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Bioclimatic rehabilitation of an open market place by a computational fluid dynamics simulation assessment

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Abstract

These days urban design of open spaces is strongly related to bioclimatic techniques and practices. It is here presented the procedure of a bioclimatic study by the use of simulation tools. The area of an open market place is characterized of decreased human thermal comfort conditions during summer time. The employment of computational fluid dynamics has contributed in the understanding of what interventions should be made at the open space in order to succeed the defined thermal related targets. Table of the proposed rehabilitation explains what the interventions would contribute in the improvement of the local environment.

Keywords: Bioclimatic design; Urban CFD; Open space intervention; Urban heat island; Thermal comfort; Cool materials

Introduction

It is widely approved that densely urban developments in conjunction with the use of inappropriate external materials, the increased human related thermal energy emission and the lack of green areas, increase environmental temperature leading to significant environmental impacts and increased energy consumption (Santamouris et al. 2012a; Santamouris et al. 2012b; Fintikakis et al., 2011). Open spaces within urban developments are complicated due to thermal energy exchange between structures, shadowing and wind flow complication in comparison to general flow. Cooling materials (Kolokotsa et al. 2013) and other practices (water surfaces, green roofs) may be used in order to mitigate urban heat island effects (Santamouris 2014a; Mastrapostoli et al., 2014; Tang et al., 2014; Tsilini et al. in Press; Santamouris 2013; Pisello et al. 2013; Georgi and Dimitriou, 2010; Gartland, 2008; Gaitani et al., 2007; Akbari et al., 2001). The main problems that result from bad thermal conditions include decreased human thermal comfort, decreased air quality, increased heat illnesses and increased energy and water use (Stone, 2005; Baik et al., 2001).

Experimental measurements within urban developments must be carried out in order to identify the thermal situation. In the Greek territory there are intense thermal phenomena mainly during the summer period (Livada et al., 2002). These are observed in open urban areas all around country. Surface temperatures in relation to microclimatic conditions (wind, temperature, radiation) must be analyzed in order to better select rehabilitating strategy of open developments.

Simulation tools must be employed (Stavrakakis et al., 2011) in order to depict the present situation around the opencast area, usually during the warmest day of the hot period. Material identification and construction configuration must also be taken into account in the simulation process. A new configuration of materials and bioclimatic techniques is then proposed and simulated in order to show its influence to the thermal urban environment. Target of this procedure is to realize the microclimatic conditions improvement due to the rehabilitating bioclimatic techniques and practices. The selection of the measures to be proposed depends on the targets that will be defined for an improved thermal environment (e.g. thermal comfort) (Santamouris 2014b; Santamouris et al. 2011; Gulyas et al., 2006).

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Due to the complicated urban environment in terms of materials, reflection, emission, wind flows around buildings, altitude differences etc. the simulation tool must be selected very carefully. It must be able to simulate three dimensional flows with solar radiation taken into account, simultaneously. This inevitably leads to the employment of computational fluid dynamics general codes (PHOENICS) but with increased demand of computational resources. Other tools may be useful for the assessment of individual parameters, such as surface materials and trees' thermal influence (Matzarakis et al., 2006) but this would not assess the wind flow effect in geometrical detail.

It is here demonstrated the procedure of a bioclimatic study of an open urban space for a city of Northern Greece, Ptolemaida (Gaitani et al., 2014; Santamouris 2013; Skoulika et al., 2014; Gaitani et al., 2011). Experimental measurements, simulation tool verification and the simulation based assessment of the proposed architectural reformation are presented. The thermal targets of this study were defined by Center for Renewable Energy Sources and Saving (Center for Renewable Energy Sources and Saving www.cres.gr).

The effectiveness of the procedure being "measurement – simulation – bioclimatic proposal – simulation" depends on the following aspects:

1. knowledge of the area and experimental accuracy (materials, experimental instrumentation)
2. verified simulation against experimental measurements (simulation of the present situation)
3. qualified collaboration between the architectural bioclimatic design and simulation (viable architectural proposals that would improve thermal conditions e.g. green roof)
4. definition of the thermal related targets (thermal comfort, cooling degree hours, improved ventilation, surface temperatures, environmental temperature).

Documentation of the thermal bioclimatic problem in the open market place

To examine the weather conditions in the city of Ptolemaida meteorological data of the last 3 years were gathered, from the meteorological stations of the Environment Centre at the entrance of the city and the station of the Greek Public Power Corporation in Pentavrysos. Environmental Centre station located at the entrance of Ptolemaida may be considered as a suburban environment. Pentavrysos located at the north-east of Ptolemaida at a distance of about 10 km was considered as a rural environment (Fig. 1). The temporal coverage of the data covered the period

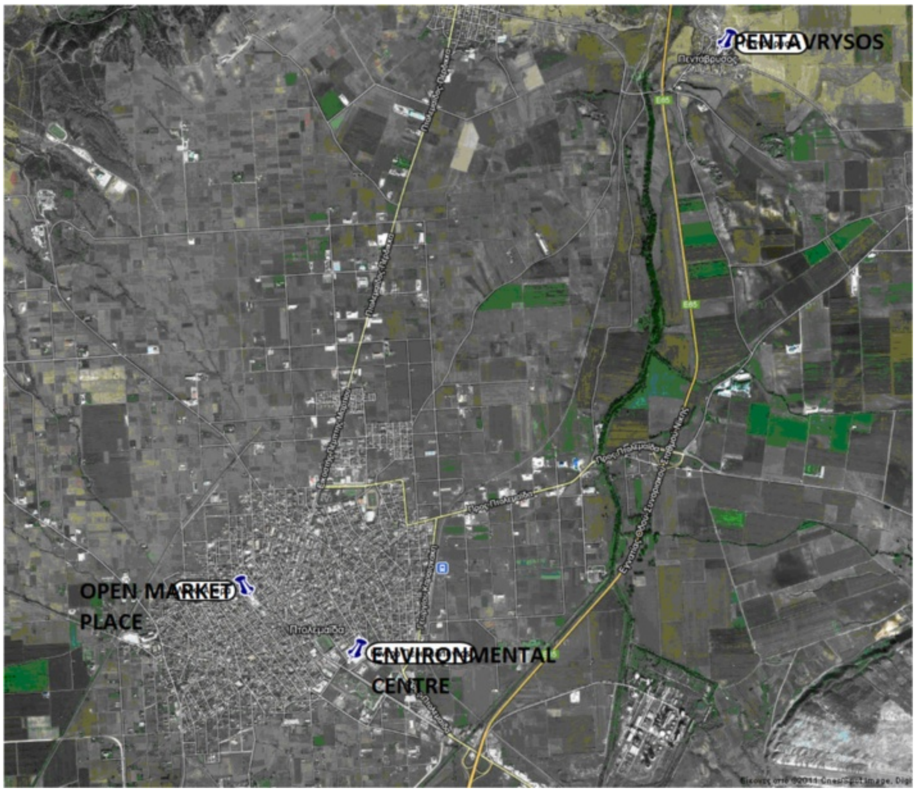


Fig. 1 Geographical representation of Ptolemaida city with the meteorological stations

between beginning of 2009 to November 2011. For both two stations hourly data were available. The meteorological parameter that was examined was the air temperature (°C).

Compared with the surrounding suburban and rural environment, urban climate varies in terms of solar radiation, characteristics of rainfall and air temperature. According to Oke (1973) almost every urban center in the world is warmer 1–4 °C than neighboring non-urban rural areas, and this enforces urban heat island effects. Also, Gilbert (1991) states that the air temperature on sunny days can be of up to 2.0 to 6.0 °C higher in urban compared to suburban locations.

