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ADAPTATION OF PUBLIC SPACES TO CLIMATE CHANGE CASE STUDY OF LODZ

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A b s t r a c t
Climate change is nowadays one of the most important problems that affects urban areas, where over half of the population lives. Due to the continuously growing population, significant number of citizens will be affected by its impact. For this reason, one of the steps to adapt cities to changing climate conditions is the implementation of adaptation strategies based on blue-green infrastructure elements.
In this article, the existing conditions of two selected public spaces in Lodz (Poland) and the impact of the proposed modernization projects were examined. The aim of the study was to determine the extent to which the proposed projects will improve microclimatic conditions and thermal comfort, and to select a more efficient urban planning option. Simulations of meteorological conditions and thermal comfort for representatives of four groups of space users were done by using the ENVI-met program.
This study reveals the relevance of the thermal comfort subject, especially for people over 65 years of age, due to the increased sensations of elderly during high temperatures and the increasing participation of this demographic group in the population of Lodz.

K e y w o r d s: **Blue-green infrastructure; Climate change; Microclimatic conditions; Numerical simulations; Public spaces; Thermal comfort.**

1. INTRODUCTION

In recent years, there have been growing interest in the subject of microclimate in urban spaces and the thermal comfort of cities residents, mainly due to progressive climate change and an increasing awareness in the shaping of urban structures. Climate change is currently one of the most significant challenges that confront civilisation. Its effects can be observable primarily in agriculture, the marine ecosystem, water management, forestry, energy, tourism, and cities. It has an impact not only directly or indirectly on the natural environment and the economy, but also on society [1–4].

The progressive process of urbanization and the constantly increasing population make urban areas particularly vulnerable. Due to the way they are developed, these terrains have a higher risk of phenomena such as Urban Heat Island, heatwaves, droughts, strong winds, heavy rain, hailstorms, and local flooding. These have a significant influence on people living in urban areas, causing thermal discomfort, and contributing to the deterioration of a residents' health.

Nowadays, more than half of the population lives in cities, and this is forecasted to increase substantially in the future [5]. This means that the issue of the negative effects of climate change in urban spaces will affect an increasing number of people. Particularly noteworthy are the groups of people who are most vulnerable and susceptible to extreme microclimatic conditions, which include, in priority, people over 65 years of age and children under 5 years old, as well as the chronically ill, disabled, the mobility impaired and the homeless dwellers [6].

Numerous studies have been carried out in recent years using numerical tools to analyse the microclimatic conditions prevailing in urban spaces. These studies focused on public squares, parks, or streets in cities such as Rome [7], Hong Kong [8], Valladolid [9], Lublin [6] and Lodz [10]. They have shown that the use of greenery and water elements in urban areas has a mitigating effect on the negative effects of climate change, while also improving compositional and aesthetic functions.

In this article, it was undertaken to examine the existing microclimatic conditions of two public spaces in a highly urbanised part of Lodz (Poland) and to investigate the impact of the current urban development on the thermal perceptions of the selected four groups of residents. In the next step, the microclimatic conditions and the Physiological Equivalent Temperature (PET) index were simulated using the ENVI-met program taking into account proposed design assumptions for the transformation projects of selected spaces. The warmest day of the summer months was chosen for the analysis, due to the highest air temperature value and the most uncomfortable outdoor environment. A special attention was given to study the thermal perceptions of the elderly that day, whose percentage in the city is steadily increasing.

2. BLUE-GREEN INFRASTRUCTURE AS URBAN ADAPTATION STRATEGIES

Many cities have already started to face the ongoing climate change and have undertaken adaptation strategies in their development policies. Adaptation is a process consisting of a series of activities to prepare cities for current or future climatic conditions.

Adaptation activities are mostly directed to enhance the proportion of blue-green infrastructure in an urban space through the introduction of forms such as parks, greens, estate and roadside greenery, green roofs, green facades, water areas, watercourses or artificial reservoirs and increased shading in the public spaces [11]. The possibilities for the implementation of a blue-green infrastructure depend on the level of investment, landform, characteristics and functions of surrounding buildings and a land property ownership. It is important to consider the degree of soil sealing, the hydrological structure and potential contamination of the area [12]. Other measures to enhance the outdoor environment in cities include changing the geometry of buildings, using special materials with high albedo values that will absorb less heat during the day and reflect solar radiation, reducing impervious surfaces, using specialised appliances to store rainwater and to facilitate infiltration water into the ground.

Literature research shows that the effects of each adaptation strategy can be various [13–20]. Effectiveness of the undertaken actions is mainly determined by the level of economic development of a city, spatial structure [21], size [22–23], geographical location [24–25], climatic zone [26–28], population and the layout of buildings [29–30]. The specific features of the urban environment frequently require combined solutions. The most challenging areas to implement adaptation activities are compact inner-city areas, due to considerable development density and the high percentage of sealed surfaces. Especially difficult are the historical city centres with historic buildings under conservation protection, which makes it impossible to interfere with the geometry of structures [12].

Urban Adaptation Plans, implemented as part of the "MPA44" project, are helpful in preparing large cities for climate change. Lodz has its own Urban Adaptation Plan, whose overarching objective is to effectively adjust the city to climate change in order to maintain sustainable development and provide safety for its inhabitants. The project analysis identified the main climate risks for the city and the most vulnerable sectors, which are public health, water management, transport, and high-intensity residential areas. A series of individual adaptation activities have also been developed for this city, which include ones that focus on increasing biologically active areas, developing a blue-green infrastructure system, and creating new public green places. The result is expected to be an increase in the thermal comfort of the residents, thereby improving their quality of life [31–35].

3. CHARACTERISTICS OF SELECTED PUBLIC SPACES

Two public spaces in Lodz (Poland) were selected for detailed analysis: the Old Market Square and the

Figure 1.
The Old Market Square currently (OM-0), project 1 (OM-1) and project 2 (OM-2), source: [36, 38]

Dabrowski Square. The common features of both areas are their location in a highly urbanised area and their way of landscaping, characterised by a predominance of impervious surfaces and little shade. In addition, both squares have transformation projects that introduce solutions for the city's adaptation to climate change. For each square, two transformation projects were selected to study microclimatic conditions and thermal comfort.

3.1. The old market square (OM)

The Old Market (Fig. 1) is located in the northern part of the city in the Baluty district, and it has a rectangular shape. Three sides of the square are surrounded by post-war historic tenement houses with arcades, each from three to four storeys hight. Whereas the south side is adjacent to a large complex of greenery called "Park Staromiejski". Currently (OM-0) the square is covered mostly with an impervious surface and little greenery. It has several large trees growing in the northern and eastern parts of the area. However, it lacks small architectural elements.

Projects from 2017 (OM-1) and 2021/2022 (OM-2) for the revitalisation of the square were selected for analysis. Both projects involve changing the pavement, increasing the biologically active areas, and adding new greenery. OM-1 envisages increasing the number of trees from 46 to 52 and OM-2 from 46 to 63. These two options also include the appearance of water fountain jets in the floor, market shelters and small architectural elements. The OM-1 project additionally introduces a glassed-in commercial building in the southern part of the square [36–37].

3.2. The Dabrowski Square (DS)

The Dabrowski Square (Fig. 2) is located at Narutowicza Street in the Central district. It has a rectangular shape and is located in the front of The Grand Theatre building. In 2009, a large unsuccessful modernisation of the square (DS-0) was implemented which degraded its functionality. Existing lawns and trees were removed at this time and the entire square was covered with an impervious surface. A fountain in the shape of a sea wave was placed in the northern part. The space is characterised to the present day by a lack of small architectural elements and sun protection objects [39].

