individual application. Thanks to city-wide programs integrated with spatial planning, cities can achieve even better results. It is possible to include NBS in a coherent network of a blue and green infrastructure. Such an approach naturally implements the last missing component of sustainable development in the form of institutional and political order. Examples of good practices in this area are the strategic instruments of German and Spanish cities such as Berlin, Hamburg, and Barcelona, i.e. [8]:

- Urban Landscape Strategy (Berlin) – a tool for integrated green management in the city. The main goal was to support the sustainable development of the city, with particular emphasis on increasing the area and improving the quality of green areas.
- Urban climate change adaptation plan (Berlin) – a plan to integrate adaptation to the effects of climate change as a permanent element of the city's development policy. The main goals were to maintain or improve the inhabitants' quality of life and to prepare solutions limiting the effects of climate change. The action plan includes 12 key projects using NBS to achieve specific goals.
- Project of adaptation of rainwater infrastructure (Hamburg) – integrated rainwater management strategy. The main goal was to develop a strategy for sustainable rainwater management in response to the progressive changes in the frequency and intensity of rainfall. The developed system aim is to restore the natural water circulation in the city and protect it against floods.
- The biotope area indicator – BAF (Berlin) – determines which part of the area, where new buildings are being introduced (construction projects and renovation) is to be biologically active areas. It is an obligatory or auxiliary planning instrument, depending on the area of the city. Its aim is to limit environmental degradation and to ensure the desired quantity and quality of blue-green areas in the city center. For different forms of land cover and different NBS, a different ecological weight was adopted – a different conversion factor for determining the ecologically effective area.
- Increasing the area of green areas by 2030 (Barcelona) – a standard of proximity and accessibility to green spaces established to support the implementation of nature-based solutions. The priority objective is to increase the green area per inhabitant by creating 160 ha of new natural zones.
- Estate management (Berlin) – the estate spatial development plan, supporting the sustainable development of housing estates. Directional programs on the scale of housing estates will enable them to be shaped directly by the inhabitants. Moreover, they are an instrument for the revitalization of estates in crisis. The main goal is to stabilize and strengthen social cohesion in three areas: housing, neighbourhood, and education.

3. The New Centre of Lodz

The New Center of Lodz is in the City's Metropolitan Zone. It covers an area bound within Narutowicza, Kopcinskiego, Tuwima, and Piotrkowska Streets. This investment was created to raise the rank of the city in the international arena, to promote and revitalize historical buildings as well as to create a new place, attractive for residents and tourists. Ultimately, it is to be a modern complex combining business, trade, culture, and transport. Currently, the New Center of Lodz is the largest investment in Central Europe.

The height of buildings in the New Center of Lodz is varied. The number of storeys in buildings ranges from 1 to 19. The dominant type are medium-hight buildings (95%). Most of the high-rise buildings are located in the Traugutta-Kilinskiego-Tuwima-Sinkiewicza quarter. The area is characterized by typical land cover of the downtown area. It is historically densely built up and artificial materials and impermeable surfaces (asphalt and concrete) dominate, while green areas are sparse. There are few lawns and trees (mostly deciduous), which make up a small percentage of the site total area, are located inside the courtyards of historical buildings and in the neighbourhood of the Fabryczna Office investment, which is currently at design stage. The areas intended for communication functions are mostly covered with impermeable surfaces. The only exception is the pedestrian and driving route – Traugutta Street (the so-called city woonerf), which was created in order to calm the traffic and increase the greenery.

The analysis of planning documents showed that there are three local spatial development plans for the area of the New Centre of Lodz. Regarding the protection and shaping of greenery, the following was established [9]:

- an order to preserve the existing green areas, shape new ones, and to preserve the existing rows of trees, with the possibility of their replacing and supplementing;
- an order to plant greenery with species resistant to urban conditions;
- a prohibition of logging trees, except for cuts necessary for safety reasons or colliding with buildings or infrastructure, and an order to compensate cut trees with new plantings.