The comparison of climate data during the three year period has shown a significant temperature difference between the suburban area (Environmental Centre) and the city center, which amounted to 6.1 °C, with a mean difference of 4.8 °C. The temperature difference is greater when the comparison is made against the rural area, about 10km from the city center (Pentavrysos), where the temperature difference amounts to 8.4 °C, with a mean difference of 7.1 °C. Thus the center acts as an urban heat island and open bioclimatic urban upgrading would be suggested.

Description of bioclimatic interventions in the open space of the market place

The 70% percent of the Greek power generation takes place in Northern Greece. Ptolemaida city is surrounded by power generation activities (lignite mining and combustion processes). In the commercial and social center of the city belongs the open market place that is heavy populated during the week. The urban summer time microclimate in this area is mainly affected by the presence of asphalt all over the ground surface of the open market. The southern part of the market along Pontou Street is neighbored by a multipurpose building with

Fig. 2 Description of the rehabilitated area (grey surface)

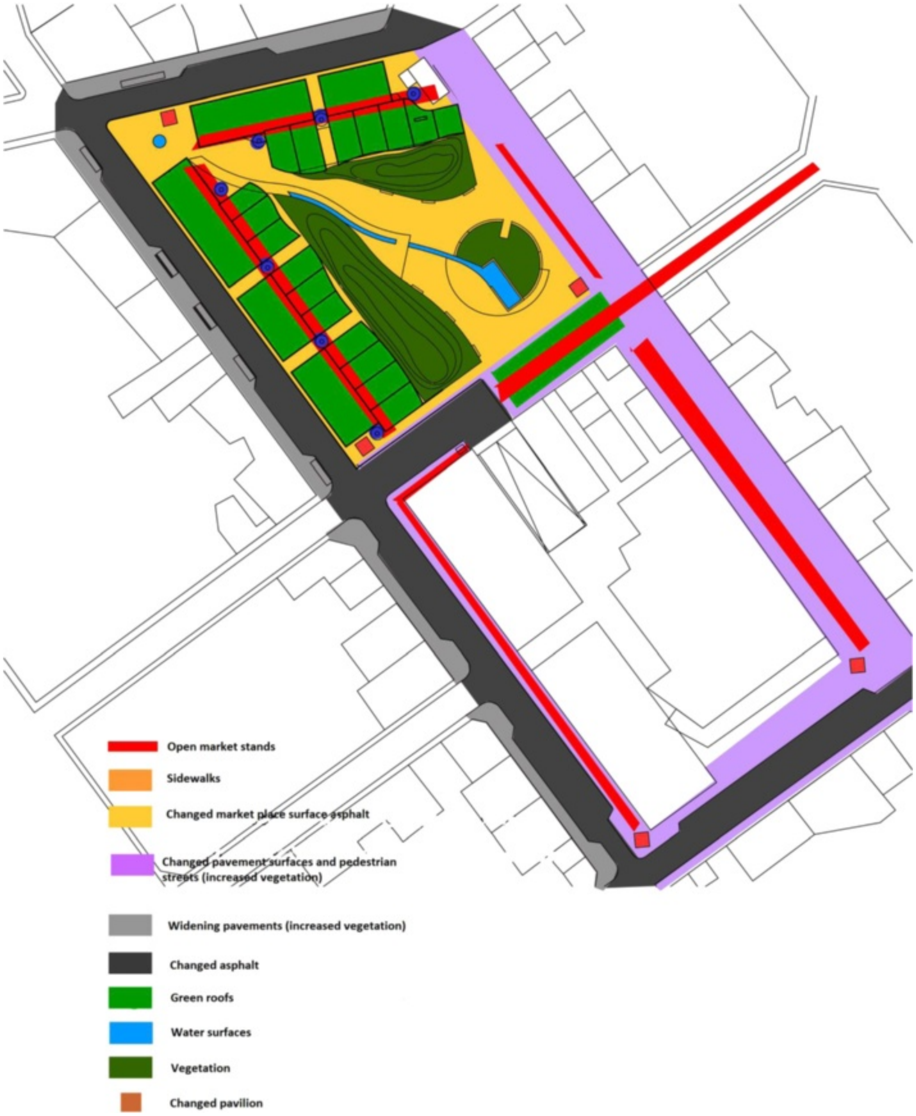


Fig. 3 Bioclimatic interventions in the rehabilitated area

vegetation and pavements. Figure 2 shows the present configuration of materials.

The rehabilitation strategy of the area targets to conserve human activities and improve human thermal conditions in the open public market. Bioclimatic interventions could be divided in two main directions (see Fig. 2):

- the open market place
- the surrounding streets of the market place (Vas. Konstantinou – South of the multipurpose building, Foufa - North, Pontou - South, Dimokratias – East and Ethnikis Antistasis – West)

The above mentioned main bioclimatic directions were characterized by increasing water surfaces, vegetation, green roofs and by installing cool asphalt and flagstones (Fig. 3).

Table 1 presents the current situation of materials and surfaces in terms of the respective percentages in surface coverings in contrast with the proposed bioclimatic based configuration.

Description of the CFD software

Advanced CFD models can calculate with a high degree of accuracy microclimatic parameters at every grid point of the meshed space. However, the more complicated is the geometry of the urban open space the more resources of input data and calculation are needed. For the efficient simulation of the thermal energy condition in the areas of interest, the detailed three dimensional tool ANSYS CFX 13 has been used. ANSYS CFX is an

Table 1 surface covering for each material before and after rehabilitation

	Present case		Rehabilitated case	
Area surface (m^2)	14,355.00			
Low plantation and water surfaces				
	Surface (m^2)	%	Surface (m^2)	%
Low plantation	0.00	0.00%	1,300.00	9.06%
Water surface	0	0.00%	85	0.59%
Total	0	0.00%	1385	9.65%
Solid surfaces (conventional materials)				
	Surface (m^2)	%	Surface (m^2)	%
Asphalt	10,290.00	71.68%	0	0.00%
Pavement flagstone	410.00	1.32%	0	0.00%
Block	3655.00	25.46%	0.00	0.00%
Marble	0	0.00%	425.00	2.96%
Total	14,355.00	100.00%	425.00	2.96%
Solid surfaces (cool materials)				
	Surface (m^2)	%	Surface (m^2)	%
Block	0	0.00%	8,235.00	57.37%
Pavement flagstone	0	0.00%	0.00	0.00%
Pebble covering	0	0.00%	740.00	5.15%
Asphalt	0	0.00%	3,620.00	25.22%
Total	0	0.00%	12,595.00	87.74%
Roofed areas				
Planted roofs	0	0.00%	1,420.00	9.89%
Shelter	0	0.00%	420.00	2.93%
Canopy	0	0.00%	240.00	1.67%
Total	0	0	2,080.00	14.49%
	Surface (m^2)		Surface (m^2)	
	Number of trees		Number of trees	
Trees	60		120	

advanced general code computational fluid dynamics model that solves the Navier Stokes differential equations and turbulence by the finite elements technique in the 3D space. It is a commercial software package that handles very detailed three dimensional geometry with the ability to solve heat transfer and fluid flow phenomena.

All simulations have been carried out in parallel by two processors (intel core™ i7-2600 CPU @ 3.40 GHz 3.00 GHz) with 16GB RAM.

Simulation details

The more detailed is the structural and 3D geometry of buildings, streets, pavements, urban equipment and vegetation the more representative and accurate simulation will be. The fluid domain (Fig. 4) encloses buildings, streets, pavements and trees as defined solids within a total dimension of 500 m * 400 m * 80 m (height) – this was at least four times the max height of structural domains in order to avoid during simulation flow reflection at boundaries and fluid returns. In the horizontal directions this was ensured due to longer boundaries.

The simulation domains have been meshed at solids' surfaces and fluid domain volume. The mesh had an element of a min length dimension of 0.2 m, with dense tetra-, hexa-, octa- surface elements (building surfaces, vegetation, water elements, etc.). The final mesh constituted of 390,530 nodes and 2,129,384 elements (Fig. 5).

