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Orginal Article

The impact of changes in spatial development on microclimate conditions and thermal comfort: the example of Manufaktura in Łódź

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Abstract: The paper presents the impact of changes in spatial development on microclimate parameters and thermal comfort. The research area covers the site of the current shopping and service centre Manufaktura in Łódź, located in the former factory complex of Izrael Poznański. Analyses were carried out for the area before and after the revitalisation process. The transformations of the building structure, reductions in green areas, and modifications of the surface were highlighted. Three-dimensional terrain models were prepared, and simulations were conducted using the ENVI-met program. The influence of development transformations on thermal comfort and microclimate was assessed. Due to the negative impact of the changes, adaptive solutions were proposed. The data obtained showed a positive influence of the implemented blue-green strategies on thermal conditions and the microclimate.

Keywords: microclimate, thermal comfort, spatial development, ENVI-met, blue-green infrastructure

1. Introduction

Modern cities have undergone significant transformations in terms of infrastructure, construction, and spatial changes. Their number is continuously increasing [1,2], with the creation of vast agglomerations, and research suggests that the population in the largest cities will continue to grow [3,4]. In this context, implementing the concept of sustainable development in urban areas becomes particularly important, as improving the quality of the environment and the lives of citizens is crucial. Knowledge about the typical features of the urban climate and the factors that modify them is becoming increasingly relevant [5].

The most common phenomenon in the urban climate is the urban heat island (UHI), first described several decades ago [6,7]. This phenomenon involves an increase in air temperature in urban agglomerations compared to rural areas. Many UHI observations have been made over the years [8-13], and numerous empirical and modelling studies have been conducted on the intensity of this phenomenon [8,14].

Climate changes occurring in cities negatively impact the health and well-being of residents. Dense buildings, limited sunlight and greenery, altered wind directions and intensities, and the formation of urban heat islands over cities discourage people from living in such conditions. As a result, suburbanization is increasingly observed, especially in post-industrial cities, where people move from city centres, often surrounded by degraded, undeveloped areas, to suburban locations [15-17]. A potential solution is the revitalisation process, which enables economic and spatial transformations as well as the implementation of participatory activities in post-industrial areas [18-20]. Appropriate urban design and adaptation to climatic conditions will help create a resident-friendly environment [21-23].

Łódź, a post-industrial city, has undergone significant urban planning changes over the years. Numerous revitalisation projects have transformed the urban fabric, particularly in the city centre, into the so-called Greater City Zone of Łódź. The impact of these changes on the environment is reflected in the microclimatic conditions of the area. Currently, the city authorities support projects that incorporate elements of blue and green infrastructure. Increased awareness of the impact of climate on human health and comfort contributes to a more sustainable spatial policy [24,25].

This study presents the impact of spatial development changes related to the revitalisation of former post-industrial areas on microclimate conditions and human thermal comfort. The analysis focused on one of the most recognisable public spaces in Łódź in recent years: Manufaktura. Previous research indicates that changes in the building structure have modified wind conditions throughout the entire complex and in the immediate vicinity of the buildings [26]. The influence of external environmental factors (such as variable thermal, solar, and wind parameters) determines many physical processes on the external surfaces of partitions and in their near-surface zones, which significantly impacts the destructive processes of historic facades. Research in this field, specifically related to Manufaktura, has been conducted at the Lodz University of Technology, though these studies mainly focused on building physics issues, such as thermal-humidity processes in historic building partitions, pollutant adsorption, turbulent movement near architectural details, or the impact of rainfall on building walls [27,28].

The main objective of this study was to analyse the impact of changes in the spatial development of the Manufaktura area on thermal comfort and microclimate, as well as to assess the effectiveness of the implemented adaptation strategies to climate change.

2. Characteristics of the Manufaktura area

The origins of the Manufaktura Centre date back to the second half of the 19th century, when I. K. Poznański built an industrial and residential complex in the Łódka River valley. After the plant ceased operations, in 1999 the factory was taken over by Absys, and the revitalisation of the area began. As a result, the area underwent modifications in terms of space and functionality. Some buildings were demolished, as they were classified as having no historical significance and did not affect the character of the place. However, in the central part of the area, a new, extensive commercial facility was introduced, which closed off the originally open space on the west side of the complex [29]. In Fig. 1, an outline of the historical buildings (before revitalisation) and new buildings (after the revitalisation changes) is presented.

Fig. 1. Manufaktura complex (left – before revitalisation, right – current state). *Source*: http://aibcon.pl/realizacje/

The transformations introduced are visible both in the degree of surface hardening and the extent of green areas (Tab. 1). Analysing the condition before revitalisation, a large proportion of natural areas with abundant greenery is noticeable. Paved surfaces existed only in the central part of the facility, in the form of grey cobblestones, with the area being predominantly unpaved. Currently, after the revitalisation process, the proportions of these areas have changed significantly. There has been a visible decrease in green areas at Manufaktura, which were replaced by large parking lots now located around the facility, including a multi-storey concrete parking lot. Impervious surfaces are not only present in the form of parking lots but also in the form of sidewalks and spaces around the buildings. The river, which played an important role during the factory's operation, is no longer above ground and now flows through an underground canal beneath Manufaktura.

Table 1. Share of green and paved areas in the study area. *Source*: own work

	State before revitalization	Status after revitalization
Percentage of green areas	37%	16%
Percentage of paved surfaces	14%	23%

3. Application of numerical methods in the assessment of microclimatic conditions

Studies assessing the impact of urban layout on microclimatic conditions and thermal comfort are conducted using computer simulations, among other methods. These simulations provide an alternative to time-consuming field research, which often requires significant financial resources. Additionally, they allow for analyses to be performed in a relatively short time. Programs used in urban climatology include CFD applications, the RayMan program [30,31], and programs like Bioklima [32].