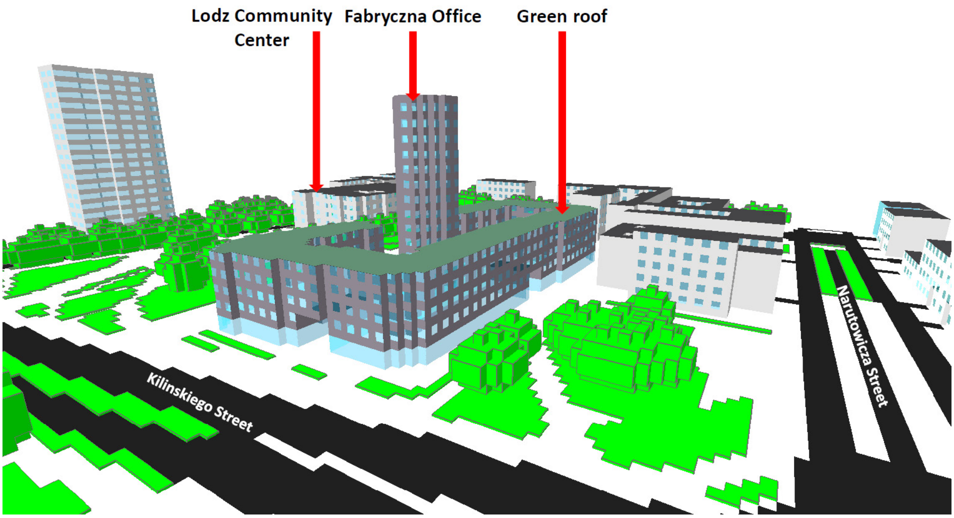

Fig. 1. The adaptive model (1). *Source:* own work

The area of the study was limited to a 4.3 ha zone bound within the following streets: Kilinskiego, Narutowicza, Sienkiewicza, Traugutta. The existing buildings constitute about 15% of the total area. The Fabryczna Office, an investment planned for implementation, served as the spatial dominant. According to the description, the building will have 13 overground storeys (55 m). The visualization of the Dutch MVRDV studio project was used as an inspiration.

The design assumptions were:

- adaptive model (1) – the design where the altitude dominant is the Fabryczna Office building (Fig. 1),
- adaptive model (2) – whose the core are the assumptions of the adaptive model (1) together with selected NBS. The introduced passive solutions include green roofs, green walls, rain gardens, blue infrastructure (fountains), new plantings, lawns, green lanes delimiting roadways, permeable surfaces, as well as a green car park (Fig. 2-3). The proposed solutions are in line with the local spatial development plans for the New Centre of Lodz.

As part of the adaptive model (2), a blue-green infrastructure was introduced in the neighbourhood of the Fabryczna Office (Fig. 2-3). The solutions were introduced in public spaces (in the courtyard of the Fabryczna Office, at the entrances to the complex from Kilinskiego and Narutowicza Street. Natural surfaces (lawns) have been added in the immediate vicinity of the Fabryczna Centre. The impermeable surfaces, which were a remnant of the demolished building, for example, the concrete parking located in the eastern part, were removed. In its place, a permeable surface (ground + grass) was implemented. Lines of trees were introduced at the entrance to the Fabryczna Office and also along Traugutta Street. Additionally, green belts with flower meadows were introduced, separating the main communication routes and fountains were implemented.

Buildings were covered with green roofs. In the case of the Fabryczna Office, both intensive and extensive forms of greenery were used. Extensive greenery was also introduced on the roof of the Lodz Community Centre (Fig. 2-3). Near the Fabryczna Office, the blind walls of the buildings were greened, and the potted plants were added. A green cubature car park was also designed (Fig. 2-3) with the use of vegetation on a special structure.