Surfaces with materials (concrete, glass, pavement, water, trees) and properties (emission and reflection coefficients) have been defined. The top and horizontal boundaries were defiened as simple openings that let air flow free to pressure gradients generated in the domain. In the north boundary was imposed the northern wind direction that was observed during the simulation period. Turbulence was simulated by the Shear Stress Transport model with K-Turbulence KE and O-Turbulence frequency (Stavrakakis et al., 2012). Thermal energy was simulated by the discritised model in surface to surface and medium to surface modes. This takes into account opposite surfaces energy exchange that is very important in the heat balance of the open spaces in case of replacing conventional surfaces with cool materials. Solar radiation has been taken into account in slope and deviation through the top boundary. This way surface temperatures were calculated by the CFD simulation in relation to the input material thermal characteristics from Table 1. Vegetation has been considered as physical barrier to wind flow with shadowing without evapotranspiration effects. Water elements were defined as free surfaces (zero friction) with a constant temperature of 15°C without evaporation effects. Boundary conditions were gathered by the experimental data (air temperature, wind speed and direction, radiation, surface temperatures) that were taken during the summer period.

Simulation time step was set at 5 sec and convergence criteria at 10^{-4} RMS of residuals for steady state or transient calculation.

Model Verification

Real experimental data of the thermal conditions in the area of interest and at surrounding locations obtained the analytical verification of the CFD model and consequently the accurate simulation of both the current situation and the proposed interventions.

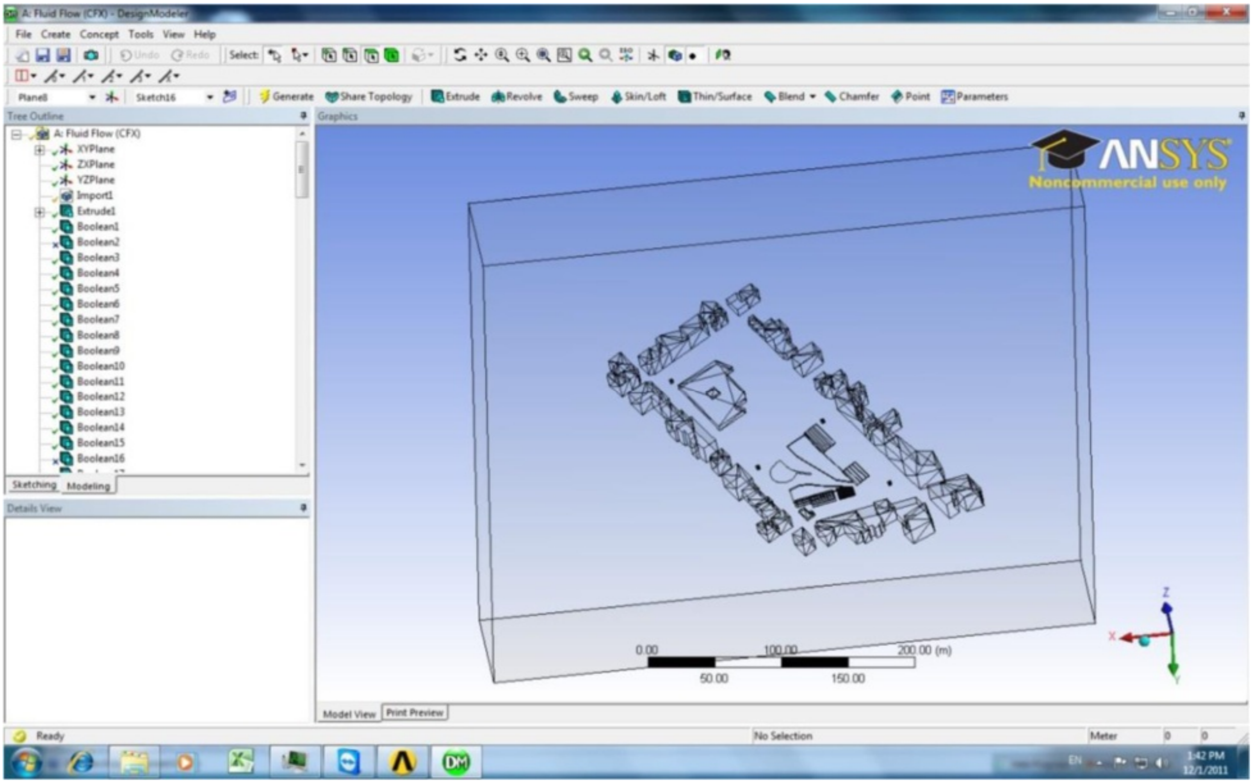


Fig. 4 Geometry configuration of the open place and the fluid domain

A number of experimental procedures were organized in the study area. The field surveys involved microclimatic monitoring by fixed measurements and a set of portable equipment. Note that, this was a measurement campaign that did not include a fully equipped monitoring station such the stations in the entrance and away from the city.

The fixed data included continuous measurements and specifically the air temperature (T), the relative humidity (RH), the wind speed (WS) and the wind direction (WD) at Environmtnal Centre site. The portable station recorded at 1.8m height the air temperature, the relative humidity, the wind speed and wind direction and solar radiation on the horizontal. The technical characteristics of the measuring instrumentation are given in Table 2 and the measuring location (ML) in Fig. 2. This height was selected as representative of the conditions prevailing at pedestrian‟s level and additionally measurements are not affected by activities at pedestrian level (walking, cars' motion).

In order to prove the ANSYS CFD model validity for the open area simulation, it was verified against experimental data that have been taken during summer 2011. From the period of experiment the warmest day was selected in terms of the completeness of the microclimatic data (i.e. air temperature, air velocity, surface temperature). It was chosen September the 1st, 2011, which recorded the highest temperatures for the period of measurement. The data used for validation of the model is the measurement data within the study area, i.e. the air temperature, the temperature of material surfaces, surface temperature of streets, sidewalks and facades of 1.8m height and the wind speed at the same height.

It was compared the simulation results against the measured values of the surface temperatures, the ambient temperature and the wind speed. Used climatic data from that period were obtained from the Environmental Centre meteorological station at the entrance of the city and climatic data were simulated in the intervention area and in places where measurement was made. Since as mentioned previously, the surface temperature measurements made during midday, the comparisons were made for the same period.

The concept of model validity was that if meteorological input from Ptolemaida's station are applied in ANSYS CFD then this could efficiently calculate the thermal behavior of within the urban complex. From

Table 3 seemed that a satisfactory convergence between experimental and simulation results. This was due to low wind velocities during hot summer days with apnea. Therefore, the achieved accuracy was quite high for the model that was developed for the study area. The above comparison substantiates the high reliability of the model for the assessment of both the current situation and bioclimatic upgrade in the study area.