The square was decided to be redesigned again and three options for a new development were presented in 2022. This article analyses two of them, chosen by the residents of Lodz in a vote held at the end of 2022 (DS-1 – first place, DS-2 – second place). Both projects envisage a view opening on to the Grand Theatre building, reducing the sealed surfaces in favour of biologically active areas, especially on the main square slab. Additionally, the projects include the rebuilding of the fountain and the construction of commercial and restaurant buildings. They are different mainly in the layout of the new greenery, the size of the water elements and the location of the new buildings. DS-1 proposes to plant 184 additional trees, increase green spaces to 27% and new water elements taking up 4% of the square terrain. The eastern part of the square will be arranged as an urban forest with a retention zone. DS-2 includes 135 new trees, increase to 29% of natural areas and 2% of the water surface [40].

4. RESEARCH METHODOLOGY

Computer simulations are becoming more prevalent in urban climate research and provide a faster alternative to existing qualitative studies. To simulate meteorological conditions and to assess thermal comfort, ENVI-met 5.0.3 was used. This is a CFD (Computational Fluid Dynamics) software, which

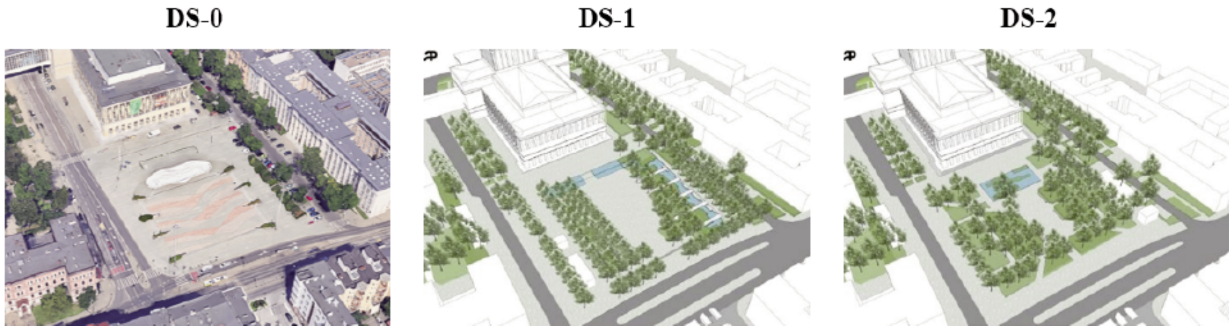

Figure 2.
The Dabrowski Square currently (DS-0), project 1 (DS-1) and project 2 (DS-2), source: [41–42]

Table 1.
Simulation input parameters, source: own elaboration

Input parameters	Data used in the models	Input parameters	Data used in the models
simulation day	5 July 2015	specific humidity	9.5 g/kg
simulation time	24 h	temperature	14.6–34.2°C
wind speed	0.8 m/s	relative humidity	20–85%
wind direction	270° (west)	adjustment factor for radiation	0.8
air pressure	996.4 hPa	surface roughness	1.0 m

enables the creation of three-dimensional, non-hydrostatic microclimatic models for urbanized areas. Using this program, it is possible to simulate the relation between substrate – vegetation – air in the twenty-four hour cycle from 24 to 48 hours [43]. The software takes into account the airflows between buildings, processes of vertical and horizontal heat exchange of surfaces, turbulence, transpiration, vegetation parameters, as well as dispersion of pollutants. This is currently one of the most popular tools used to do numerical simulations.

4.1. Meteorological parameters

The information for the warmest day of the Typical Meteorological Year, which occurred on 5 July 2015, was used for the numerical simulations [44]. Hourly values of air temperature, relative humidity, radiation, and air flow were implemented as an input data to simulate atmospheric processes. For precise analyses, the time of day with the highest temperature (2:00 p.m.) was chosen due to the presence of increased thermal discomfort conditions.

The necessary data were collected from databases of the Lodz-Lublinek measurement station located in the south-western part of the city. Due to the suburban location of the measuring station, it was necessary to convert the air flow values for the centre area of Lodz. For this purpose, the dependence proposed by Simiu was used, which made it possible to modify a logarithmic equation and calculate the value of the parameter at a height of 10 metres in the central part of the city [43]. It was assumed that the ground roughness value for the downtown area was 1.0 m, and the dominant wind direction was western. The solar radiation values have been adjusted using a correction factor of 0.8. The specifics of the software also required the determination of specific humidity at an altitude of 2500 m above sea level. The values of all input parameters that were used to carry out the numerical simulations are shown in Tab. 1.

4.2. Three-dimensional numerical models

The numerical simulations required the creation of three-dimensional models of the selected public spaces, defining the geometry of buildings, materials, pavement types and greenery elements (Fig. 3). Two models of size 90 x 90 x 30 units (the Old Market Square) and 100 x 100 x 30 units (the Dabrowski Square) were made, both with a cell resolution of 2 m x 2 m x 1 and a rotation of -11°. For the vertical structure, a grid with equal distance cells was chosen.

The analysed public spaces have surfaces that are widely found in Polish cities. The major materials are concrete pavement, asphalt or brick on roads. The surfaces are mostly in shades of grey. The exception to this is red part of the floor in Project 1 of the Old Market Square. The lawns do not exceed 10 cm and the ground underneath is natural soil. To create the high greenery, native species that are better adapted to the climatic conditions of Poland were used. The

Table 2.
Materials and components used in 3D models, source: own elaboration

Surface materials	Construction materials	Tree species
concrete pavement (dark grey, light grey, red), asphalt road, brick road, ardened soil, natural soil, grass, water.	brick, plaster (cream, sand, light yellow, light green, light grey), roofing: – roofing felt (black, red), – clay tile, – aluminium sheet (red).	Common Ash, Green Ash, Norway Maple, Silver Maple, Sycamore Maple, Swedish Whitebeam, Common Robinia, Red Oak, Common Hornbeam, Abies Alba.