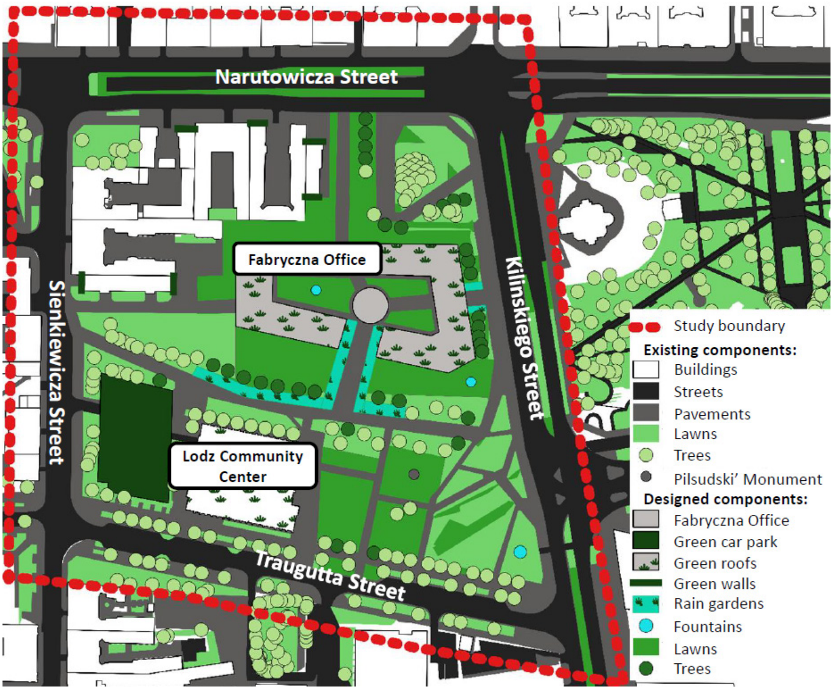

Fig. 2. The design concept for the adaptive model (2). *Source:* own work

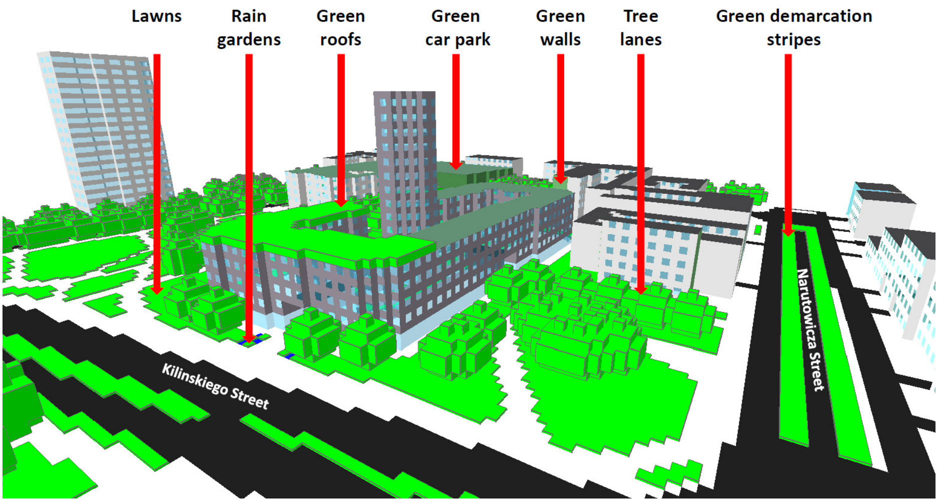

Fig. 3. The adaptive model (2). *Source:* own work

The existing pedestrian route running along the southern side of the complex was transformed into a green, pedestrian-friendly avenue. Tree plantings were introduced there. Numerous rain gardens in infiltration type containers appeared in the public space, i.e., along the mentioned green alley and at the entrances to the Fabryczna Office (Fig. 2-3).

4. Research methodology

One of the research methods used in the field of urban climatology is numerical simulation. Currently, one of the most widely used tools is ENVI-met, which is a CFD (Computational Fluid Dynamics) software. It was developed by a team of prof. M. Brus from the University of Mainz. It enables the simulation of the substrate – vegetation – air dependence in the urban environment in a daily cycle (from 24 to 48 hours). The program takes into account the flow of air between buildings, the processes of heat exchange of horizontal and vertical surfaces, turbulence, parameters of vegetation and dispersion of pollutants. S. Lenzholer includes ENVI-met among the tools that consider the parameters determining thermal comfort in the external environment, such as: air temperature, relative humidity, wind direction and speed, and average radiation temperature [10-11]. In this study, this tool was used to analyse the microclimatic conditions in the area of the New Centre of Lodz and to determine the people thermal comfort in the external environment.

4.1. Three-dimensional numerical model of the New Centre of Lodz

Carrying out the analyses required the creation of three-dimensional terrain models. The area bounded by Kilinskiego, Narutowicza, Piotrkowska and Tuwima Streets was treated as the base model. Adaptive models were created for the following quarters: Kilińskiego, Narutowicza, Sienkiewicza, Traugutta. The models are based on a rectangular grid of cells. An equidistant grid was used, the vertical structure of which was made of elements of a constant height. The grid parameters are presented in Tab. 1.

Then, the parameters of materials characteristic for construction objects located in the area of the New Centre of Lodz were defined. The thickness of the walls of the buildings as well as the physical parameters of building materials and roofing were determined (Tab. 2).

Table 1. Numerical model parameters. *Source*: own work

Model	Model resolution (x,y,z)	Grid size xyz [m]
Base	171×161×30	4×4×3
Adaptive 1/2	147×156×40	2×2×2
Common parameters for all models: Date: 5.07.2015 Location: the New Centre of Lodz Rotation: -9°		

The adaptive model (1) assumed the introduction of a newly designed facility – the Fabryczna Office. In this case, the impact of changing the structure of buildings on microclimatic conditions as well as thermal comfort was tested. The adaptive model (2) assumed the implementation of blue-green solutions in the form of tall greenery, green roofs, green walls, lawns, rain gardens and fountains. This activity was aimed at determining the impact of adaptation strategies on the conditions prevailing in the external environment. It should be mentioned that the adaptation scenarios considered the complex geometry of the buildings, gate passages, the diversity of building materials for the existing and designed structures (including glazing).

Table 2. Numerical model parameters. *Source*: own work

Parameter	Wall		Roof
	Inner layer - brick -	Outer layer - plaster -	- roofing felt -
Thickness [m]	0.64	0.02	0.01
Absorption [%]	60.00	50.00	94.00
Permeability [%]	0.00	0.00	0.00
Reflection [%]	40.00	50.00	6.00
Emissivity [%]	90.00	90.00	90.00
Specific heat [J/(kg×K)]	650.00	850.00	1460.00
Thermal conductivity [W/(m×K)]	0.44	0.60	0.18
Density [kg/m^3]	1500.00	1500.00	1000.00

4.2. Meteorological parameters

The microclimatic conditions for the warmest day of the Typical Meteorological Year (the 5th of July 2015) were used as input data for the simulation process of the base model[2]. Hourly values of air temperature, relative humidity, radiation, and the average daily value of air flow velocity were used (Tab. 3). The value of the subsoil roughness was chosen for the urbanized area.