Methodology

Climatic Targets

The bioclimatic concept of this study was defined according to what could be succeeded in terms of the thermal environment improvement. The climatic targets of the proposed interventions were defined by the Centre for Renewable Energy Sources and Saving, under the framework of “Bioclimatic Reformations of Open Public Spaces”, OPERATIONAL PROGRAMME ENVIRONMENT AND SUSTAINABLE DEVELOPMENT 2007–2013, AXIS 1 "Protection of Atmospheric Environment & Urban Transport - Addressing Climate Change - Renewable Energy". The microclimatic parameters that should be improved were the following:

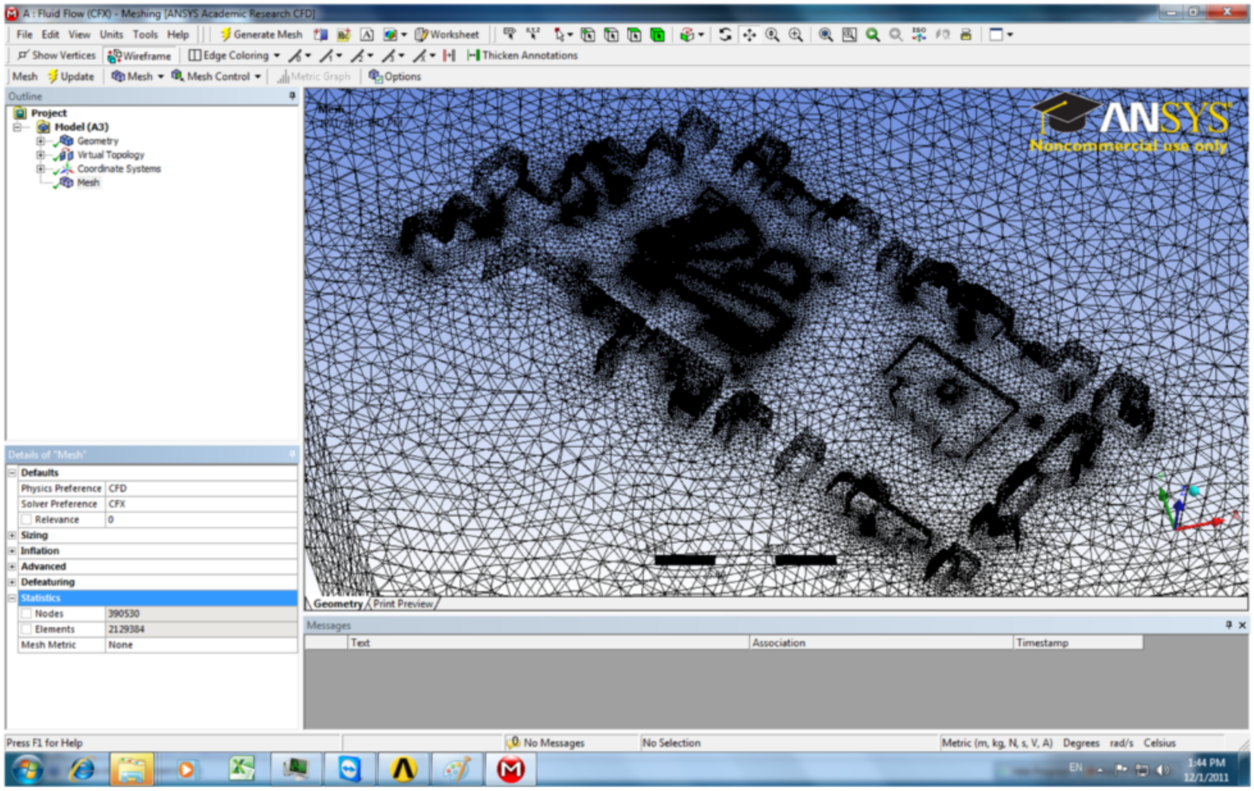
1. Mean maximum summer temperature during noon of the warmest day. The use of the term mean maximum depicts the hottest thermal conditions during noon.
2. Conditioning hours during the typical day
3. Mean surface temperature during noon of the warmest day
4. Mean human thermal comfort index
5. Wind field during the typical summer day

Materials Definition

Materials with their properties of the area (solar reflectance and thermal emission) to existing and proposed configuration are presented in Table 4.

Simulation results and discussion

The simulations were carried out for the present situation and for the proposed rehabilitated configuration. The same meteorological data from the station in Ptolemaida were applied for the simulation before (i.e. Fig. 2) and after (i.e. Fig. 3). Then, the results were compared in order to obtain the microclimatic improvement. In order to clarify matters, the input data of meteorological measurements were different between the verification of the model and the simulation



Details of "Mesh"

Defaults	
Physics Preference	CFD
Solver Preference	CFX
☐ Relevance	0
Sizing	
Inflation	
Advanced	
Defeaturing	
Statistics	
☐ Nodes	390530
☐ Elements	2129384
Mesh Metric	None

Fig. 5 Mesh screenshot of the open space

Table 2 Technical characteristics of measurement instrumentation

Temperature / Relative Humidity	HOBO Pro V2 Temp/RH Data Logger	
	Sampling Rate	1 Second to 18 Hours
	Temperature Measurement Range	−40°C to 70°C (−40° to 158°F)
	Temperature Accuracy	±0.2°C over 0° to 50°C
	RH Measurement Range	0 to 100% RH
	RH Accuracy	±2.5% from 10 to 90%
	Radiation Shield, model RS1	
		Solar Radiation Shield protects external sensors from the effects of sunlight and rain to ensure high accuracy measurements and is designed to allow maximum air flow around the sensor
	Outdoor Temperature sensor	
	Temperature	from −50°C to +90°C
	accuracy	±0,15°C
	Radiation Shield, model RS3	
		Solar Radiation Shield protects external sensors from the effects of sunlight and rain to ensure high accuracy measurements and is designed to allow maximum air flow around the sensor
	data logger	stylitis10
Wind Speed / Wind Direction	WindSonic Ultrasonic Wind Sensor	
		2-axis ultrasonic wind sensor
	Wind Direction Range	0 to 359°
	Operating Temperature	−35°C to +70°C
	Wind Speed Range	0 -60 m/s (116 knots)
	Accuracy	±2% @12 m/s
	Resolution	0.01 m/s (0.02 knots)
	Response Time	0.25 seconds
	Threshold	0.01 m/s
Photo-Radiometer	Delta OHM 2102.2 photo-radiometer	
	Operating Temperature	−5° C to +50° C
	storage temperature	−25° C to +65° C

Table 3 Comparison between experimental measurements and simulation results. Meteorological station temperature at midday was 34.0 (°C)

Location	Air temperature (°C) at 1.8m height measurement / Simulation	Air velocity (m/sec) at 1.8m Height measurement / Simulation	Surface temperature (°C) measurement / Simulation
Asphalt	36.0 / 36.6	1.1 / 1.2	48.2 / 48.0
Pavement	35.9 / 36.2	1.1 / 1.2	47.0 / 47.3
Building Surface	35.8 / 35.2	1.1 / 1.2	37.4 / 37.8

procedure (i.e. selection of the warmest day) due to the necessity of having actual microclimatic measurements in the verification procedure.

Mean maximum air temperature at noon of the warmest day

Simulation of the average (i.e. the mean value from a specific number of grid points) maximum summer period temperature has been carried out in the open area during noon of the warmest day. The warmest day was obtained from the period of the three year 2009–2011 being the 16th of July 2011. Meteorological

Table 4 Thermal and optical properties of materials defined in the CFD model

Conventional flooring and views materials	Reflection Coefficient	Emission Coefficient
Street Asphalt	0.10[a]	0,85-0,93 (0,89)[b]
Light-colored covering roofing/roofs (sheathing with pavement flagstones)	0.35[a]	0.90[c]
Light-colored coating	0.60[a]	
Medium-colored coating (beige, gray)	0.40[a]	
Gray color		0.87[c]
Dark colored coating	0.20[a]	
Conventional structural material		0.80[a]
Cool materials coverings/coatings[d]		
Asphalt Ecorivestimento grigio photocatalitic concrete based mortar (speciment 1)-Fotofluid	0.37	0.89
Sidewalk blocks (Block CE light gray (N^{o} 5) or CE beige (N^{o} 6))	0.67	0.89
Pavement flagstones (white flagstone (N^{o} 12))	0.68	0.92

[a] (Greek Technical Chartered Institution 20701–1 2010),
[b] (Incropera De Witt, 1990),
[c] (Santamouris, 2006),
[d] (ABOLIN)

Table 5 Warmest day data input from Environmental Centre meteorological station (16/7/2011)

Date	Time	Pressure (mbar)	Temperaure (°C)	Relative Humidity(%)	Wind Speed(m/s)	Wind Direction (o)	Solar Radiation (W/m2)
16/07/11	13:00	946	34.2	31	0.7	188	783

data (Table 5) from that day at noon were used in the simulation, in steady state mode, for the present and the rehabilitated situations. At each case the same meteorological data from Environmental Centre station were applied as input in ANSYS CFD with the respective materials and interventions of each configuration. This way modeling predicted the thermal situation in the urban complex by the use of the city's meteorological data.