Currently, a widely used tool in the field of urban climatology is the ENVI-met application [33-35]. This computational fluid dynamics tool allows for analyses of a three-dimensional environment to determine the distribution of microclimatic parameter values in space, as well as the level of thermal comfort experienced by people in outdoor environments. The analysis is typically performed over a period of 24 to 48 hours [36,37]. It considers the interactions between air, surfaces, and vegetation. Simulations account for turbulence, air flow between buildings, heat exchange, vegetation parameters, and pollution. Temperature, relative humidity, wind speed, and mean radiant temperature are treated as the primary prognostic variables. In later stages of research, these parameters are used to determine thermal comfort indicators [38-40].

3.1. Numerical model

To determine the impact of changes in spatial development on microclimatic conditions, three-dimensional models of the Manufaktura area were created (before revitalisation – 1989, and after the revitalisation process – 2015). Simulations were carried out for the warmest days of the year (16 August 1989 and 5 July 2015, respectively). The first model was made for the urban layout prior to the revitalisation activities (Fig. 2). The area studied was located within the boundaries of Drewnowska, Zachodnia, Ogrodowa, and Karski streets. The model dimensions were 212 m x 190 m x 30 m, with a resolution per cell of 4 m x 4 m x 2 m. The model was rotated by 6° relative to the north to adjust the urban layout into a rectangular grid of cells.

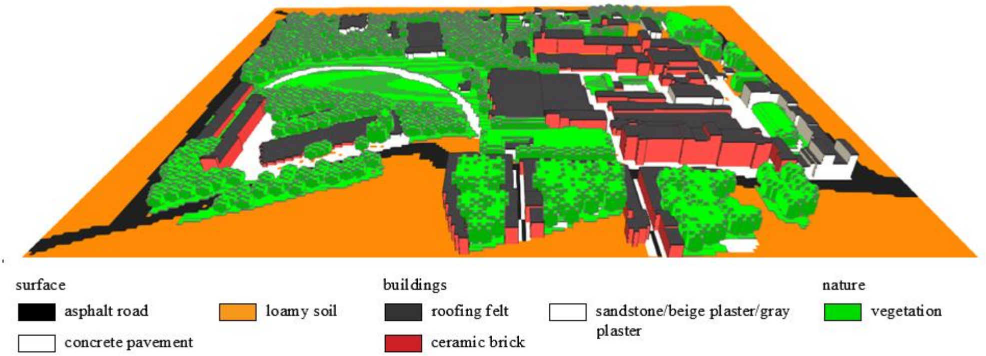


Fig. 2. The urban layout before the revitalisation process (south view from Ogrodowa Street). *Source*: own work

Initially, it was necessary to modify the ENVI-met application database. It was supplemented with materials typical for the Łódź Metropolitan Zone (Tab. 2) [41]. Ceramic brick was added to model the building walls, with exceptions for the buildings at the intersection of Drewnowska and Karski Streets (facade – plaster) and the Poznański Palace located on Zachodnia Street (walls – sandstone). The roofs of all buildings were covered with felt.

The second model (Fig. 3) was created for the Manufaktura after the revitalisation activities were completed (2015). Its dimensions were 212 m x 190 m x 30 m, with a resolution per cell of 4 m x 4 m x 2 m. The model was rotated by 5.5°.

In this case, not only the building materials typical for the Metropolitan Zone were taken into account (Tab. 2), but also those used for the modernisation of the facilities (Tab. 3). Concrete was used for the multi-storey parking lot. Glazing was introduced on the front façade of the main commercial building. Concrete and steel were also used as façade elements of the cinema located in the north-eastern part of the study area.

Table 2. Parameters of building materials implemented in the ENVI-met application database (Manufaktura model before the revitalisation activities). *Source*: own work based on the ENVI-met database

Parameters	Roofing felt	Ceramic brick	Sandstone	Beige plaster	Gray plaster
Thickness	0.01 m	0.64 m	0.02 m	0.02 m	0.02 m
Absorption	94%	60%	28%	28%	50%
Transmittance	0%	0%	0%	0%	0%
Reflexivity	6%	40%	72%	72%	50%
Emissivity	90%	90%	67%	90%	90%
Specific heat	1460 J/kg·K	650 J/kg·K	1000 J/kg·K	850 J/kg·K	850 J/kg·K
Thermal conductivity	0.18 W/m·K	0.44 W/m·K	2.3 W/m·K	0.6 W/m·K	0.6 W/m·K
Density	1000 kg/m^3	1500 kg/m^3	2400 kg/m^3	1500 kg/m^3	1500 kg/m^3

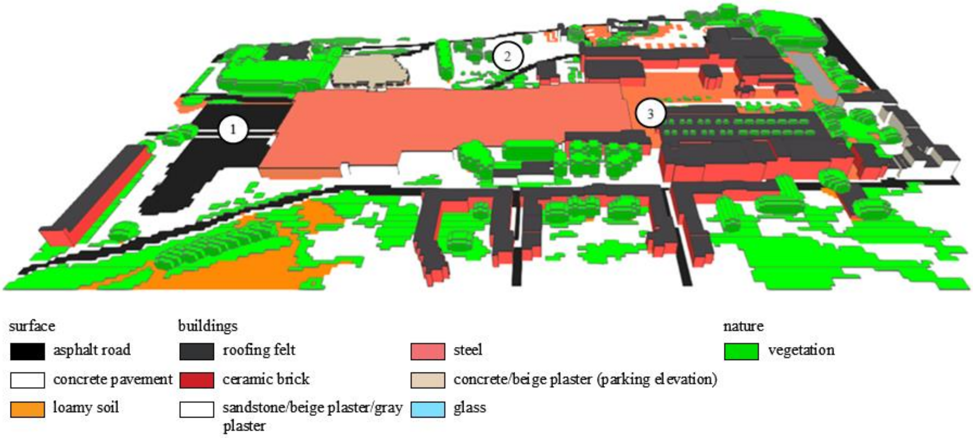


Fig. 3. The model of Manufaktura (po. 1. western parking lots, po. 2. northern parking lots, po. 3. main entrance to the shopping mall; view from Ogrodowa Street, 2015). *Source*: own work

Table 3. Parameters of building materials implemented in the ENVI-met application database (Manufaktura model after revitalisation transformations). *Source*: own work based on the ENVI-met database

Parameters	Concrete	Steel	Glass
Thickness	0.3 m	0.015 m	0.02 m
Absorption	70%	21%	5%
Transmittance	0%	0%	0%
Reflexivity	30%	79%	90%
Emissivity	90%	10%	5%
Specific heat	840 J/kg·K	420 J/kg·K	750 J/kg·K
Thermal conductivity	1.3 W/m·K	45 W/m·K	1.05 W/m·K
Density	2000 kg/m^3	8000 kg/m^3	2500 kg/m^3

3.2. Meteorological parameters

To determine the input parameters for the simulation, data from the suburban meteorological station Łódź Lublinek were used. The information was collected for the warmest days of the year. In the first case, data from 1989 were used (industrial function of the facility). The second simulation used data from 2015 (current status – commercial facility). The graphs display the input parameters of the models (Fig. 4-5).