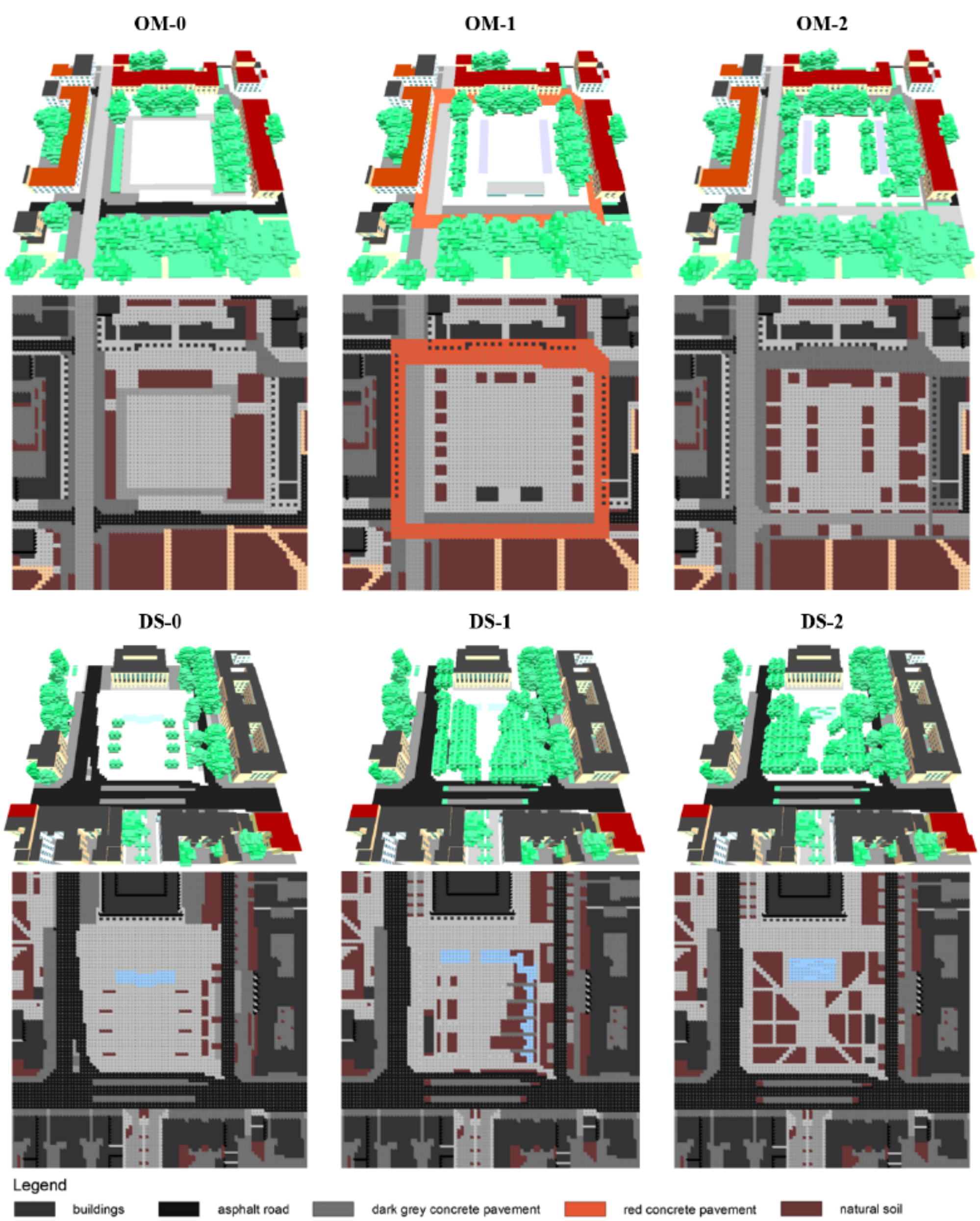

Figure 3.
3D and 2D models of the Old Market Square (OM) and the Dabrowski Square (DS) currently (0) and proposed modernizations (1, 2), source: own elaboration

shelters in both the Old Market Square projects were made using the "shading plexiglass" material. In creating buildings, it was necessary to identify structural elements typical for Lodz's city centre. The wall construction consists of internal plaster (0.02 m), ceramic brick (0.64 m) and external plaster (0.02 m). The roof construction consists of internal plaster (0.02 m), ceramic brick (0.64 m) and a suitable roof covering (0.01 m). It should be mentioned that physical parameters for each materials such as thickness, absorption, transmission, reflection, emissivity, specific heat, thermal conductivity, and density were determined. All the materials and elements used to make the three-dimensional models are shown in Tab. 2.

4.3. Thermal comfort

Thermal comfort is defined as the condition of mind which expresses satisfaction with the thermal environment [45]. A more specific definition describes thermal comfort as a state of sustainable human-environment thermal balance. It means that the heat produced by the body, generated during the metabolic process, is equal to the heat given off to the environment by processes such as convection, radiation, and conduction. Comfortable conditions are achieved when the heat balance equals zero. A value other than zero is formed when the thermal balance is disturbed [46].

The heat balance and the sensation of thermal comfort are affected by physical environmental parameters such as air temperature, mean radiant temperature, relative air velocity and vapour pressure in ambient air, as well as a person's activity level and thermal resistance of clothing [47].

The thermal comfort of the outdoor and indoor environment can be evaluated using a significant number of indices. Literature research shows that there are currently more than 165 measures, which can be divided into empirical and rational [48].

In this study, for each development option for the two selected public spaces, a thermal comfort was assessed using the PET (Physiologically Equivalent Temperature) index. This is the most frequently used index, defined as air temperature at which, in a typical indoor setting (without wind and solar radiation), the heat budget of a human body is balanced with the same core and skin temperature as under complex outdoor conditions [49]. PET values are measured in Celsius degrees on a nine-stage scale for temperate climates (Tab. 3). Comfortable conditions occur when the PET value is between 18.1°C and 23.0°C. Above 23°C there will be heat stress and below 18°C – cold stress. The more the temperature value deviates from the comfortable range, the greater the stress intensity increases [50].

The research in this article includes representatives of four groups of public spaces users, paying especial attention to dwellers over 65 years old, who are among the most vulnerable groups. They accounted for almost 25% of Lodz's population in 2022 and their percentage will increase in the next years. Simulations were therefore made for a person of pre-working age, a woman and a man of working age and a person of post-working age. The parameters of the selected users are shown in Tab. 4.

Table 3.
PET index scale, source: [20]

PET [C]	Thermal sensation	Physiological stress level
< 4.1	very cold	extreme cold stress
4.1 – 8.0	cold	strong cold stress
8.1 – 13.0	cool	moderate cold stress
13.1 – 18.0	slightly cool	slight cold stress
18.1 – 23.0	comfortable	no thermal stress
23.1 – 29.0	slightly warm	slight heat stress
29.1 – 35.0	warm	moderate heat stress
35.1 – 41.0	hot	strong heat stress
> 41.0	very hot	extreme heat stress

5. ANALYSIS OF THE SIMULATION RESULTS

The conducted studies of microclimatic conditions were limited to the three main parameters that are most influential in the context of climate change and human thermal comfort. Air temperature, humidity and wind speed were analysed for both public spaces.

Table 4.
Parameters of public space users applied in the simulations, source: own elaboration

No.	Gender	Age [years]	Height [m]	Weight [kg]	Metabolism [met]	Other parameters
1.	man	8	1.4	30	2.0	Clothing insulation [clo]: 0.5 (light summer clothes) Movement speed [m/s]: 1.2 (average walking speed)
2.	woman	35	1.7	65	1.4	
3.	man	35	1.8	75	1.5	
4.	man	80	1.7	65	1.4	

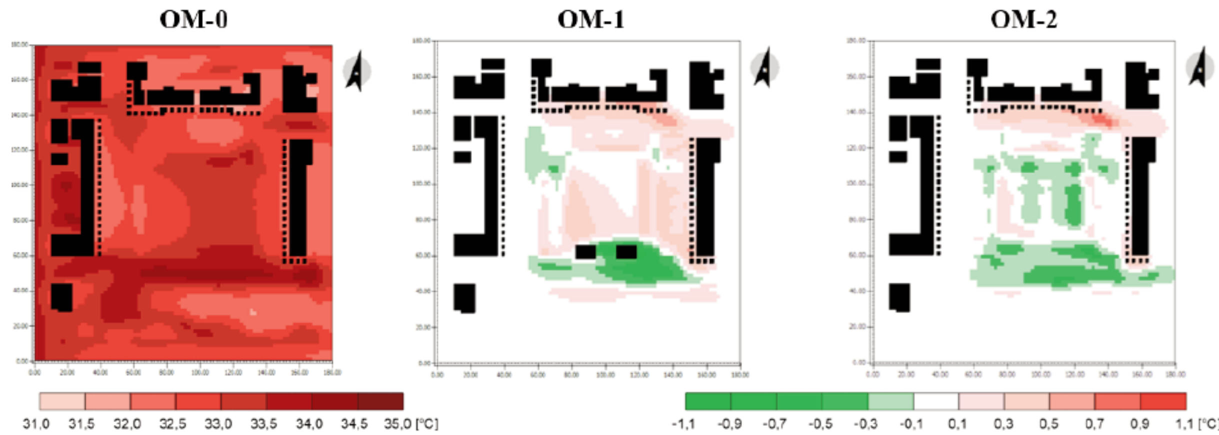

Figure 4.
Air temperature in the Old Market Square currently (OM-0) and differences after the implementation of project 1 (OM-1) and project 2 (OM-2), source: own elaboration

Microclimatic conditions and thermal comfort analysis were carried out at 2:00 p.m. at the level of human movement (1.5 m).

5.1. Microclimatic conditions of the old market square

The air temperature value in the Old Market Square (Fig. 4) during the surveyed day is in the range of 31.5–34.5°C, thus exceeding 30°C throughout the area. The highest temperatures (around 34°C) can be seen along the roadway on the southern side of the square, where the surface is made of asphalt. Higher air temperatures (around 33°C) are also found in the shadeless centre of the square. Lower temperature values (around 32°C) are observed on the western side by the stone-paved Zgierska Street and in areas of high greenery.