It was considered that in the open urban space of the street market and in the surrounding roads of the market in Ptolemaida, the average maximum temperatures were appeared during the selected warmest day. Moreover, simulation has shown that the maximum temperatures within roads and the street market appeared at the same times. The area of interest was divided in the surface of the open market place and in five surrounding streets (Fig. 2). For each road and the market's surface the respective air temperatures were calculated at noon of the warmest day. Then, the resulted average maximum air temperature was compared for the case before and after rehabilitation.

Figures 6–7 depict air temperature field at each street and the market place at 1.8m height during noon of the warmest day before and after rehabilitation.

The simulated air temperature for each individual space (streets and open market) was obtained from at least 500 grid points of the mesh at 1.8m height. Table 6 shows the predicted air temperatures before and after rehabilitation with the surface areas on the 16th of July 2011. The calculated total air temperature before and after case was 37.61 °C and 35.42°C, respectively. So, the air temperature improvement if bioclimatic measures are taken would be 2.19°C.

Conditioning hours during the typical day

Conditioning hours of 26 °C base at 1.80 m height have been calculated for the typical day. From meteorological data analysis during 2009–2011 from Environmental Centre station in Ptolemaida it was obtained that the

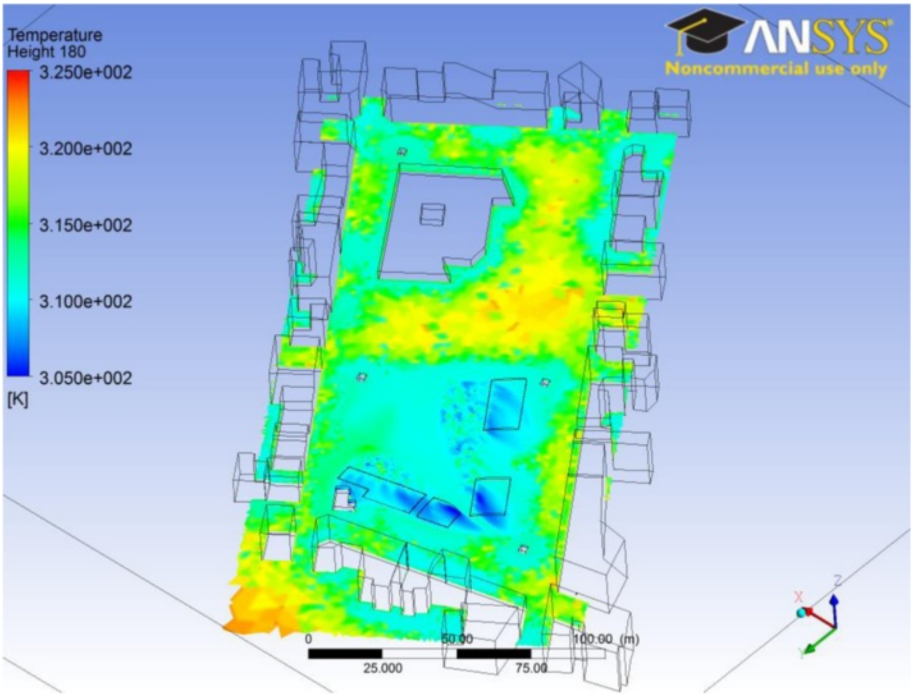


Fig. 6 Air temperature at 1.80 m height at present situation (*Note that, the structural elements e.g. green roofs, are disabled in terms of their thermal properties in the present case constituting free slip surfaces.*)

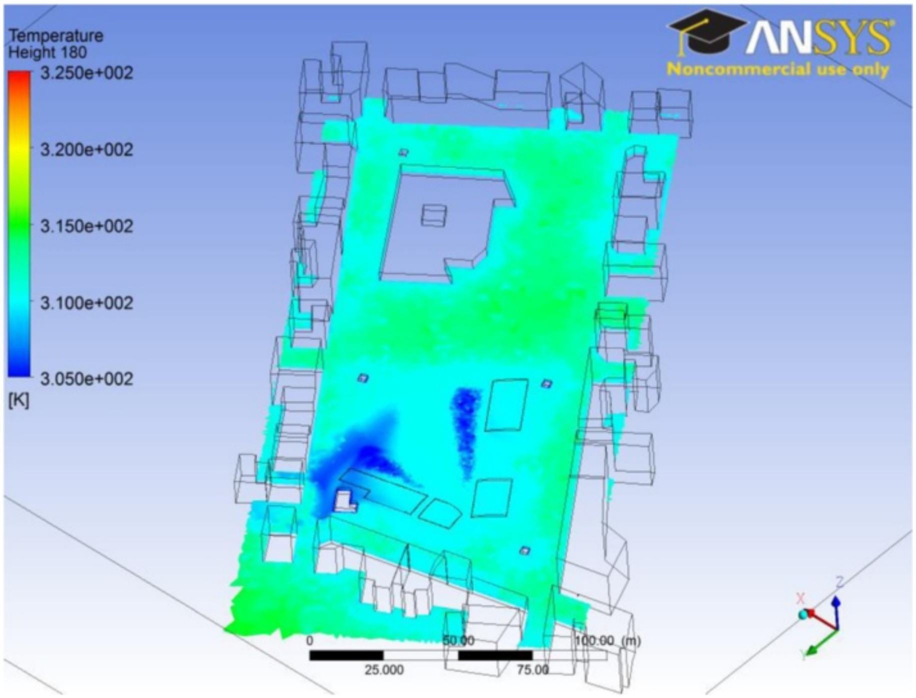


Fig. 7 Air temperature at 1.80 m height after rebilitation

warmest month was July 2011, with a mean air temperature of 23.9 °C. On the 25th of July 2011 it was observed the closer mean daily air temperature to that value being 23.6 °C. So, the 25th of July 2011 was selected as the typical summer day.

Transient simulations have been carried out with data from the meteorological station in Ptolemaida at Environmental Centre (Table 7) for the selected typical day before and after bioclimatic reformation. Conditioning hours have been calculated with a degree base of 26 °C. In Table 8 it is presented the calculated hourly air temperatures before and after reformation between 10:00 and 20:00 hours. The air temperature from sunset to 10:00 o'clock was lower than 26 °C and thus, it were not taken into account. The mean hourly air temperature for each road and the open market place was calculated from at least 500 grid points.

The predicted conditioning hours of 26 °C base due to the calculated mean air temperatures during 7:00 to 20:00 hours for the typical summer day, were 41.9 for the present case and equal to 26.7 for the proposed bioclimatic case (Table 9).

Mean surface temperature at noon of the warmest day

In order to improve thermal microclimate in the area of the open market new cool materials must be used that may reduce surface temperatures of buildings, streets and sidewalks. The proposed materials have relatively high reflectivity of solar radiation and increased emission rate. The structural surfaces should be reduced and replaced by water surfaces, soil and vegetation. Green roofs in the open area or where people are accommodated would also contribute in the reduction of material thermal storage.

CFD simulations have been carried out for the present case and for the proposed bioclimatic one. The results of the two simulations have compared concerning the warmest day of the 16th of July 2012 (Figs. 8–9).