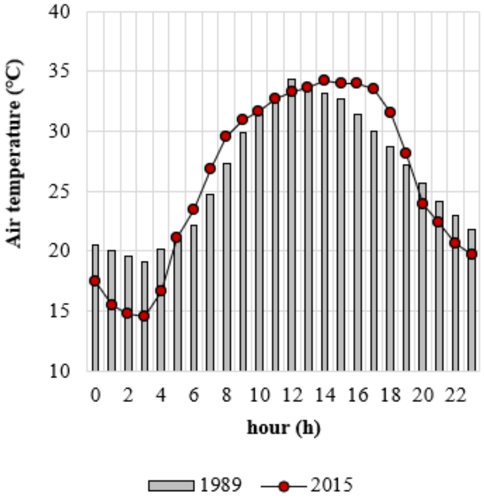


Fig. 4. Input model data: air temperature (16 August 1989 and 5 July 2015). *Source*: own work

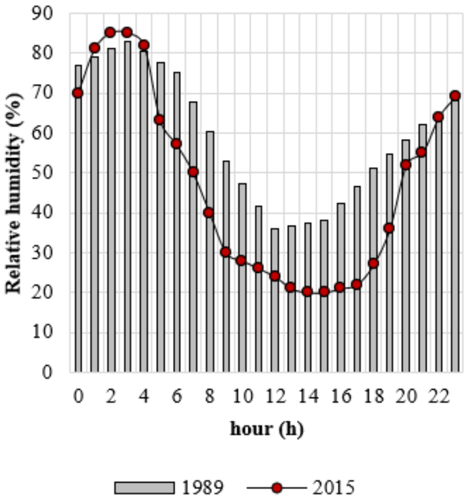


Fig. 5. Input model data: relative humidity (16 August 1989 and 5 July 2015). *Source*: own work

In the later part of the paper, for thermal conditions, the simulation results are presented for 12:00 p.m. (the time of discomfort conditions due to the most intense solar radiation; input value: ta=34.3°C for 1989, ta=33.3°C for 2015) and 6:00 p.m. (the period when the highest number of users move around the Manufaktura area; input value: ta=28.7°C for 1989, ta=31.6°C for 2015).

To estimate the wind speed in Manufaktura, a modified version of the logarithmic formula [42] and the dependency proposed by Simiu [43] were used. The method is described in [44]. The air flow at a height of 10 m in the downtown area of Łódź was estimated at v=1.84 m/s. The air inflow from the western sector, considered the dominant wind direction in the city, was assumed.

Hourly solar radiation values for the Manufaktura area had to be entered as input data. The ENVI-met tool automatically determines solar radiation based on geographic location. In this case, it was necessary to adjust the application settings, which indicated more intense sunlight than typical for the Łódź area. The correction factor used was 0.84. Hourly solar radiation values are presented in Fig. 6.

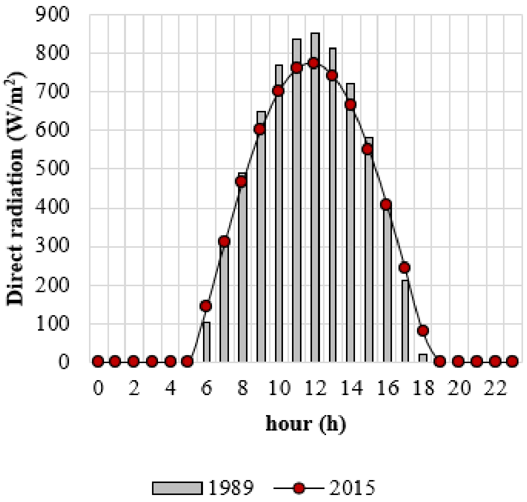


Fig. 6. Input model data: direct radiation (5 July 2015). *Source*: own work

4. The impact of changes in the spatial development of the Manufaktura area on the microclimate

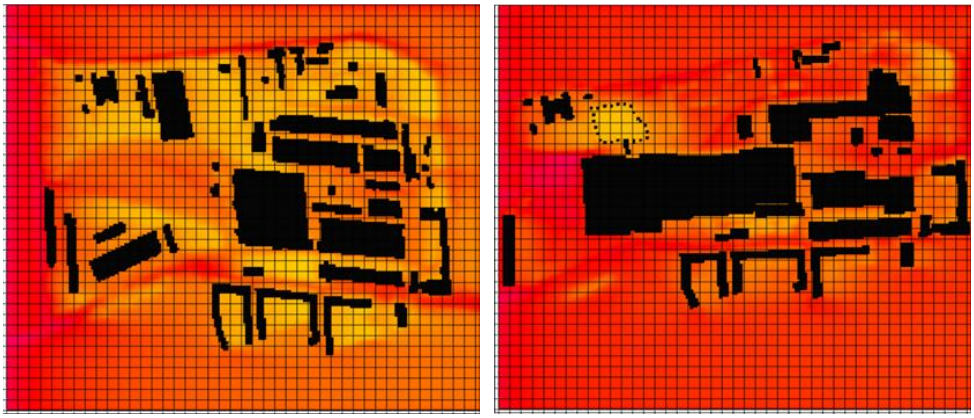
To determine the impact of changes in the spatial development of Manufaktura, numerical simulations of key microclimate parameters were carried out, including air temperature, solar radiation intensity, and surface temperature. The data was generated at a height of 1.5 meters – within the pedestrian zone. The results enabled the assessment of thermal comfort for individuals in the outdoor environment.