OM-1 provides the largest change (about -0.5°C) along Podrzeczna Street, where the asphalt surface has been changed to concrete pavement. The next improvement in value can be noticed around the new building. The maximum value of the temperature at that location decreases by 0.8°C compared to the basic model. Temperature increases of about 0.2°C, which is observed in the northern and eastern parts of the square, and is attributed to the change in the colour of the road surface from grey to red. The air temperature is also negatively affected by market shelters, where values increase by around 0.4°C.

OM-2 also introduces a values reduction of 0.3–0.6°C along Podrzeczna Street, where the pavement is changed. The improvement in conditions can also be seen in the southern and central part of the square, where new trees and natural soils are added. The maximum decrease in temperature value is 0.6°C compared to the basic model. An increase in temperature values (around 0.5°C) can be noticed on the northern side of the square due to the use of darker paving than in the base model. In this option, the negative impact of the market shelters can also be seen, which is mitigated by the adjacent greenery. The OM-2 option provides value improvements over a larger area than the OM-1.

The distribution of relative humidity (Fig. 5) is closely related to air temperature. As the temperature rises in a given location, the relative humidity value decreases. The relative humidity values in the Old Market Square range from 22% to 29%. Significantly higher values can be observed at the location of high greenery. Lower humidity is found along roads, particularly with an E-W orientation. The western part of the model, from where the wind comes in, is also less humid.

OM-1 reduces the maximum humidity by 0.4% compared to the basic model. The parameter value increases of 0.5–1.2%, which can be seen at the location where new trees are added, the paving is changed from asphalt and around the new building. However, a large part of the square is characterised by a decrease in relative humidity, particularly at the place with shopping shelters.

The OM-2 option reduces the maximum value of the parameter by 0.1%. The greatest increase in value (by 2%) occurs in the central part of the square, in place with the new greenery. An improvement in humidity (around 1%) is also observed along Podrzeczna Street. A value decrease (around -1%) can be observed on the northern and southern parts

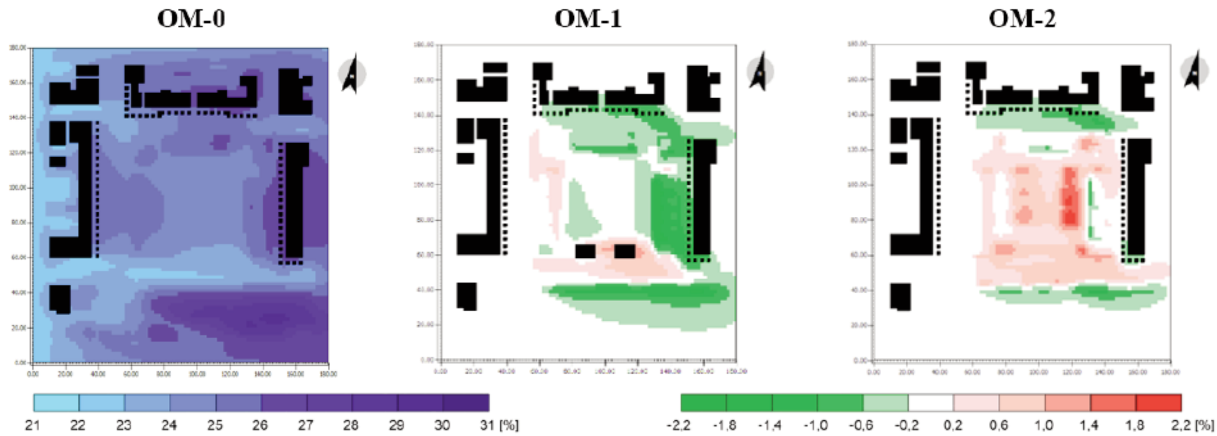

Figure 5.
Relative humidity in the Old Market Square currently (OM-0) and differences after the implementation of project 1 (OM-1) and project 2 (OM-2), source: own elaboration

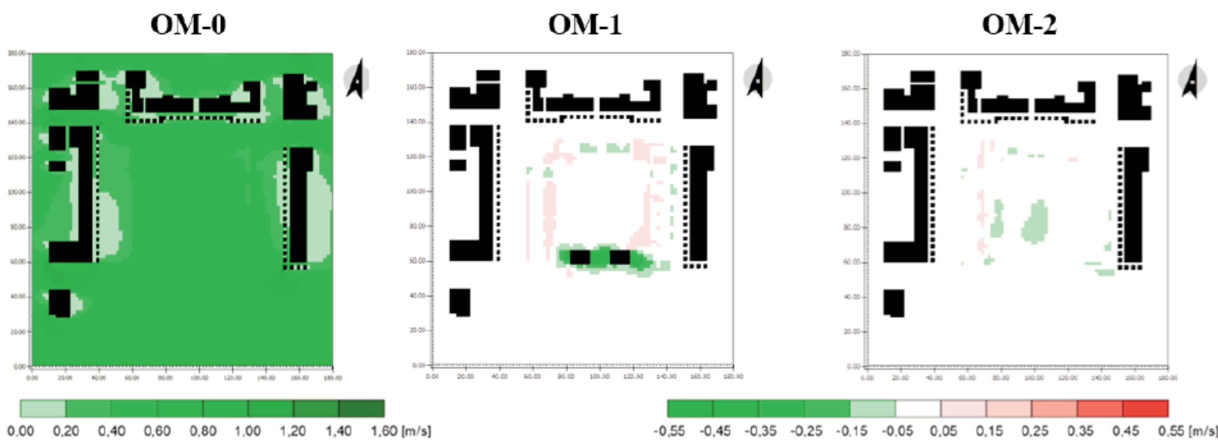

Figure 6.
Air flow in the Old Market Square currently (OM-0) and differences after the implementation of project 1 (OM-1) and project 2 (OM-2), source: own elaboration

of the square. The OM-2 option is more likely to give the desired increase in humidity than the OM-1.

The Old Market Square is characterised by a low air flow between 0.0 and 1.2 m/s (Fig. 6). The higher values can be seen along roads with an E-W orientation and at the corners of buildings. Due to the westerly wind direction, lower values of the parameter also occur on the eastern sides of the buildings (leeward side).

In OM-1, the largest changes (by -0.6 m/s) can be found around the new building. A slight increase in wind speed (by around 0.1–0.2 m/s) can also be noted in the area of the shopping shelters. In OM-2 option, the maximum decrease in the parameter value is 0.1 m/s and occurs in the central part of the square. Air flow speed also increases (by approximately 0.1 m/s) in the area surrounding the shopping shelters on the west side. The implementation of both project 1 and project 2 does not result in significant changes in air flow values.

5.2. Thermal comfort of the old market square

The PET index values for all analysed groups (Fig. 7–10) range from 41°C to 59°C. It means that the entire study area has extreme heat stress conditions, described as "very hot". The highest values (50–59°C) occur in the central part of the square and along communication routes, especially with a N-S orientation. Higher PET values are a result of the lack of greenery, the lack of shade and materials with low albedo. The lowest values (41–46°C) can be seen in parts with high greenery and on the northern and eastern sides of buildings, as a result of the location of the sun on the sky at this time of year and day.

Analysing the PET index value for the surveyed people, the smallest range between the highest and lowest values are for a child (12.0°C) while the biggest differences are for an adult woman (17.0°C) and an elderly person (16.9°C). The maximum perceived PET for a child during the summer season is about 3°C lower than for adults. This means that summer conditions in the Old Market are assessed as much more discomfortable by the elderly than by younger people.

The OM-1 project brings the biggest changes for adults. An increase in PET values (approximately 2–4°C) occurs at points where natural soil was changed for sealed pavement. The critical areas in terms of thermal comfort are spaces under the shopping shelters. There, the PET index is over 54°C. The maximum increase in a value relative to initial development is higher for the elderly (5–6°C) than for a child (3.4°C). The reduction of PET index mainly occurs at the location of new trees and in the undercroft of the new building. Compared to the base model, the maximum value of the PET index decreases by almost 9.5°C for adults and by 5.4°C for a child.