Table 6 Average maximum summer air temperature at noon of the 16th of July 2011

Individual spaces	Tair, max (before) °C	Tair, max (after) °C	Surface (m^2)
Vas. Konstantinou str	37.70	36.80	1,202.20
Dimokratias str	37.50	36.10	2,377.97
Ethnikis Antistasis str	37.10	36.20	2,132.97
Open market space	37.80	34.80	10,212.00
Pontou str	37.50	36.30	784.60
Foufa str	37.00	36.10	1,028.70
Average maximum environmental temperature Tair, max	37.61	35.42	
Difference ΔT		2.19	

Table 7 Meteorological data of the typical day (25/7/2011)

Date	Time	Pressure (mbar)	Temperaure (°C)	Relative Humidity(%)	Wind Speed(m/s)	Wind Direction (o)	Solar Radiation (W/m2)
25/07/11	01:00	937	18.6	74	0.4	175	0
25/07/11	02:00	937	18.4	72	0.5	94	0
25/07/11	03:00	937	16.4	80	0.5	255	0
25/07/11	04:00	936	16.2	79	0.4	217	0
25/07/11	05:00	936	15.2	84	0.4	258	0
25/07/11	06:00	937	15.7	81	0.5	65	14
25/07/11	07:00	937	17.4	73	0.5	257	124
25/07/11	08:00	937	21.4	54	0.5	230	289
25/07/11	09:00	938	24	44	0.9	71	463
25/07/11	10:00	938	25.7	48	1	59	608
25/07/11	11:00	938	27.3	47	0.7	14	722
25/07/11	12:00	938	27.7	45	0.7	227	665
25/07/11	13:00	938	29.1	40	0.9	284	720
25/07/11	14:00	938	30.6	35	0.8	296	815
25/07/11	15:00	937	30.2	31	1	258	676
25/07/11	16:00	937	31.5	36	1.2	289	608
25/07/11	17:00	937	30.8	46	1.5	287	459
25/07/11	18:00	938	29.2	55	1.2	296	242
25/07/11	19:00	938	26.8	30	0.8	301	37
25/07/11	20:00	938	25.5	31	0.5	321	15
25/07/11	21:00	938	24.1	34	0.4	269	0
25/07/11	22:00	939	22.7	38	0.5	278	0
25/07/11	23:00	939	21.9	39	0.6	303	0
25/07/11	24:00	940	20.9	41	0.4	345	0

Table 8 Hourly mean air temperature during 10:00 to 20:00 hours – present/predicted cases

Hour/Street	Vas. Konstantinou (before/after)	Dimokratias (before/after)	Ethinikis Antistasis (before/after)	Market Place (before/after)	Pontou (before/after)	Foufa (before/after)
10:00	25.8/25.4	25.6/25.4	25.5/25.2	25.8/25.5	25.4/25.1	25.3/25.1
11:00	27.5/27.4	27.3/27.1	27.4/27.1	27.4/27.2	27.5/27.3	27.4/27.1
12:00	30.3/29.2	30.2/29.1	29.9/28.9	30.7/28.8	30.0/28.8	30.0/28.8
13:00	31.3/30.1	31.0/30.2	31.4/29.8	31.6/29.8	31.0/29.4	31.0/29.6
14:00	32.0/30.4	31.9/29.9	32.1/30.4	32.2/30.3	31.9/30.1	32.4/30.2
15:00	32.4/30.1	32.6/29.5	32.2/30.3	32.7/30.2	32.6/30.0	32.6/30.5
16:00	31.6/29.9	31.5/29.7	31.7/29.8	32.4/29.8	32.4/29.8	32.3/29.9
17:00	31.4/29.8	31.3/29.5	31.6/30.1	31.7/29.5	31.6/29.5	31.6/29.4
18:00	30.8/29.1	30.9/28.8	30.9/28.9	31.1/28.7	30.8/28.5	30.9/28.4
19:00	26.9/26.0	27.1/26.4	27.2/26.5	27.2/26.2	26.9/26.2	27.1/26.3
20:00	25.3/25.2	25.4/25.2	25.5/25.1	25.8/24.9	25.4/24.8	25.3/24.8

Table 9 Conditioning hours before and after rehabilitation

Hour	Mean air temperatures Tm(t)	Conditioning hours (before)	Mean air temperatures Tm(t)	Conditioning hours (after)
10:00	25.7		25.4	
11:00	27.4		27.2	
12:00	30.4		28.9	
13:00	31.4		29.8	
14:00	32.1		30.3	
15:00	32.6		30.1	
16:00	32.1		29.8	
17:00	31.6		29.6	
18:00	31.0		28.7	
19:00	27.1		26.3	
20:00	25.6		25.0	
		41.9		26.7

It was assumed that the mean surface temperature peaks during the warmest day and then, it was calculated for all the individual roads and the market place separately. Therefore, it was assumed that the calculated surface temperatures were maximums for each individual road or open space. The mean surface temperature during noon of the 16th of July for all surfaces reached 43.73°C in contrast with the proposed bioclimatic configuration (Fig. 3) that reached 36.62°C (Table 10). The total predicted temperature difference was 7.11°C. The significant material surface temperature reduction was due to shadowing from vegetation, water surfaces, green roofs, cool asphalt and cool flagstones of pavements and sidewalks.

Mean thermal comfort index during the typical day

The most important effect of the proposed bioclimatic intervention (Harlan et al., 2006) would be the improvement to human living conditions. This has been assessed by the calculation of thermal comfort indices across the area under consideration. The thermal comfort index should take into account climatic factors like global solar radiation on the horizontal and thermal radiation, environmental temperature, air velocity and humidity. The

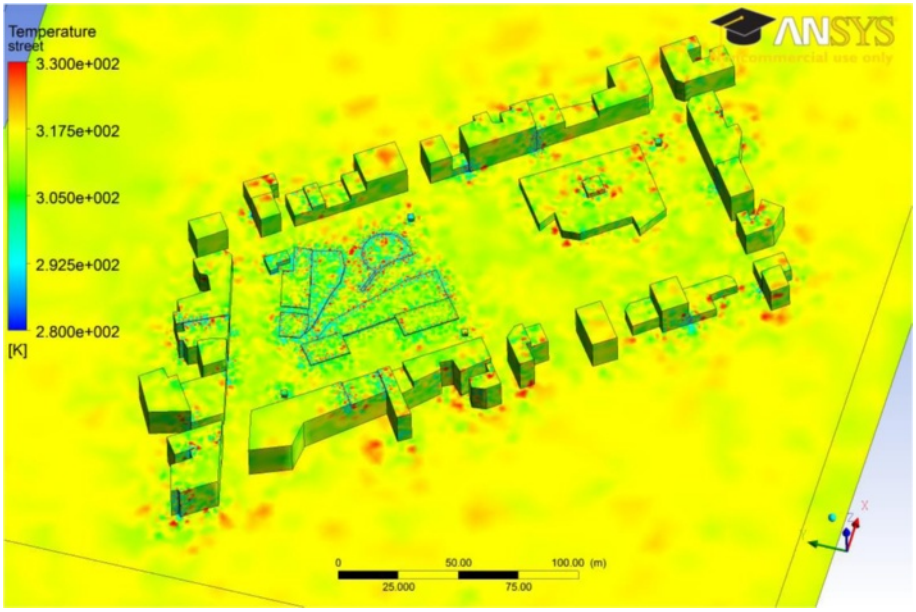


Fig. 8 Surface temperatures of the present case. (*Note that, the structural elements e.g. green roofs, are disabled in terms of their thermal properties in the present case constituting free slip surfaces.*)