The results of the simulation analyses are presented below, focusing on key parameters relevant to the formation of the heat island effect in Łódź, namely air temperature and pavement temperature. The data refers to 12:00 noon (a period of strong solar radiation) and 6:00 p.m. (due to high traffic intensity of space users), both before the revitalisation process and in the current state.

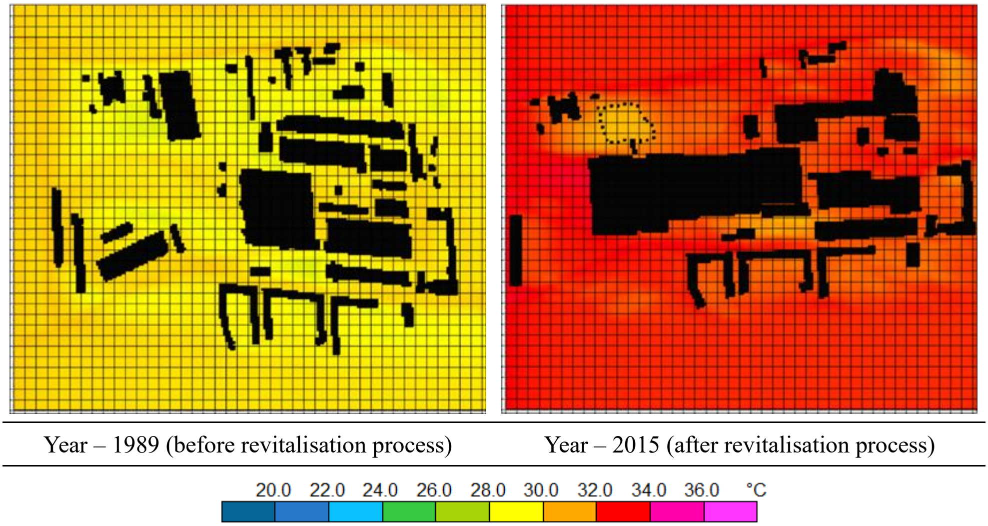
The analysis of microclimatic conditions following the revitalisation process revealed unfavourable changes in the Manufaktura area, with a deterioration in thermal conditions. This was due to demolitions in the western, northern, and north-western parts of the area, where some industrial facilities were replaced with new buildings. During the revitalisation, the area was supplemented with transport infrastructure, and large parking lots with impermeable surfaces were introduced, reducing the albedo of building materials (Fig. 3, po. 1-2). As a result, elevated temperatures were observed. Furthermore, transformations within the main square of Manufaktura also led to unfavourable outcomes (Fig. 3, po. 3). The demolition of industrial facilities and the increased exposure of the area to solar radiation resulted in persistently high temperatures (Fig. 7).

An increase in air temperature was observed both at noon and in the evening. The highest air temperatures were recorded in the square at the main entrance to the shopping mall, as well as in the parking areas located in the northern and western parts of the Manufaktura complex.

Air temperature (noon: 12:00 a.m.)



Air temperature (evening: 6:00 p.m.)



Year – 1989 (before revitalisation process) Year – 2015 (after revitalisation process)

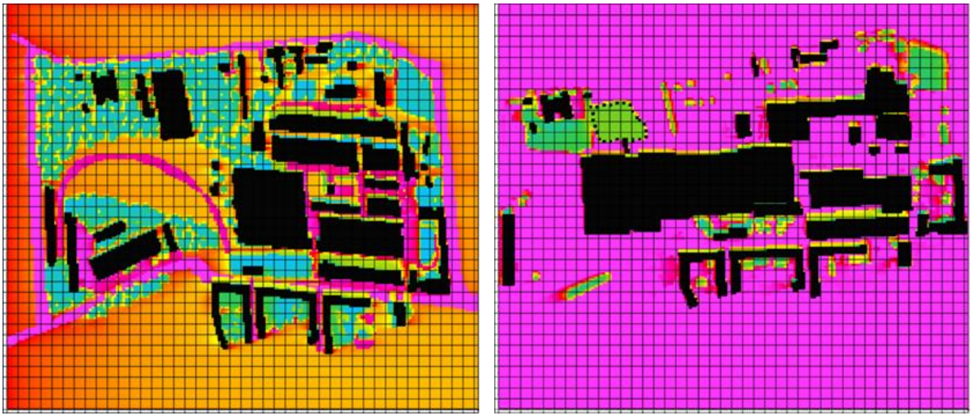
Fig. 7. Air temperature in the pedestrian zone (h = 1.5 m). *Source*: own work

The maximum surface temperature values ranged from 28 to 33°C (Fig. 8). These were recorded in areas with strong exposure to solar radiation, such as surfaces covered with impermeable materials like asphalt or paving stones (with low albedo, e.g., the main square, pedestrian zones, parking lots). As a result, these surfaces heated up significantly during the day, and the accumulated heat was released at night.

In areas where tall greenery was preserved, favourable thermal and humidity conditions were recorded. It should be emphasised that the vegetation provided additional benefits, such as enhancing the aesthetics of the surroundings and creating "cool islands" on hot days.

The minimum temperature, 20.43°C (3:00 a.m.), was observed in areas with dense tree cover. The greenery had the ability to reflect (higher albedo) and absorb solar radiation (through photosynthesis). This not only lowered the air temperature but also reduced the surface (ground) temperature.

Surface temperature (noon: 12:00 a.m.)



Surface temperature (evening: 6:00 p.m.)