After the implementation of the OM-2 option, there are a few unfavourable changes. The PET index increase occurs at the locations of the shopping shelters. Their damaging effects mainly has an impact on the elderly. Disadvantageous conditions can also be seen where pavement has been changed. The maximum increase in parameter value is almost 7.2°C for adults and 2.9°C for children. Positive impacts might be noted in places where new trees and biologically active areas have been introduced. Conditions are definitely becoming better in the central part of the square. The maximum decrease in PET index is almost 9.5°C for adults and 5.4°C for a child.

Option OM-2 introduces more positive changes in the study area than option OM-1. Noticeably, the child is less affected by the changes taking place in the square compared to the other people surveyed. The most significant differences are particularly for older people.

5.3. Microclimate conditions of the Dabrowski Square

The air temperature in the Dabrowski Square (Fig. 11) ranges from 31.5°C to 35.5°C. The highest temperatures (approximately 34.5°C) are found along roads with asphalt pavement. High temperatures (around 33.5°C) also occur in the western and southern parts of the square near the streets. Slightly lower values (around 33°C) are observed in the eastern part, at the site of single trees. The lowest temperatures (below 32°C) are noticeable in the courtyards of tenement houses, however this does not affect the sensations in the square area.

The DS-1 project results in a decrease in maximum air temperature of 0.4°C. The biggest changes (around -1.2°C) occur where the blue-green infrastructure elements are implemented. The maximum value of the parameter decreases by 1.4°C in the south-eastern part of the square. A temperature increase (of 0.5°C) compared to the base case is noticeable only in the centre of the square, as a result of the pavement change.

The DS-2 option reduces the maximum air temperature by 0.3°C. As in the case of project 1, the greatest improvements occur at the location of the blue-green infrastructure elements. The biggest decrease

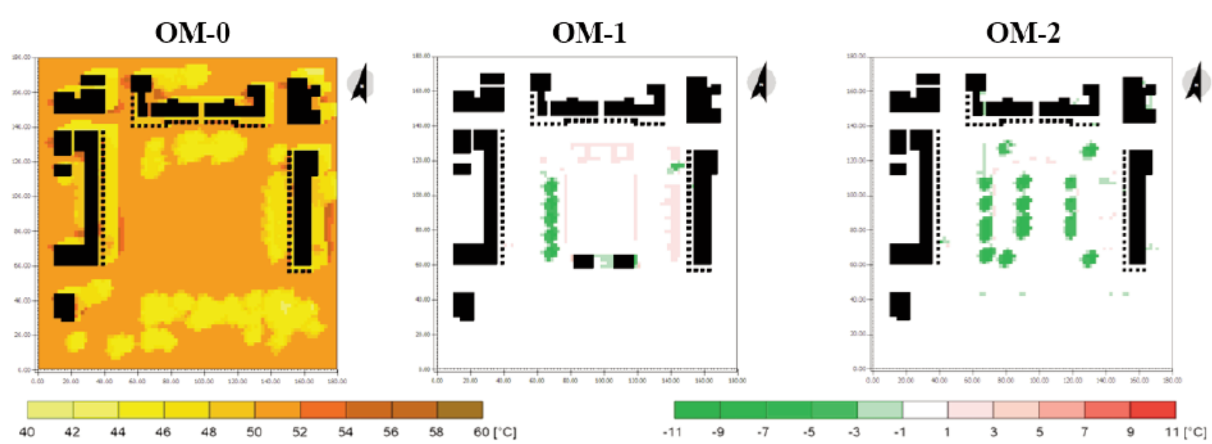

Figure 7.
PET index for a child in the Old Market Square currently (OM-0) and differences after the implementation of project 1 (OM-1) and project 2 (OM-2), source: own elaboration

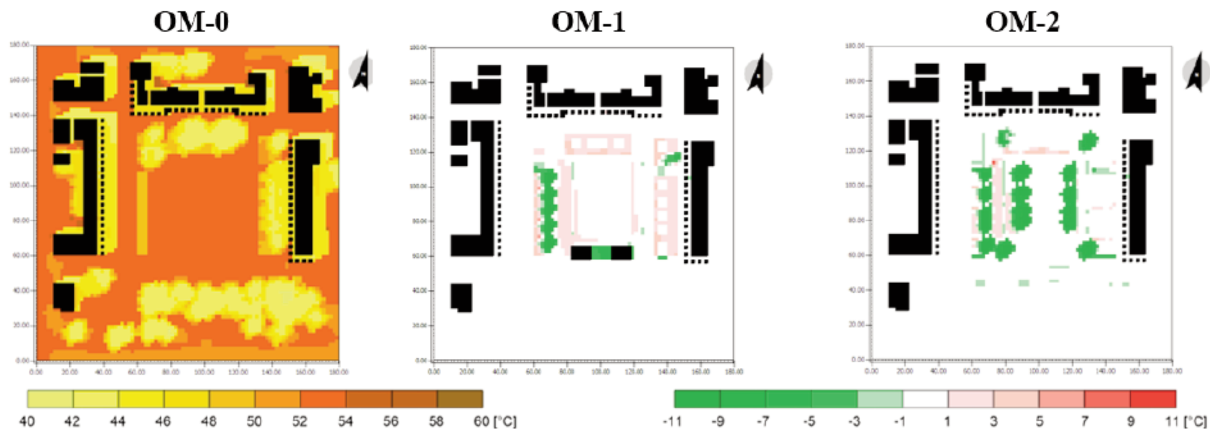

Figure 8.
PET index for adult man in the Old Market Square currently (OM-0) and differences after the implementation of project 1 (OM-1) and project 2 (OM-2), source: own elaboration

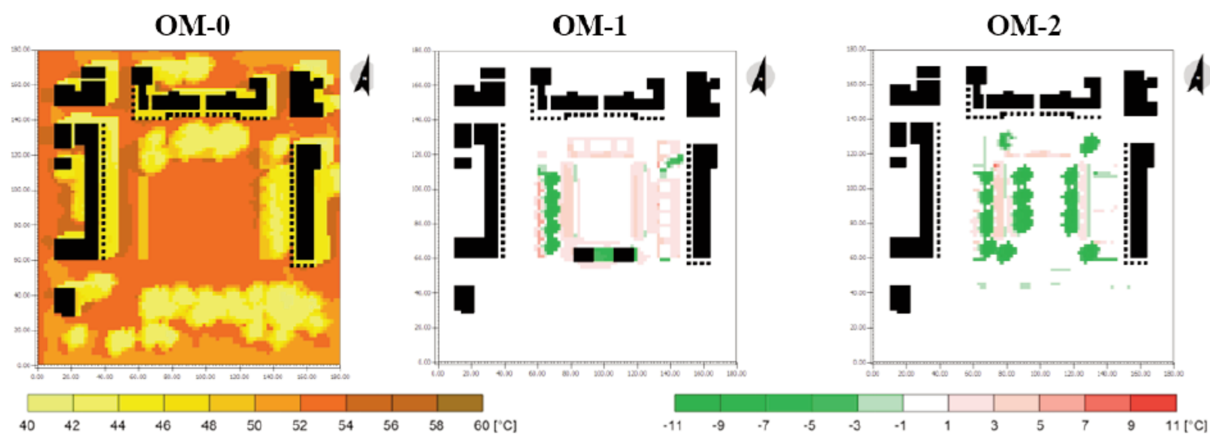

Figure 9.
PET index for adult woman in the Old Market Square currently (OM-0) and differences after the implementation of project 1 (OM-1) and project 2 (OM-2), source: own elaboration