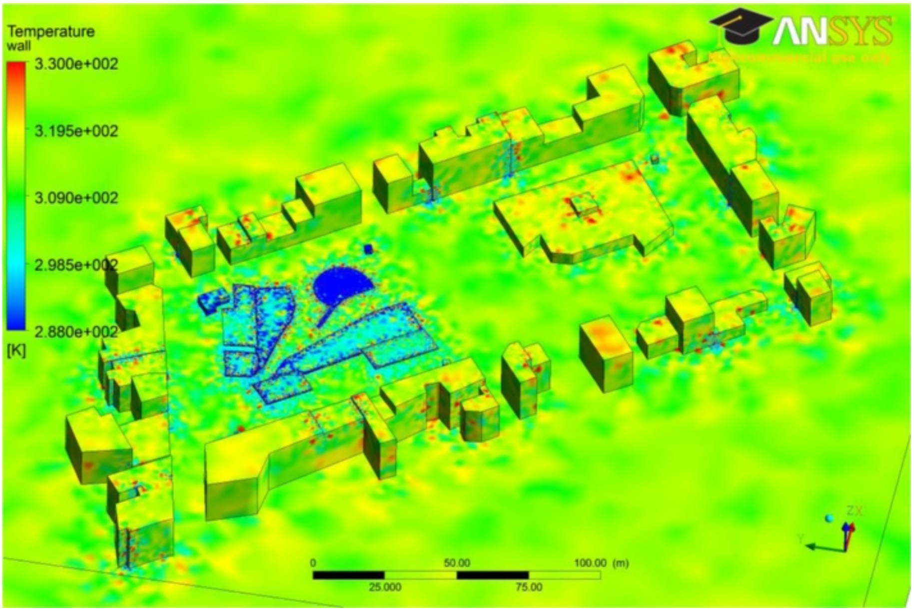


Fig. 9 Surface temperatures of the reformatted case

TSP (Thermal Sensation Perception) index (Monteiro et al. 2009) was selected being as an appropriate one for external spaces. This index has been considered and validated for the assessment of several thermal comfort studies of open spaces against real experimental data. The equation of its calculation was the following:

$$TSP = -3.557 + 0.0632\,T\alpha + 0.0677\,Tmrt + 0.0105\,RH - 0.304\,V \quad (1)$$

where :

Tα is the environmental temperature, (°C)

Tmrt the mean radiant temperature, (°C)

RH the relative humidity (%), and

V the air velocity, (m/sec)

When TSP index lies between −0.5 to +0.5 then thermal comfort is obtained, between 0.5 to +1.5 environment is assumed warm, 1.5 to +2.5 very warm and higher than 2.5 excessively warm. For intervals of −0.5 to −1.5 environment is considered cool, −1.5 to −2.5 cold and below −2.5 excessively cold.

From the transient simulation have been gathered the hourly air temperature, mean radiant temperature and wind velocity for the typical summer day between 10:00 to 18:00 hours. Note that, the mean radiant temperature was estimated by considering shadowing effects at each road and the market place, global solar radiation on the horizontal from meteorological station and material surface temperatures. Relative humidity has been obtained from the meteorological station of Environmental Centre in the 25th of July 2011.

In Table 11 is shown the calculated values of microclimatic data and TSP index at each road and in the market place before and after rehabilitation. All parameters where calculated by the mean values of at least 500 mesh points at each defined location. In Table 11 it was calculated the mean spatial thermal comfort index TSP at each individual space during 10:00 to 18:00 o'clock.

From Table 12 it is perceived that the human thermal comfort before and after rehabilitation belongs mainly in the warm interval (0.5 to +1.5). This was expected due to the thermal analysis of surface and air temperatures where significantly high temperatures were observed during summer time. However, the present mean spatial TSP index of 0.88 is improved to a value of 0.64.

Table 10 Mean maximum material surface temperature

Street	Tsurf, max (before) (°C)	Tsurf, max (after) (°C)	surface (m^2)
Vas. Konstantinou str	43.20	37.10	1202
Dimokratias str	43.10	36.80	2378
Ethnikis Antistasis str	42.90	37.20	2133
Open market space	44.20	36.20	10212
Pontou str	43.70	37.10	785
Foufa str	42.90	38.20	1029
Mean maximum material surface temperature Tmax	43.73	36.62	
Difference ΔT			7.11

Table 11 Simulated climatic parameters and TSP index at each road and the market place before and after rehabilitation

Vas. Konstantinou str								
Hour	WS	RH	Tα(before)	Tα(after)	Tmrt(before)	Trad(μετά)	TSPπριν	TSPμετά
10:00	0.4	48	25.8	25.4	26.8	26.4	0.27	0.22
11:00	0.3	47	27.5	27.4	29.5	29.2	0.58	0.55
12:00	0.3	45	30.3	29.2	31.7	31.2	0.89	0.78
13:00	0.4	40	31.3	30.1	32.9	31.3	0.95	0.76
14:00	0.4	35	32	30.4	35.2	32.1	1.09	0.78
15:00	0.5	31	32.4	30.1	35.1	32.2	1.04	0.70
16:00	0.6	36	31.6	29.9	34.4	31.7	0.96	0.67
17:00	0.7	46	31.4	29.8	33.7	31.2	0.98	0.71
18:00	0.3	55	30.8	29.1	31.9	31.4	1.04	0.89
Dimokratias str								
Hour	WS	RH	Tα(before)	Tα(after)	Tmrt(before)	Tmrt(after)	TSPbefore	TSPafter
10:00	0.4	48	25.6	25.4	26.7	26.4	0.25	0.22
11:00	0.3	47	27.3	27.1	29.4	29.1	0.56	0.53
12:00	0.3	45	30.2	29.1	31.9	30.9	0.89	0.76
13:00	0.4	40	31	30.2	32.5	31.1	0.90	0.76
14:00	0.4	35	31.9	29.9	34.9	32.2	1.07	0.76
15:00	0.5	31	32.6	29.5	35.2	32.3	1.06	0.67
16:00	0.6	36	31.5	29.7	34.8	31.4	0.99	0.64
17:00	0.7	46	31.3	29.5	33.5	31.3	0.96	0.70
18:00	0.3	55	30.9	28.8	31.7	31.1	1.03	0.85
Ethnikis Antistasis str								
Hour	WS	RH	Tα(before)	Tα(after)	Tmrt(before)	Tmrt(after)	TSPbefore	TSPafter
10:00	0.4	48	25.5	25.2	26.6	26.2	0.24	0.19
11:00	0.3	47	27.4	27.1	28.9	28.7	0.53	0.50
12:00	0.3	45	29.9	28.9	30.9	30.4	0.81	0.71
13:00	0.4	40	31.4	29.8	32.4	31.2	0.92	0.74
14:00	0.4	35	32.1	30.4	34.9	31.3	1.08	0.73
15:00	0.5	31	32.2	30.3	35.4	30.8	1.05	0.62
16:00	0.6	36	31.7	29.8	34.6	32.8	0.98	0.74
17:00	0.7	46	31.6	30.1	34	30.9	1.01	0.71
18:00	0.3	55	30.9	28.9	31.4	29.8	1.01	0.77
Market place								
Hour	WS	RH	Tα(before)	Tα(after)	Tmrt(before)	Tmrt(after)	TSPbefore	TSPafter
10:00	0.4	48	25.8	25.5	26.9	26.5	0.28	0.23
11:00	0.3	47	27.4	27.2	30.2	29.5	0.62	0.56
12:00	0.3	45	30.7	28.8	31.1	30.3	0.87	0.70
13:00	0.4	40	31.6	29.8	32.8	30.9	0.96	0.72
14:00	0.4	35	32.2	30.3	35.3	31.5	1.11	0.74
15:00	0.5	31	32.7	30.2	36.1	31.9	1.13	0.68
16:00	0.6	36	32.4	29.8	35.5	31.1	1.09	0.63
17:00	0.7	46	31.7	29.5	34.4	30.8	1.05	0.66
18:00	0.3	55	31.1	28.7	32.2	30.6	1.07	0.81
Pontou str								

Table 11 Simulated climatic parameters and TSP index at each road and the market place before and after rehabilitation *(Continued)*