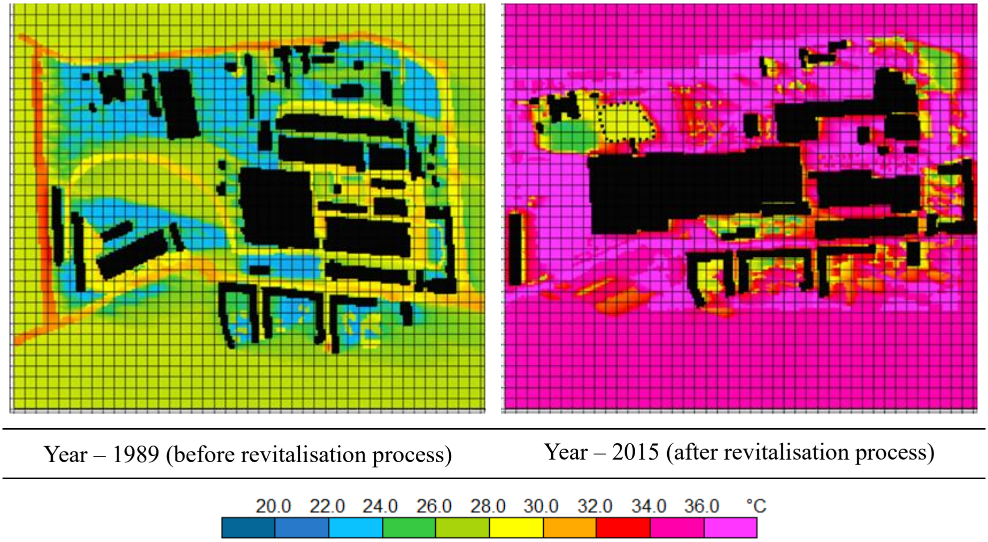


Fig. 8. Surface temperature. *Source*: own work

5. Thermal comfort

The impact of microclimate parameters on the thermal comfort of Manufaktura users was assessed using the PET index (Physiological Equivalent Temperature; Tab. 4), which determines the temperature of the isothermal external environment (Fig. 9). The PET index is currently the most frequently used indicator in the field of urban climatology [44-46]. It is defined as the air temperature at which, in a typical indoor setting (without wind and solar radiation), the heat budget of the human body is balanced with the same core and skin temperatures as under the complex outdoor conditions being assessed. This approach allows individuals to assess outdoor conditions based on their prior experience of indoor environments. In this case, the MEMI model is used to describe the human heat balance (further details in: [47]).

The least favourable thermal conditions were considered—the warmest day of the year. The data generated, in accordance with the ISO 7730 standard, relates to an adult (35 years old) with specific physical parameters (gender: male, weight: 75 kg, height: 1.75 m). Clothing appropriate for the summer season was factored in (thermal insulation = 0.5 clo). It was assumed that the values would be estimated for a person walking in the Manufaktura area (1.21 m/s).

Table 4. PET index scale. *Source*: own work

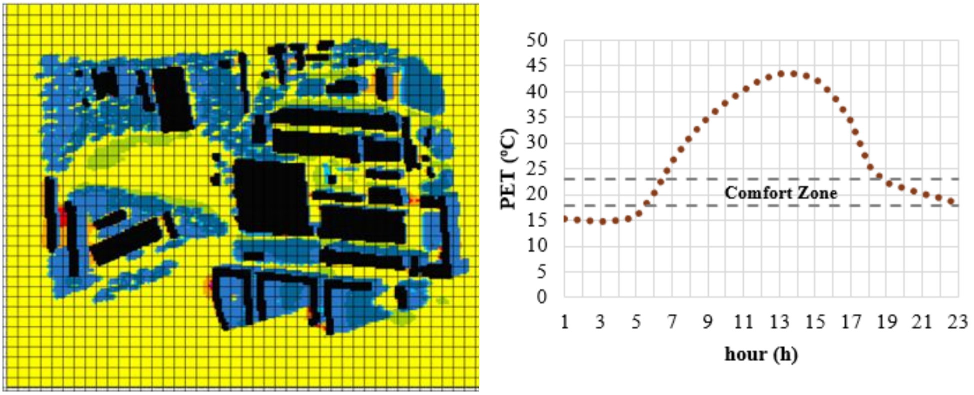
PET °C	Thermal Perception	Grade Of Physiological Stress
	very cold	extreme cold stress
4°C		
	cold	strong cold stress
8°C		
	cool	moderate cold stress
13°C		
	slightly cool	slight cold stress
18°C		
	comfortable	no thermal stress
23°C		
	slightly warm	slight heat stress
29°C		
	warm	moderate heat stress
35°C		
	hot	strong heat stress
41°C		
	very hot	extreme heat stress

The revitalisation of the area had a significant impact on thermal sensations. In the afternoon, the conditions became unacceptable (extreme heat stress). The value of the indicator was much higher than before the changes introduced in Manufaktura, reaching [+49°C].

The comparative analysis showed that the microclimatic conditions in the Manufaktura complex worsened after the revitalisation process. There were changes in both radiation and thermal parameters, with increases in both ambient and surface temperatures. The key changes contributing to the modification of the microclimate are outlined below:

1. The northern, western, and north-eastern parts of the area, before the revitalisation process, were characterised by large permeable surfaces and green areas. As part of the revitalisation, large-scale parking lots made of impermeable materials were constructed in these areas. The resulting extensive surface area being heated had a negative impact on thermal conditions, leading to an increase in air temperature.
2. The main square of Manufaktura was paved with red paving stones after the revitalisation process. This impervious surface, exposed to strong sunlight, maintained high temperatures throughout the day. The small amount of vegetation introduced did not have a significant impact on improving the thermal comfort experienced by pedestrians.