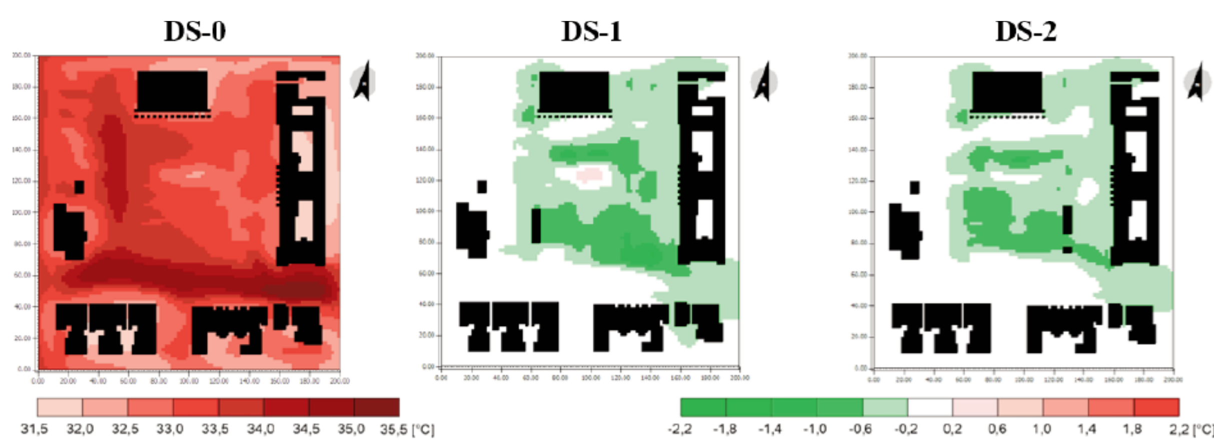

Figure 10.
PET index for elderly person in the Old Market Square currently (OM-0) and differences after the implementation of project 1 (OM-1) and project 2 (OM-2), source: own elaboration

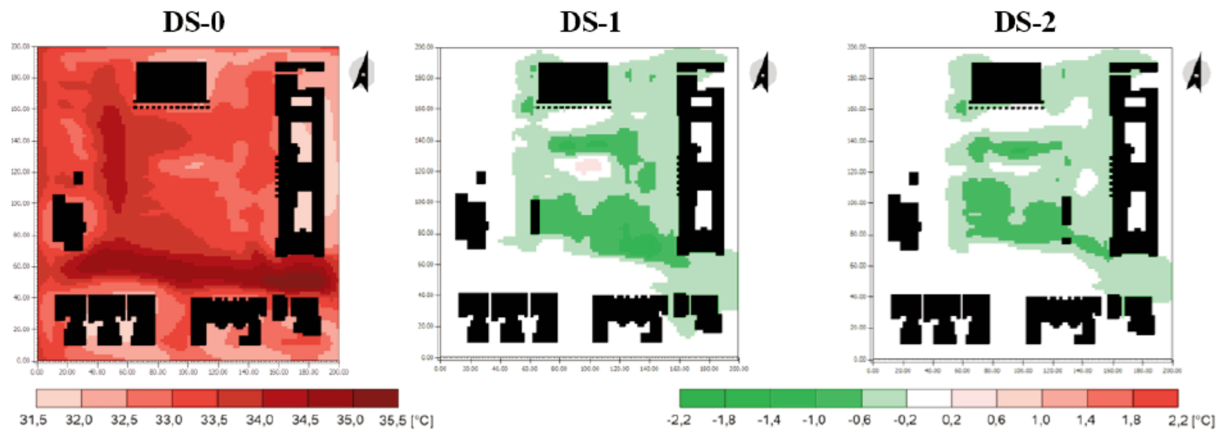

Figure 11.
Air temperature in the Dabrowski Square currently (DS-0) and differences after the implementation of project 1 (DS-1) and project 2 (DS-2), source: own elaboration

(around -1.0°C) can be found in the southern and western parts of the square. The increase in temperature values is a maximum of 0.2°C which is almost imperceptible. Both projects result in similar temperature improvements throughout the area.

The relative humidity values in the Dabrowski Square (Fig. 12) range from 21 to 27%. A lower value for this parameter (around 22%) can be observed along communication routes, particularly with an E-W orientation, and in the western part of the area. A higher value is found on the eastern side of the square. Maximum (around 26%) is observed in the courtyards of tenement houses and the District Court in Lodz.

The DS-1 project results in an increase in the maximum humidity value of 2.1% compared to the current development. An increase in relative humidity occurs over the entire study area. The greatest changes (by 3-4%) are in the south-eastern and eastern parts of the square, where greenery and water bodies are added. The decrease in humidity values (-0.3%) is practically unnoticeable.

The DS-2 option increases the maximum value of the parameter by 1.8% compared to the base model. The greatest improvement in conditions (approximately 4.3%) occurs in the southern and south-western parts of the square, where the new biologically active terrains are added. The decrease in value is not perceptible and is lower than in the DS-1 case (-0.01%). Both projects introduce significant improvements to the relative humidity at the Dabrowski Square.

The Dabrowski Square is characterised by low air flow between 0.0 and 1.7 m/s (Fig. 13). The maximum wind speeds (approximately 1.6 m/s) are found at the corners of the buildings: the south-west corner of the Grand Theatre and the District Court in Lodz, and the north-east corner at the junction of Narutowicza and Knychalskiego Streets. A lower value (around 0.2 m/s) can be observed on the eastern side of the study area.

The DS-1 option results in lower values (approximately -0.4 m/s) in the central part of the square and around the new building. An increase in wind speed (approximately 0.2 m/s) occurs in the eastern and western parts of the square, where the new trees are added.

The DS-2 option introduces analogous changes. The maximum wind speed decrease is -0.4 m/s and is observed in the central part of the square and within the new building. The air flow increases by around 0.1 m/s in the vicinity of the new trees. In both cases, there are no significant changes of parameter values.

5.4. Thermal comfort of the Dabrowski Square

The PET values at the Dabrowski Square for all analysed groups (Fig. 14-17) range from 39°C to 59°C. This means that the entire area is characterised by strong and extreme heat stress conditions described as “hot” and “very hot”. High values (over 50°C) present almost throughout the entire area are a consequence of scarce greenery and the presence of sealed surfaces. The critical terrain with the highest PET index value is in front of the main entrance to the District Court building (57–58°C). Lower values (42–46°C) are found in areas shaded by trees and on the northern and eastern sides of buildings. The smallest differences between the highest and lowest PET values are for a child (13.7°C) and the largest for

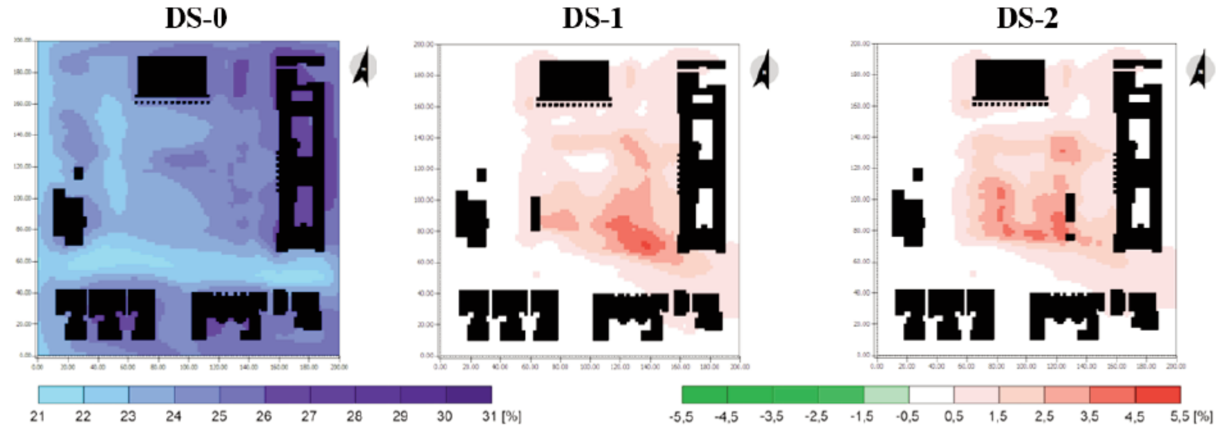

Figure 12.
Relative humidity at the Dabrowski Square currently (DS-0) and differences after the implementation of project 1 (DS-1) and project 2 (DS-2), source: own elaboration