2 This study uses the data of the warmest day of a Typical Meteorological Year, created based on information from 2004-2015, in order to show the maximum impact of the introduced adaptation strategies on microclimatic conditions, as well as the thermal comfort of a person in the external environment. More at: [12].

Table 3. Meteorological parameters of the base model. *Source*: own work

Hour	1:00	2:00	3:00	4:00	5:00	6:00	7:00	8:00	9:00	10:00	11:00	12:00
T_a*[°C]	15.50	14.80	14.60	16.70	21.10	23.40	26.80	29.60	31.00	31.70	32.70	33.30
RH*[%]	81.00	85.00	85.00	82.00	63.00	57.00	50.00	40.00	30.00	28.00	26.00	24.00
Hour	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00	
T_a* [°C]	33.70	34.20	34.00	34.00	33.50	31.60	28.10	23.90	22.40	20.60	19.70	
RH*[%]	21.00	20.00	20.00	21.00	22.00	27.00	36.00	52.00	55.00	64.00	69.00	

Average daily wind speed: 0.80 [m/s]
Air inflow destination: west
The substrate roughness: 1.00 [m]
Adjustment factor for radiation: 0.80

*T_a – air temperature
*RH – relative humidity

The western direction of air inflow was assumed. Wind speed data was obtained from the Lublinek weather station, which is located in the suburban area of Lodz. Therefore, it was necessary to recalculate air flow within the strict city centre. For this purpose, the Simiu dependency was used, which made it possible to link the conditions of the suburban-downtown zone[3]. Consequently, the air flow velocity profile in the city centre was determined.

Then, the meteorological conditions were simulated for the base model, which made it possible to assess the influence of the building structure on the microclimate of urban spaces. The generated parameters served as input data for the simulation of adaptive models (1 and 2). The boundary conditions were the values calculated at the measurement point located in the vicinity of the Fabryczna Office complex (Tab. 4).

Table 4. Numerical model parameters. *Source:* own work

Hour	1:00	2:00	3:00	4:00	5:00	6:00	7:00	8:00	9:00	10:00	11:00	12:00
T_a* [°C]	20.63	19.83	19.38	19.55	20.86	22.39	24.18	25.75	27.20	28.28	29.10	29.89
RH*[%]	57.63	60.51	62.09	62.89	59.95	55.96	51.61	46.11	40.95	37.06	34.59	32.55
Hour	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00	
T_a* [°C]	30.40	30.82	31.01	31.07	30.87	30.32	29.47	28.02	26.75	25.71	24.79	
RH*[%]	30.63	29.12	28.49	28.34	28.63	29.88	32.35	36.50	40.07	43.35	46.49	

Average daily wind speed at a height of 10 m: 0.44 [m/s]
Air inflow destination: west
The substrate roughness: 1.00 [m]
Adjustment factor for radiation: 0.80

*T_a – air temperature at the height of 2 m
*RH – relative humidity at the height of 2 m

4.3. Thermal comfort

The ISO 7730 standard defines it as ‘a state of mind expressing satisfaction with the thermal environment’ [14]. In this study, thermal comfort was estimated using the PET (Physiological Equivalent Temperature) index. The following meteorological data were taken into account: air temperature, average radiation temperature, air humidity and wind speed. Information on human physical parameters, thermal insulation of clothing, as well

[3] More at: [13].

as the type of physical activity performed was used. The assumptions adopted for this study are presented in Table 5.

Table 5. Parameters used to estimate the PET index value. *Source:* own work

Parameter	Value
Clothing insulation [clo]	0.50 (light summer clothes)
Movement speed [m/s]	1.21
Human metabolism [met]	1.43
Height [m]	1.75
Weight [kg]	75.00
Age [years]	35

5. Microclimatic conditions in the New Centre of Lodz urban spaces

The conducted research was limited to three parameters which, in the context of climate change and the increasing frequency of the urban heat island occurrence, have a significant impact on human thermal comfort. Air temperature, surface temperature, and wind speed were analysed. Measurements were made at the level of human movement in public spaces (at a height of 1.4–1.5 m, depending on the resolution of the model). The thermal comfort of people in an urban environment was determined using the PET index.

5.1. Air temperature

There was a clear differentiation of the parameter in the study area. During the day, the difference between the coldest and hottest points was 2.79°C (Fig. 4). The occurrence of local heat islands within communication routes and in areas covered with impermeable surfaces characterized by low albedo were detected.

In the case of the adaptive model (1), the maximum value of air temperature was lower by 1.05°C compared to the base model (Fig. 4). This was due to the different spatial management of both areas. Near the Fabryczna Office (adaptive models), a greater number of natural surfaces was observed.