The Physiological Equivalent Temperature (before the revitalisation process: 1989)



The Physiological Equivalent Temperature (after the revitalisation process: 2015)

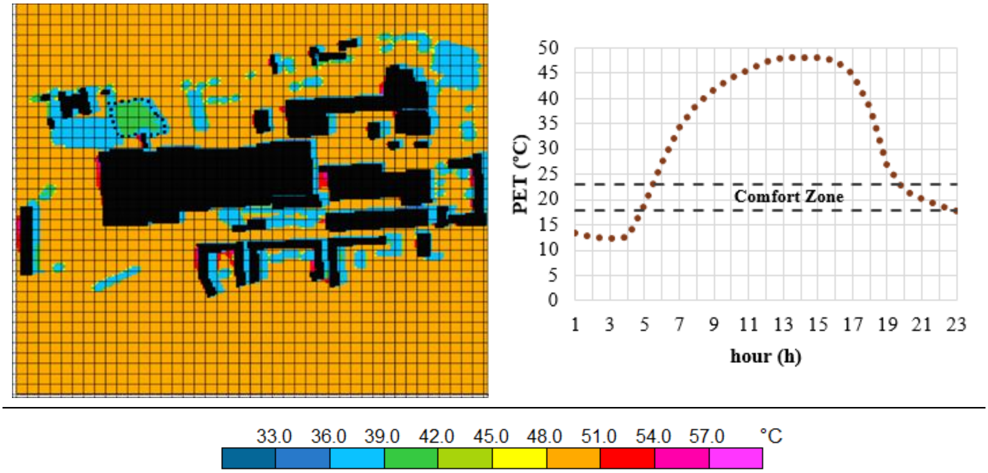


Fig. 9. Average values of thermal comfort indicators estimated in the pedestrian zone for the entire study area (h = 1.5 m); thermal comfort - PET index; pedestrian zone (h = 1.5 m). *Source*: own work

6. Possibilities for improving microclimate conditions and human thermal comfort in the Manufaktura area

As simulation studies have shown, the revitalisation activities negatively impacted the microclimatic conditions and the thermal comfort experienced by users of Manufaktura's spaces. Therefore, adaptation measures were proposed, which focused on introducing elements of blue-green infrastructure (in Scenario 2).

The first proposal was to create an extensive green roof over the entire surface of the Manufaktura main building (Fig. 12, po. 1). The base of the structure consisted of two layers of sandy clay (10 cm) with a layer of styrofoam (5 cm), topped with perennial plants (30 cm). The purpose of introducing natural roof coverings was to modify environmental parameters by reducing ambient temperature and improving air quality. An additional benefit was the creation of a large green area without the need to allocate extra land for implementation.

The multi-storey parking building was enhanced with new vertical plantings (Fig. 12, po. 3). The facility's structure, made of concrete with a low albedo value, was prone to strong heating. To mitigate this effect, climbing plants (ivy) were introduced on the facades, with perennial plants used on the southern facade, the most exposed to the sun.

For the large parking lots, it was proposed to replace the impermeable (concrete) surface with a semi-permeable (openwork) one (Fig. 12, po. 2-3). This change would allow water to soak into the ground during heavy rains, thereby improving the city's sewage system.

Additionally, high greenery in the form of rows of trees was planted in the parking lot on the western side of the main Manufaktura building (Fig. 12, po. 2). Commonly used espalier species were proposed, including small-leaved linden, common hornbeam, and horse chestnut.

Near the main building of Manufaktura, a blue infrastructure element was proposed – a retention reservoir (Fig. 12, po. 1 and 4). Its main function would be to retain and purify rainwater. Low vegetation (shrubs) and tall vegetation (trees) were planted around it. This solution would support water retention, improve air quality, reduce noise from the internal road, and lower the level of thermal discomfort felt by people in the outdoor environment.

6.1. Effectiveness of the adopted solutions

The impact of selected blue-green adaptation strategies is presented in Fig. 10. The greatest reduction in air temperature was observed in the western, northern, and north-eastern parts of the Manufaktura complex, where semi-permeable surfaces were introduced in parking lots. The air temperature decreased by up to 1.8°C. A significant modification of thermal conditions was observed in the area where the retention reservoir was introduced, leading to a reduction in ambient temperature by 1.0–1.2°C. The transformations carried out in the main square also contributed to a positive change in microclimatic conditions. Green infrastructure, such as green walls and the natural roof covering of the main shopping facility, created a cooling effect.

The blue and green infrastructure also impacted surface temperatures, as shown in Fig. 11. Vegetation, with its higher albedo compared to building materials, reflected a significant amount of solar radiation, with some energy being used in the process of photosynthesis. As a result, natural surfaces heated up less than artificial materials. The introduction of grass in parking lots resulted in a surface temperature reduction of up to 16.6°C, helping to lower ambient temperatures. In the main square, surface temperatures were reduced by as much as 19.4°C. The implementation of blue infrastructure, such as the water reservoir, further contributed to a cooling effect. Planting grass on roof slopes and ivy on the walls of the large parking lot also influenced the thermal conditions in the immediate vicinity of these adaptive solutions.

Additionally, the impact of the introduced adaptation strategies on thermal comfort was assessed at selected measurement points (Fig. 12). The analyses were conducted at pedestrian walking height (h = 1.5 m).

The effectiveness of the chosen adaptation strategies: the basic scenario vs. the adaptation scenario

air temperature difference
(noon: 12:00 a.m.)

air temperature difference
(evening: 6:00 p.m.)

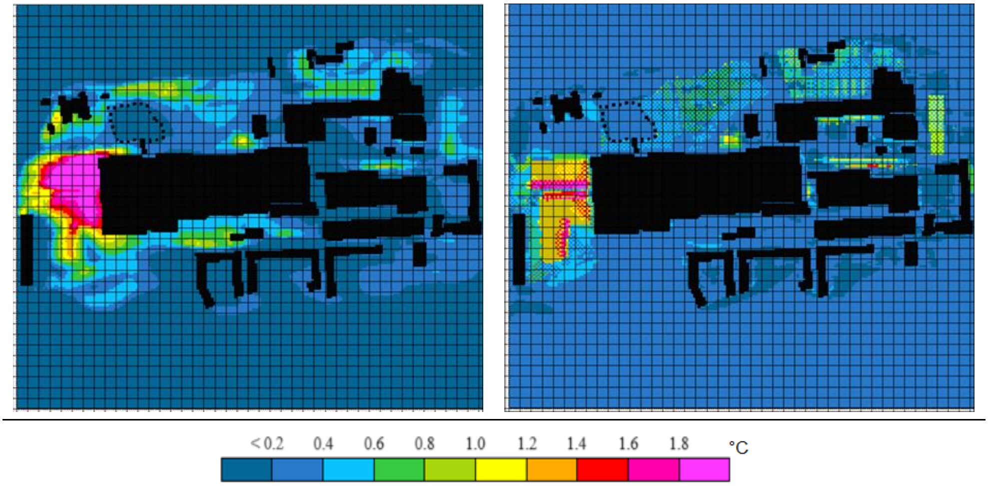


Fig. 10. Reduction in air temperature resulting from the implementation of selected adaptation strategies (pedestrian zone, h = 1.5 m). *Source*: own work

The effectiveness of the chosen adaptation strategies: basic scenario vs. adaptation scenario

surface temperature difference
(noon: 12:00 a.m.)

surface temperature difference
(evening: 6:00 p.m.)