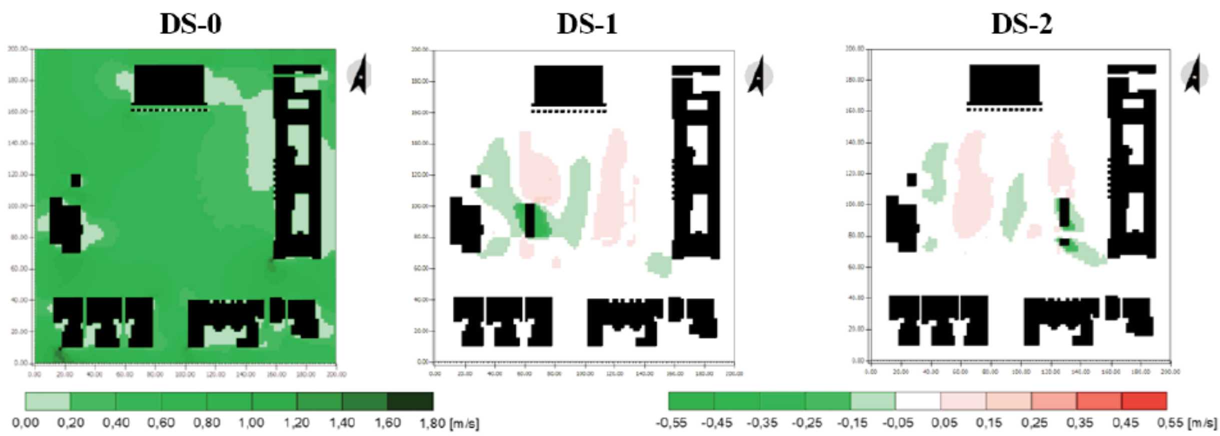

Figure 13.
Air flow in the Dabrowski Square currently (DS-0) and differences after the implementation of project 1 (DS-1) and project 2 (DS-2), source: own elaboration.

an adult woman (18.7°C). In this case, the minimum PET value for an elderly person is similar to the minimum PET value for a child. Whereas, the minimum values for man and woman in this case are perceived as strong heat stress, not extreme.

The DS-1 project implements index value improvements across practically the whole study area. The greatest changes occur around new greenery and trees, especially for adults. Thermal sensations in these places are 10.8°C lower for a child and about 12.5°C lower for adults. A slight increase in value can be seen in the eastern part of the square, where has been a change from greenery to sealed surface. The maximum increase is 0.5°C for a child and 2.2–2.3°C for adults.

The introduction of the DS-2 option results in a reduction in thermal stress intensity, particularly in the eastern and western parts of the square. The PET value decreases by a maximum of about 12.5°C for adults and 10.7°C for a child where new trees and greenery are added. A slight increase in PET is observed in the eastern part of the square, where PET rises by a maximum of 3.4–3.6°C for adults and 0.7°C for a child. As in option DS-1, this is a consequence of the pavement change and such implications are inevitable with a rearrangement of spaces.

Due to the use of a large number of new trees in both projects, it is difficult to say whether the introduction of water elements, commercial and restaurant buildings result in a significant improvement in the PET value. However, they introduce a wide variety to the development. Furthermore, the analysed projects implement a reduction of the minimum PET values for a child and an elderly person, so much so that the conditions can also be described as “hot”, not “very hot”.

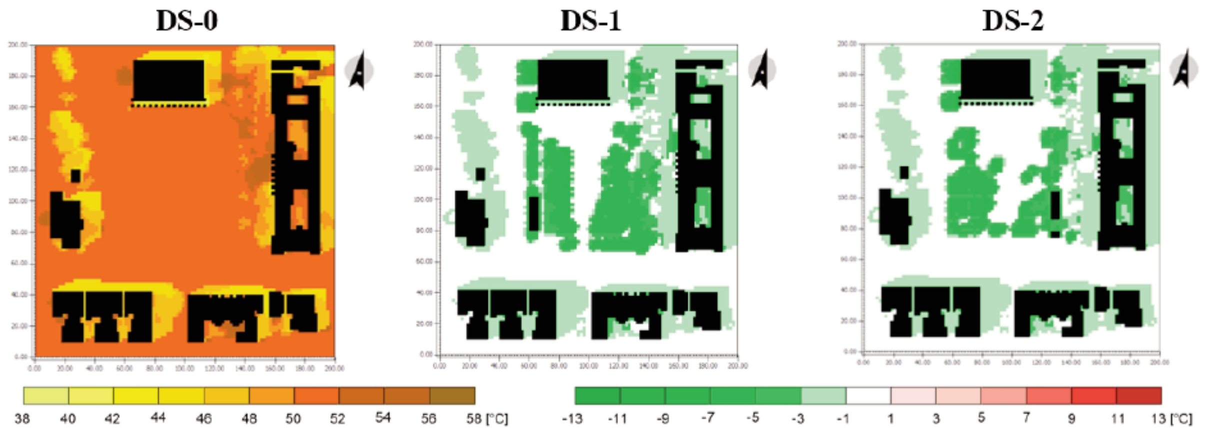

Figure 14.
PET index for a child in the Dabrowski Square currently (DS-0) and differences after the implementation of project 1 (DS-1) and project 2 (DS-2), source: own elaboration

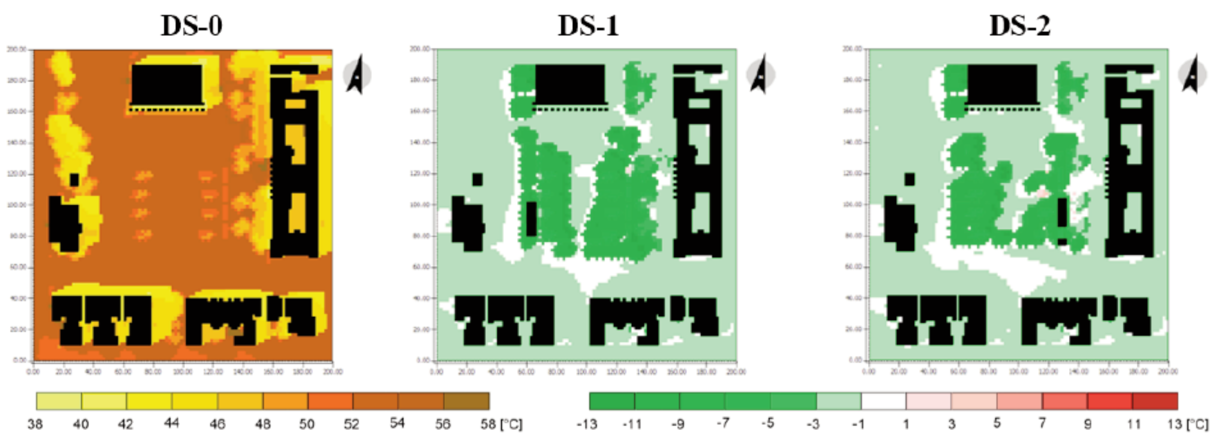

Figure 15.
PET index for adult man in the Dabrowski Square currently (DS-0) and differences after the implementation of project 1 (DS-1) and project 2 (DS-2), source: own elaboration