The adaptive model (2) assumed the implementation of blue-green solutions (Nature Based Solutions). High greenery, green roofs, green walls, lawns, rain gardens and fountains were introduced in the area of the study. The introduced adaptation strategies contributed to the improvement of microclimatic conditions. The analyses showed that the air temperature was reduced. The value of the parameter during the day fluctuated between 28.82-31.65°C (Fig. 4). This meant a decrease in the minimum value by 1.12° C, and the maximum value by 1.08°C as compared to the base model.

Fig. 4. Air temperature at the pedestrian height, at 2 pm (the base model (a), the adaptive model 1 (b), the adaptive model 2 (c)). *Source:* own work

5.2. Surface temperature

The surface temperature oscillated between 13.74–48.66°C. The value of the parameter varied in study area. During the day the difference between the coldest and hottest points was 25.14°C, and at night it was 6.49°C (Fig. 5). During the day, the minimum values of the parameter were observable in places limiting direct solar radiation reaching the ground surface, shaded by trees and buildings. Additionally, the maximum values were detected in places with artificial surfaces.

In the case of the adaptive model (1), the surface temperature values fluctuated between 22.96-47.63°C during the day (Fig. 5). Critical places where the highest value of the parameter was observed were communication areas (communication routes, Lodz Community Centre parking), as well as the space in the vicinity of the City Gate. This is related to the type of surface used; those particular areas were impermeable surfaces covered with asphalt.

In the case of the adaptive model (2), the minimum value of the surface temperature decreased by 0.81°C, and the maximum value by 1.1°C during the day compared to the base model (Fig. 5). The removal of asphalt surface in the vicinity of the Fabryczna Office was of key importance in reducing the temperature.

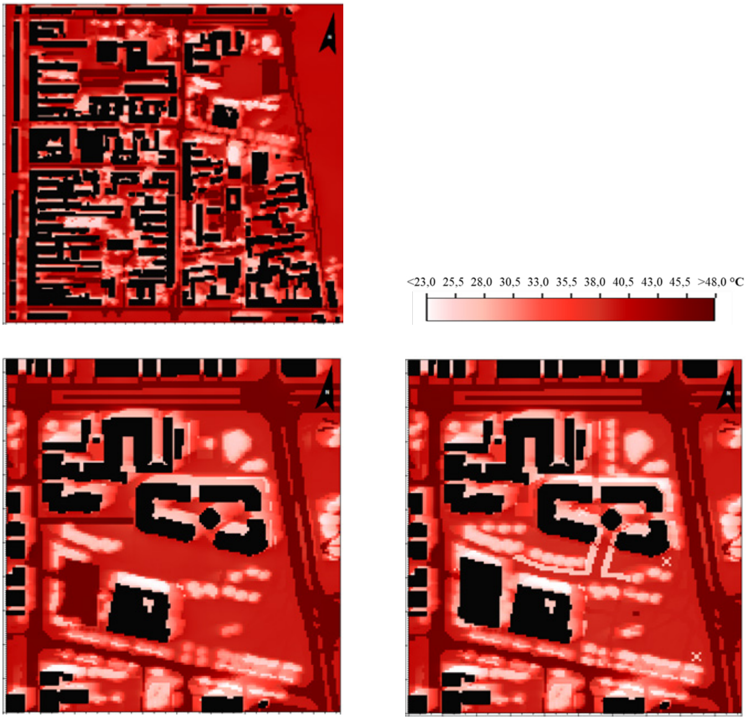

Fig. 5. Surface temperature at 2 pm (the base model (a), the adaptive model 1 (b), the adaptive model 2 (c)). *Source:* own work

5.3. Relative humidity

The distribution of relative humidity highlighted zones with the lowest density of buildings and the location of green areas. The maximum values of the parameter were observed particularly in the north-eastern part of the study area (Fig. 6).

In the case of the adaptive model (1), the areas characterized by the highest relative air humidity were located within the green belts along the streets, as well as on the east side of the Lodz Community Center. The minimum value of relative humidity was higher by 4.82% compared to the base model (Fig. 6). It was recorded in areas covered with impermeable surfaces (passageways, car parks).

In the adaptive model (2) was a visible increase in relative humidity in places where passive adaptation solutions were introduced. An increase in the minimum value by 4.9%, as compared to the base model was recorded (Fig. 6). The occurrence of ‘cold areas’ was observable in the eastern and central parts of the area.