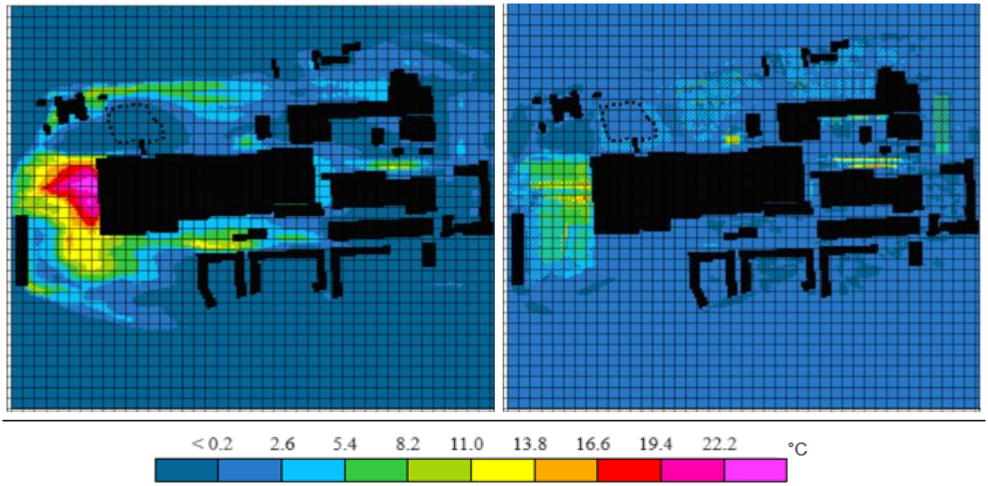


Fig. 11. Reduction in surface temperature resulting from the implementation of selected adaptation strategies. *Source*: own work

The introduced adaptation strategies influenced the thermal comfort conditions on the eastern façade of the main building of Manufaktura. The measuring point (point 1 – eastern façade) was located near the main square, where natural (water) surfaces and new greenery were added. The green roof also contributed to the modification of thermal sensations (Fig. 13). The PET value was reduced by a maximum of 5.03°C. Comfortable conditions lasted significantly longer after the introduction of the adaptation strategies. However, the selected blue-green solutions did not lead to a substantial improvement in thermal conditions overall. The hardened surface of the main square remained exposed to strong sunlight, resulting in persistently high air temperatures.

Fig. 12. Location of measurement points (1 - eastern façade, 2 - western façade, 3 - multi-storey parking lot, 4 - retention reservoir). *Source*: own work

The use of large semi-permeable (grass) surfaces in parking lots proved to be an effective adaptive solution, leading not only to the modification of microclimatic conditions but also to improved thermal comfort (point 2 – western façade), (Fig. 14). A significant reduction in the PET index was observed, with a change of 26.48°C. During this time, conditions described as "warm" were recorded. The use of semi-permeable natural surfaces should be considered a beneficial strategy, potentially translating into not only better microclimatic conditions but also improved water management, with greater rainwater retention.

The walls of the multi-storey (concrete) parking lot were covered with plants (ivy, perennials). Research results (point 3 – multi-storey parking lot) showed that the implementation of green walls was an effective strategy for modifying thermal conditions (Fig. 15). The maximum change recorded in the PET indicator was 16.28°C, with sensations described as "warm".

In the Manufaktura area, a water reservoir was created near the northern façade of the main building (point 4 – retention reservoir; Fig. 16). Greenery was planted around it. Thermal comfort analyses using PET indicated improved thermal conditions, which were downgraded to the "warm" level.

A significant improvement in thermal conditions was achieved through the introduction of green solutions in the Manufaktura complex. Large areas of parking lots in the vicinity were transformed, with semi-permeable (openwork) surfaces installed. Additionally, new vertical plantings, including green walls on the large parking lot, were introduced. These measures positively impacted thermal sensations at the water reservoir.

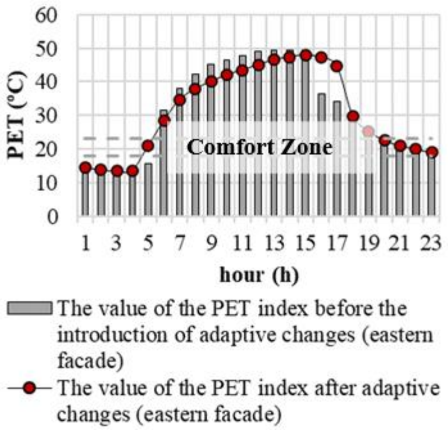


Fig. 13. The PET index near the east façade of the main building in the Manufaktura complex (po. 1); estimated in the pedestrian zone (h = 1.5 m). *Source*: own work

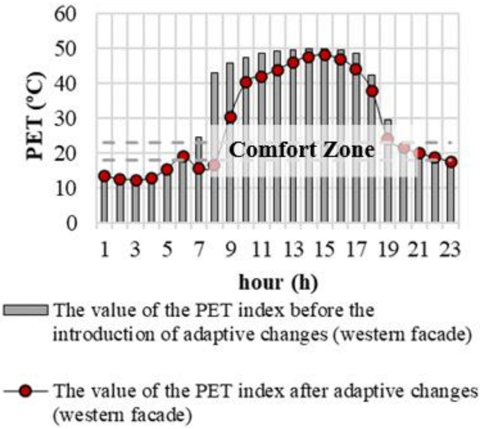


Fig. 14. The PET index near the west façade of the main building in the Manufaktura complex (po. 2); estimated in the pedestrian zone (h = 1.5 m). *Source*: own work