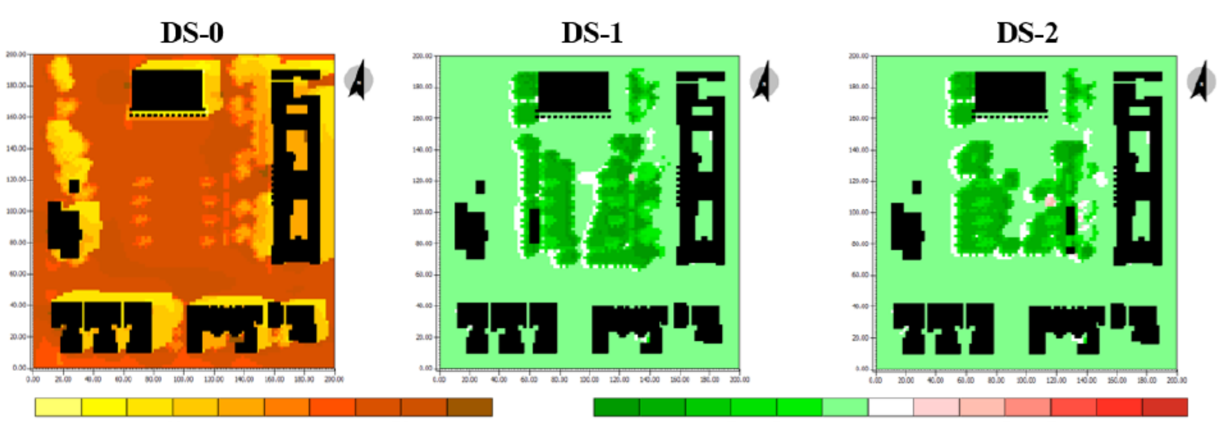

Figure 16.
PET index for adult woman in the Dabrowski Square currently (DS-0) and differences after the implementation of project 1 (DS-1) and project 2 (DS-2), source: own elaboration

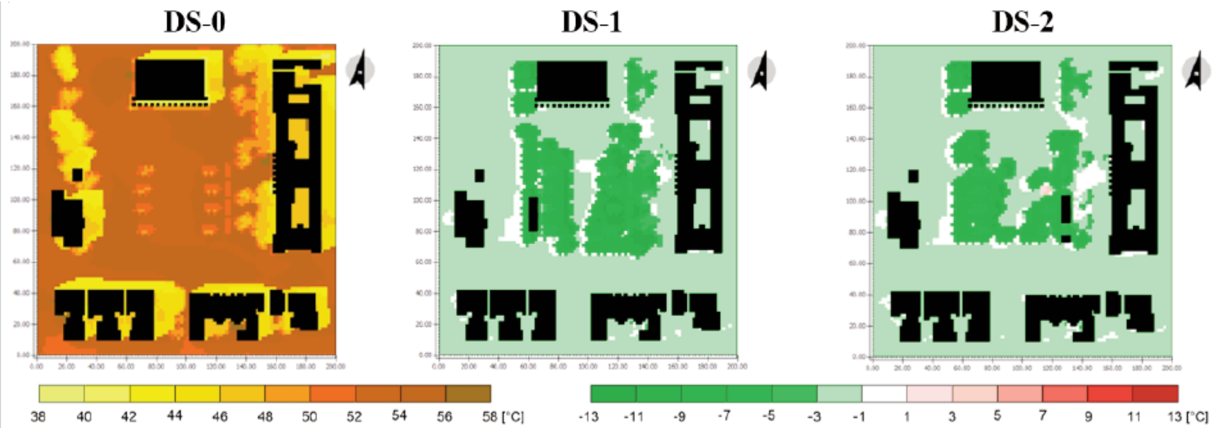

Figure 17.
PET index for elderly person in the Dabrowski Square currently (DS-0) and differences after the implementation of project 1 (DS-1) and project 2 (DS-2), source: own elaboration

6. SUMMARY OF MAIN ANALYSIS

In the face of observed and predicted climate change, the adaptation of urban spaces to new conditions is significant. Moreover, this is expected to remain a priority for many years to come. In order to support sustainable development and guarantee a high quality of residents' life, adaptation activities should undoubtedly be included in the planning policy documents of all major cities.

The perception of thermal comfort by public space users is extraordinarily complex and relates not only to the temporary perception of temperature, but also to a vast number of variables, including the individual characteristics of each person and their level of acclimatisation to the prevailing conditions.

The aim of the study was to assess the effectiveness of adaptation strategies using numerical tools. The meteorological conditions and thermal comfort in two public spaces in Lodz were analysed. The research showed that during the hottest day of a Typical Meteorological Year with the current development, the Old Market Square and the Dabrowski Square are affected by strong and extreme heat stress conditions described as "hot" and "very hot". The air temperature in both cases exceeds 30°C, and the PET indicator shows values above 39°C. The central parts of the squares are identified as the most problematic areas due to the lack of high greenery and shade.

Attempts were made to assess the effectiveness of the proposed projects for modernising the squares and to select the more effective option in terms of the impact on microclimatic parameters and thermal comfort. For this purpose, simulations of the conditions following the assumptions of the selected projects and an analysis of the changes taking place were carried out (Tab. 5). In the case of the Old Market Square, the introduction of OM-2 is more favourable due to the greater improvement of the conditions in the central part of the square, the introduction of more greenery and the greater reduction in PET values. For the Dabrowski Square, the more beneficial conditions are provided by DS-1. This option introduces more of a positive change in PET values for all analysed people. Moreover, with such a scenario it is possible to mitigate thermal sensations of users by approximately 2°C. This means a reduction in thermal stress in some places from being described as "extreme" to "strong".

The analyses carried out show that older people, compared to people of working age and children, experience higher temperature values and higher heat stress. Due to the constantly increasing numbers of elderly people in the demographic of Lodz and the general ageing of the population, the topic of the thermal comfort of this social group should be a particular subject of study and one of the priorities in planning the development of public spaces.

The most significant changes take place where high greenery and biologically active areas are introduced. The thermal comfort of the surveyed people can decrease by 10–12°C at the location of the new additional trees. The conclusion is that high trees are a great solution for reducing the amount of solar radiation reaching the ground and for alleviating the perceived air temperature. Furthermore, they can contribute to the reduction of the Urban Heat Island problem, the concentration of air pollutants and the

Table 5.
Maximum and minimum changes occurring in the selected spaces after the introduction of projects, source: own elaboration

PARAMETER		OM-1		OM-2		DS-1		DS-2	
		Min	Max	Min	Max	Min	Max	Min	Max
Air temperature [°C]		-0.8	0.6	-0.6	0.8	-1.4	0.5	-1.0	0.2
Relative humidity [%]		-1.7	1.2	-1.1	2.0	-0.3	4.7	-0.01	4.3
Wind speed [m/s]		-0.6	0.1	-0.1	0.1	-0.4	0.2	-0.4	0.1
PET [°C]	child	-5.4	3.4	-6.8	2.9	-10.8	0.5	-10.7	0.7
	adult man	-9.5	5.3	-10.4	7.2	-12.7	2.2	-12.5	3.4
	adult woman	-9.5	6.1	-10.4	7.2	-12.8	2.3	-12.4	3.6
	elderly person	-9.4	5.9	-10.4	7.2	-12.4	2.3	-12.2	3.6

improvement of humidity. The recommended solution for highly urbanised areas of developed cities is to use additionally building materials with high albedo values. Such a solution absorbs less heat during the day, preventing the pavement from heating up. During the modernisation, it is suggested to analyse several ways of the space development, especially considering the location of the blue-green infrastructure elements, in order to select the most favourable option, taking into account in particular the climate of the region.

7. CONCLUSIONS

This study can be taken as a guideline for urbanist in creating thoughtful public spaces. This also confirms the importance of analysing the microclimate of each space before preparing adaptation strategies. A complex examination of the parameters affecting the users' well-being can aid the appropriate use of an area and provision the necessary elements that are missing.

The implementation of adaptation activities through development changes can positively affect the thermal sensation of users in the outdoor environment. The use of blue-green infrastructure elements can reduce the values of microclimatic parameters, which will bring the improvement of the thermal comfort of residents. However, it is worth remembering that adaptation and the associated changes in development, as well as interference with existing buildings should take place with respect of the local architectural, urban forms and traditions.

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