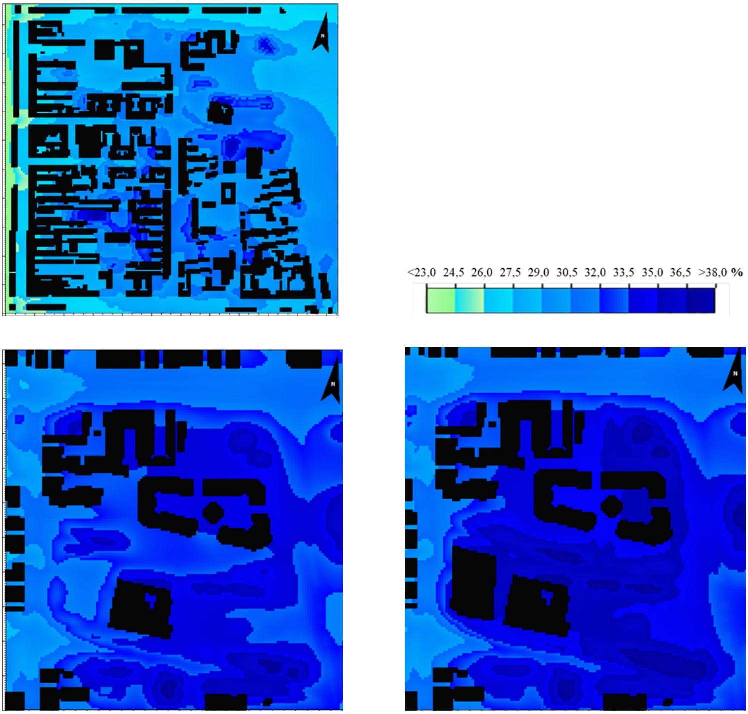

Fig. 6. Relative humidity at the pedestrian height, at 2 pm (the base model (a), the adaptive model 1 (b), the adaptive model 2 (c)). *Source:* own work

5.4. Air flow

For the considered cases, the western direction of air inflow to the city was assumed. The base model showed slow air flow in N – S street canyons ranging from 0.0 to 0.4 m/s (Fig. 7). This was due to the dense building structure located on both sides of the communication routes. Also, on the leeward side of the buildings, lower values of the parameter were observed. Minimal numbers were recorded in the area of closed courtyards of tenements.

In adaptive models, there was a noticeable slowdown in airflow in the vicinity of the Fabryczna Office. The lowest values were observed on the leeward sides of the buildings, inside the courtyards of historic buildings, as well as in the courtyard of the designed Fabryczna Office Centre. It should be noted that the Fabryczna Office traffic routes are located in the north, south and east. The shape of the building was closed from the west, which did not allow free air flow in the vicinity of the building. The described situation was the cause of low wind speed inside the courtyard, and thus air stagnation. As an effect, the air temperature increased, and consequently, thermal conditions experienced by humans deteriorated.

In the adaptive model (2), it should be additionally noted that wind speed slowed down at the Lodz Community Centre. The reason was the introduction of a green cubature car park, which acted as a barrier to inflow of air masses. The second place where a reduced value of wind speed was noticed was in the green alley. The plantings weakened air exchange in the vicinity of the Fabryczna Office (Fig. 7).

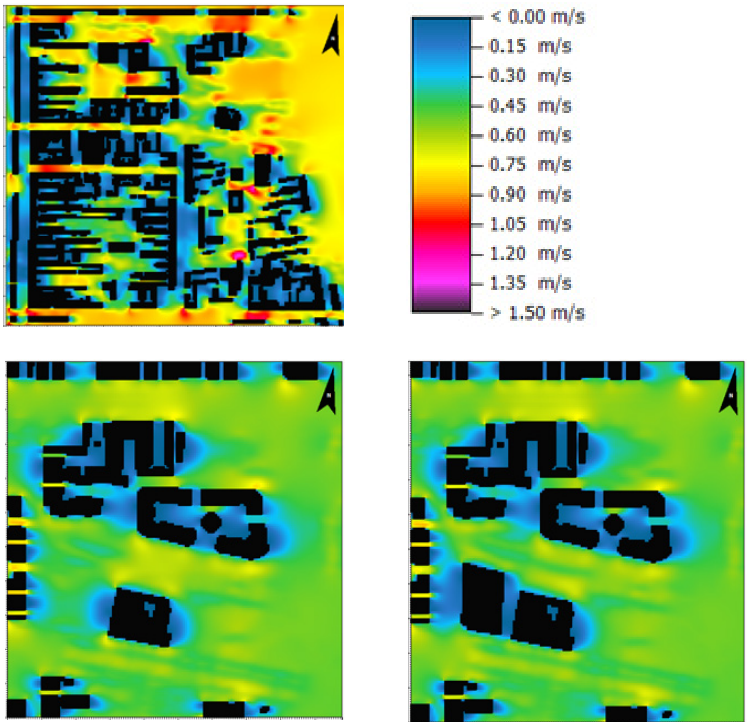

Fig. 7. Air flow at 2 pm (the base model (a), the adaptive model 1 (b), the adaptive model 2 (c)). *Source:* own work

5.5. Human thermal comfort – PET

Thermal comfort of a person in the external environment was estimated using the PET index. The value of the parameter was at the level of 11.55–57.80°C during the warmest day of the Typical Meteorological Year (Fig. 8). This meant the occurrence of 'hot' and 'very hot' conditions during the day. The highest values were recorded in the path of N–S orientation communication routes, as well as inside closed inner-city yards. Negative thermal impressions of people staying in urban spaces were largely the result of their spatial management. The surfaces were dominated by impermeable, artificial materials with a low albedo (asphalt, concrete) and there was a deficit of greenery. A characteristic closed building geometry of historic courtyards limited free flow of air, and air stagnation was observed within them. Due to the limitation of direct sunlight, the 'warm' conditions prevailed in the areas shaded by anthropogenic (buildings) as well as natural (green) elements (Fig. 8).