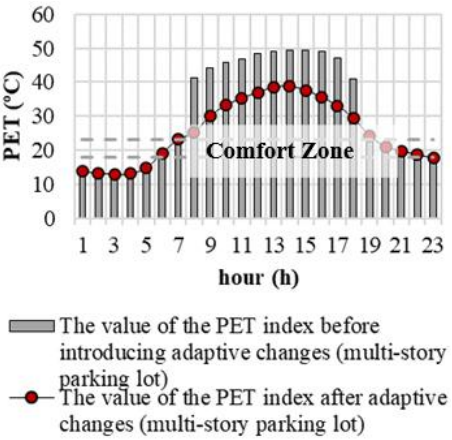


Fig. 15. The PET index near the façade of the multistorey car park in the Manufaktura complex (po. 3); estimated in the pedestrian zone (h = 1.5 m). *Source*: own work

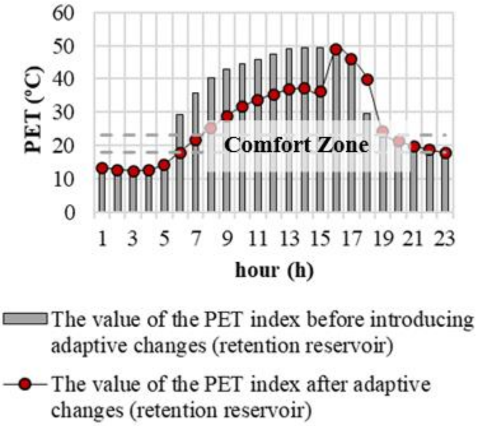


Fig. 16. The PET index near the water reservoir in the Manufaktura complex (po. 4); estimated in the pedestrian zone (h = 1.5 m). *Source*: own work

Literature studies confirm that urban building parameters play a key role in shaping microclimatic conditions. The introduction of natural adaptation strategies has a moderate impact on improving meteorological parameters, and thus, on enhancing the thermal comfort perceived by humans. Acero et al. [48] assessed the effectiveness of vertical greenery implementation in a forecourt surrounded by high-rise buildings in Singapore. This area was substantial in size (399 m x 414 m), and free airflow was maintained between the surrounding buildings. The spatial-mean PET reduction was 4°C on the east façade, which receives significant daytime sunlight. A smaller effect was observed when blue infrastructure elements were applied. Sözen & Oral [49], who conducted a study in Mardin, Turkey, reported a maximum PET reduction of 1.4°C and confirmed that the impact of blue-green strategies depends on building dimensions, height-to-width ratios, and the number of layout openings.

Herath et al. [50] indicated that elements of blue-green infrastructure modify microclimatic conditions. Conducting research in Colombo, Sri Lanka, they demonstrated that the introduction of significant greenery reduced air temperature by 1.76–1.90°C during peak temperatures. In this study, a similar reduction in ambient temperature was observed. It can be assumed that the cooling effect would be even more pronounced if the selected strategies were implemented across all facilities in the Manufaktura complex.

According to Rui et al. [51], adaptive solutions contribute to improving thermal comfort in outdoor environments. Their research in Nanjing, China, confirmed that planting tall greenery helps reduce thermal discomfort. Analyses using the PMV index showed an 18% reduction in thermal sensations in areas with trees. The cooling effect was directly related to the amount of vegetation introduced. Comparative analysis showed that the reduction in the indicator in the Manufaktura area was three times greater. The introduction of green roofs, green walls, tree lines, a retention reservoir, and the replacement of parking lot surfaces significantly improved thermal sensations.

7. Conclusions

Modern cities are grappling with the effects of climate change, driven by ongoing anthropogenic transformations, including dense downtown developments, the creation of large impervious surfaces, and the reduction of green spaces. These factors significantly modify thermal conditions, one of the manifestations being the urban heat island phenomenon, where temperatures in city centres rise compared to open areas. This effect is further intensified by poor ventilation in urban areas.

One of the most intense heat islands was recorded in the Łódź area, primarily due to the city's urban layout, featuring compact and dense tenement buildings in the centre, as well as unfavourable weather conditions. Contributing factors included extensive paved areas, minimal greenery, and built-up riverbeds. To improve conditions in the city, an adaptation plan was developed, focusing on the introduction of blue and green infrastructure elements.

This study analysed the Manufaktura complex, a shopping, service, and entertainment centre located in the quarter bounded by Drewnowska, Zachodnia, Ogrodowa, and Karski streets. First, the microclimatic conditions present in 1989, when the area still served industrial functions, were assessed. At that time, the area had less development, a higher proportion of permeable surfaces, and large areas of tall vegetation. Human thermal sensations during this period were described as "uncomfortable".

Next, the impact of spatial development changes, which occurred during the revitalisation of Manufaktura, on microclimatic conditions and thermal comfort was evaluated. The results were compared to the base scenario (when the area served industrial functions). The transformations introduced to the Manufaktura complex negatively impacted microclimatic conditions due to (1) the demolition and expansion of buildings, (2) the creation of a multi-storey large-scale parking lot, (3) the introduction of large parking lots covered with significant impervious surfaces, and (4) the reduction of green spaces. These changes altered radiation conditions (increased sunlight exposure) and thermal conditions (increased air temperature and heating of building materials).

To improve microclimatic conditions, several blue-green infrastructure elements were proposed:

- creation of a green roof on the main building of Manufaktura,
- planting vegetation on the green walls of the multi-storey parking lot,
- replacement of parking lot surfaces with openwork slabs,
- introducing vegetation and blue infrastructure elements in the main square,
- planting rows of trees next to the large parking lot,
- introducing a retention tank at the northern façade of the main Manufaktura building.

The effectiveness of these blue-green infrastructure elements was assessed through numerical simulations using the ENVI-met application. The adaptation strategies influenced the thermal conditions in the Manufaktura area, resulting in reduced air and surface temperatures. The most effective solutions were (1) the introduction of openwork surfaces for parking lots, (2) the creation of a water reservoir, (3) horizontal greening (green roof), and (4) vertical greening (green walls). However, no significant improvement was observed in the main square of Manufaktura, where the large surface area made of artificial materials continued to negatively impact thermal conditions.

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