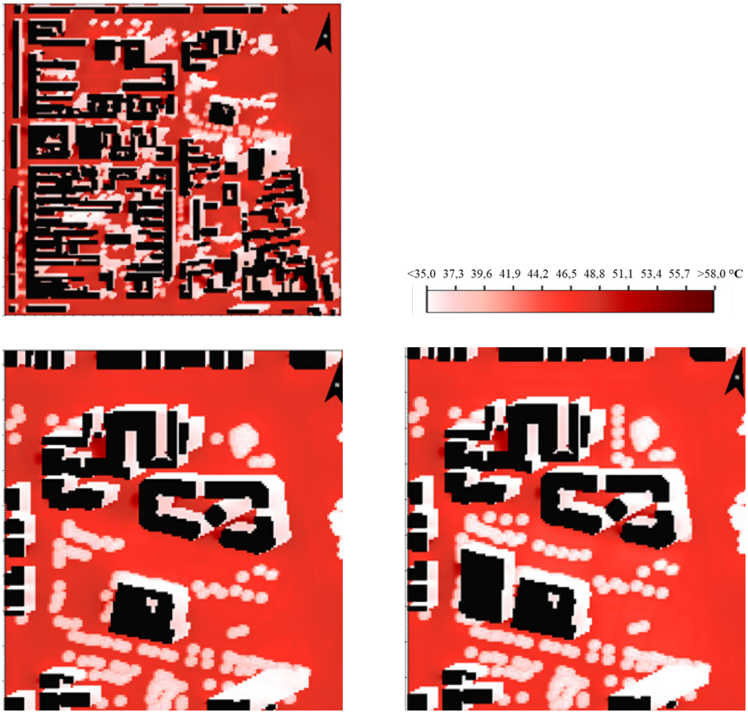

Fig. 8. Thermal comfort index – PET, 2 pm (the base model (a), the adaptive model 1 (b), the adaptive model 2 (c)). *Source:* own work

Supplementing the building structure with newly designed objects (the Fabryczna Office) influenced the modification of thermal conditions (adaptive model (1)). There was a decrease in the minimum value of PET by 1.73°C, and the maximum value by 3.20°C in relation to the base model. The indicator oscillated between 14.47–54.60°C. Daytime conditions were described as 'warm', 'hot' and 'very hot'. Areas critical in terms of thermal comfort were communication routes, the Fabryczna Office courtyard and the parking area located at the corner of Sienkiewicza and Traugutta Streets. The most favourable ('warm') conditions were noticed in areas shaded by buildings and by trees.

The introduction of blue-green solutions (the adaptive model (2)) contributed to the modification of thermal conditions in the area. A reduction in the intensity of thermal stress was observed in the surroundings of the Fabryczna Office. There was a decrease in the maximum value of PET by 3.8°C, and the minimum value by 2.41°C during the day, compared to the parameters obtained in the base model. The improvement of thermal conditions was visible in the Fabryczna Office courtyard, in Narutowicza and Kilińskiego Streets, and in the vicinity of the green cubature car park at the corner of Sienkiewicza and Traugutta Streets. The lowest values were recorded in places shaded by trees.

6. Summary – assessment of the adopted planning solutions' impact on the microclimate of urban spaces and human thermal comfort

The aim of this study was to assess the impact of planning activities on the microclimate and thermal comfort of humans in the urban spaces of the New Centre of Lodz. The results of the carried-out research clearly indicate the importance of spatial development of the area. The adopted strategies using NBS solutions contributed to the improvement of microclimatic conditions and thermal comfort in the external environment. The analysed parameters improved, i.e., air temperature, surface temperature, relative humidity, and the PET thermal comfort index.

Table 6. Microclimatic parameters in the New Centre of Lodz. *Source:* own work

Parameter	Values 2:00 pm					
	Base model		Adaptive model			
			1		2	
	Min	Max	Min	Max	Min	Max
Air temperature [°C]	29.94	32.73	29.16	31.68	28.82	31.65
Surface temperature [°C]	23.52	48.66	22.96	47.63	22.71	47.56
Relative humidity [%]	23.84	37.82	28.66	37.14	28.74	37.61
Wind speed [m/s]	0.00	1.37	0.00	0.87	0.00	0.87
PET [°C]	34.38	57.80	32.65	54.60	31.97	54.00

The introduction of tall greenery and rain gardens was a significant development, thus increasing biologically active areas while eliminating building materials typical for the downtown zone – anthropogenic elements of the existing urban space development in the form of impermeable, artificial surfaces, such as asphalt or concrete. Also, particular attention should be paid to compact buildings, such as a city courtyard, where unfavourable microclimatic conditions prevailed including significant thermal stress. This place is a great challenge for the implementation of adaptation strategies – very often there is no possibility of significant interference. Limiting the proportion of hardened surfaces to the necessary minimum should be a priority within this type of structure. Passive solutions should be implemented there, such as elements of blue-green infrastructure that contribute to reducing thermal stress.

An example that proves the effectiveness of such solutions is the surroundings of the Fabryczna Office. The cooling effect of passive adaptive solutions was observed in the adaptive model (2), where the most favourable thermal conditions prevailed. The use of permeable surfaces, numerous lawns, as well as the introduction of fountains in the courtyard area allowed to reduce thermal stress. The results of the study of microclimatic conditions in the immediate vicinity of the building were also promising. The maximum reduction in air temperature was 0.37°C at the southern facade, and 0.21°C at the eastern façade (in comparison to similar studies, such a result is comparable and significant [13]). Additionally, the conducted analyses showed that the value of the daily air temperature amplitude in the green area was lower by 2.05°C in relation to the area of the asphalt street. Research conducted around the world confirms the effectiveness of the NBS in the mitigation process (Tab. 7). It should be noted that the extent of impact of the introduced solutions varies and depends on many factors, such as the selection of plant species, the size of trees, green area, water availability in cities and weather conditions. This is illustrated in the table below (Tab. 7). Even when the same NBS is used, the results depend on a variety of factors and the best effect was achieved in New York.

However, in this case, it should be emphasized that the research was conducted for the Central Park, which, due to the range of the green area or the size of the trees, most likely differs from the characteristics of other locations. The values obtained for the NCL are satisfactory, especially in relation to results obtained for Warsaw in the case of the park impact analysis. The implementation of additional solutions, primarily in the form of numerous high green areas, as well as increasing the percentage of blue infrastructure, could significantly improve the result obtained in the New Centre of Lodz.

Table 7. The influence of the applied NBS on the local temperature value reduction. *Source:* own study* based on [15-17]

Location	Mitigation temperature	Introduced NBS type
New York (Central Park)	12.2	Green areas / parks
Portugal	2.5-9.0	Green areas
Sweden	2.0-6.0	Parks
India	6.0	Trees
Israel	2.0-4.0	Lawns / trees
Netherlands	0.6-4.0	Green areas
Japan	2.0	Trees
Hong Kong (residential district)	0.5	Trees
Warsaw	1.0-3.0	Parks
New Centre of Lodz	0.3-2.5 *	Trees / green roofs / green walls / lawns / rain gardens

In the New Centre of Lodz, an unfavourable impact of changes in spatial development on anemometric conditions were observed. After introducing the new high-rise building (Fabryczna Office), the wind speed in its vicinity decreased. Due to its closed form from the west (from which air inflow was defined), air stagnation was observed inside its courtyard. The effect of the described phenomenon was an increase in air temperature and, as a result, deterioration of thermal conditions in the urban space. This case emphasizes the importance of the method of shaping the body of building objects that will consider the microclimatic requirements of a given area. Also, it shows how important it is to analyse the impact of the newly introduced cubature on the prevailing meteorological conditions at the design stage. Thanks to such modifications, such as a slight modification of the building's form (in the analysed case, introducing an opening allowing free air inflow from the west at the height of pedestrians' movement), ventilation of urban spaces could be improved. Moreover, the research showed the importance of method of shaping the structures of downtown buildings along communication routes. Slower air flow in N–S street canyons was evident (with the assumed flow of air from the west – the dominant direction in Poland), which resulted in intensification of thermal stress. In the case of canyons oriented in such a way, it may be good practice to introduce gaps between the buildings along the streets to allow free inflow of fresh air, as well as greenery – rows of trees and green belts separating the roadways.

It is worth emphasizing that shaping the microclimate of urban spaces should be an integral element of urban policy. NBS works well not only in individual applications. Thanks to city-wide programs integrated with spatial planning, cities can achieve even better results. They would make it possible to include NBS in a coherent network of blue and green infrastructure. Such approach naturally implements the last missing component of sustainable development in the form of institutional and political order.

The models used in the study can be treated as a guide for designers of urban spaces who want to create them in a way that ensures optimal, external thermal comfort. The usage of urban microclimatic models provides the ability to predict various thermal conditions.

The perception of the microclimate of a given urban space results in its different use by occupants in different climatic conditions. Therefore, an in-depth analysis of the microclimatic features of urban spaces, gives new opportunities for their growth, and increases the chances of optimizing their development in relation to the outside conditions throughout the year.

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