Hour	WS	RH	Tα(before)	Tα(after)	Tmrt(before)	Tmrt(after)	TSPbefore	TSPafter
10:00	0.4	48	25.4	25.1	26.8	26.4	0.25	0.20
11:00	0.3	47	27.5	27.3	30.4	29.6	0.64	0.57
12:00	0.3	45	30	28.8	31.3	30.7	0.84	0.72
13:00	0.4	40	31	29.4	32.7	31.1	0.91	0.70
14:00	0.4	35	31.9	30.1	24.8	32	0.38	0.76
15:00	0.5	31	32.6	30	35.1	32.1	1.05	0.69
16:00	0.6	36	32.4	29.8	34.5	31.6	1.02	0.66
17:00	0.7	46	31.6	29.5	33.5	31.3	0.98	0.70
18:00	0.3	55	30.8	28.5	31.8	30.8	1.03	0.82
Foufa str								
Hour	WS	RH	Tα(before)	Tα(after)	Tmrt(before)	Tmrt(after)	TSPbefore	TSPafter
10:00	0.4	48	25.3	25.1	26.7	26.4	0.23	0.20
11:00	0.3	47	27.4	27.1	30.5	30.1	0.64	0.60
12:00	0.3	45	30	28.8	31.2	30.6	0.83	0.72
13:00	0.4	40	31	29.6	32.2	30.9	0.88	0.70
14:00	0.4	35	32.4	30.2	34.8	32.2	1.09	0.78
15:00	0.5	31	32.6	30.5	35.2	32.4	1.06	0.74
16:00	0.6	36	32.3	29.9	34.3	32.2	1.00	0.71
17:00	0.7	46	31.6	29.4	33.8	31.1	1.00	0.68
18:00	0.3	55	30.9	28.4	30.8	30.6	0.97	0.80

Wind field during the typical summer day

Transient simulation of the wind field during the typical summer day with meteorological input of the area has been carried out. The typical wind field between 10:00–18:00 hours has been simulated in the area under consideration. From Figs. 10–11 it was concluded that at 1.80 m height the wind velocity and turbulence would not change significantly due to the proposed bioclimatic interventions. Velocity vectors in the streets and in the market place do not differ significantly at two cases with low velocities below 1.5 m/s at all spaces. Generally, human comfort would not be affected at all open locations due to the low wind velocities before and after rehabilitation.

Table 12 Mean thermal comfort index THA(i) = TSP at each street and in the market place before and after rehabilitation

Street	TSP before	TSP after
Vas. Konstantinou	0.9	0.7
DImokratias	0.9	0.7
Ethnikis Antistasis	0.8	0.6
Market place	0.9	0.6
Pontou	0.8	0.6
Foufa	0.9	0.7
Mean spatial thermal comfort index	0.88	0.64

Conclusion

Computational fluid dynamics simulation predicted the thermal conditions at the present case and the bioclimatically reformatted one. In Table 13 is given the percentages of improvement for each targeted parameter if the proposed rehabilitation would take place in future. From the table is obvious that relatively low air temperature improvement may lead to significant thermal comfort improvement. This is because thermal comfort is rather independent from air temperature but mostly correlated to radiant temperature. Note that, the wind field of velocities was approximately the same for the case before and after rehabilitation and therefore, did not influence significantly the human thermal comfort conditions. It would not be possible to obtain significant thermal comfort condition improvement by just targeting to air temperature improvement.

Approximately 100% replacement of ground surface conventional materials by cool ones, an increase of about 15% in roofed areas, doubled trees and 10% increase of green and water surfaces caused an improvement in surface temperature of 16.30%. Reflection coefficients of cooled materials were higher than the

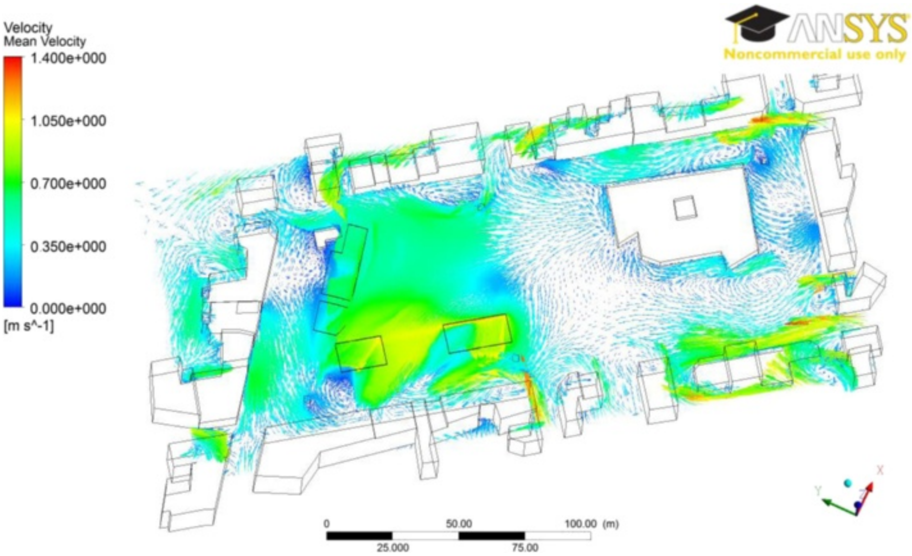


Fig. 10 Wind field in the present case

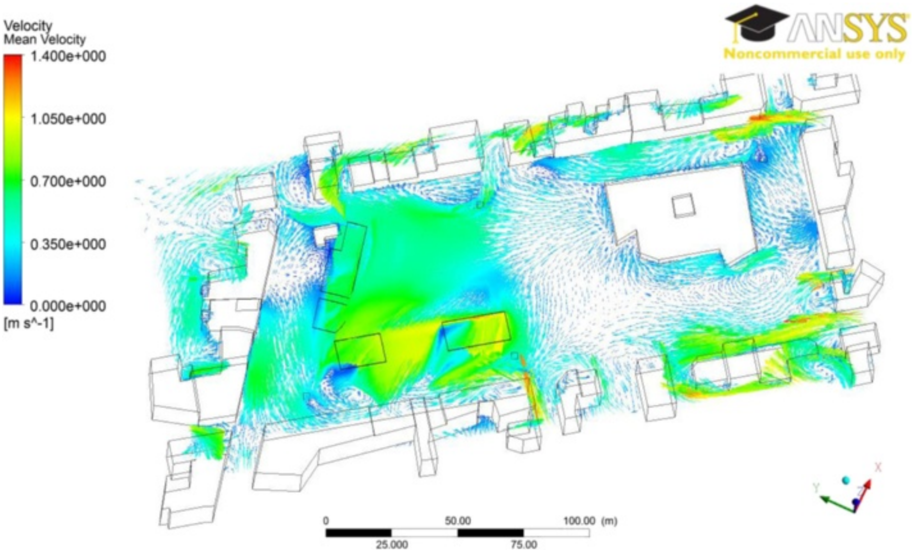


Fig. 11 Wind field after rehabilitation

conventional materials but emission coefficients were approximately the same. Therefore, it is rather obvious the significance of roofs, green areas and trees within the open urban complex in relation to the improvement of air temperature. Relatively high thermal comfort improvement is "easier" to be succeeded if surface thermal exchange is manipulated by any of the abovementioned ways. The exact influence of a bioclimatic intervention to microclimatic parameters must be studied in relation to urban complexity and climatic zone characteristics.

Table 13 Prediction of the microclimatic parameters' improvement

Microclimatic parameter	Percentage of improvement
air temp	5.8%
cooling hours	36.3%
surface temperature	16.3%
thermal comfort	27.2%

Competing interests

The authors declare that they have no competing interests.

Authors' contributions

SZ was the overall scientific responsible that directed the present study AD contributed at material and civil engineering guidance VE contributed in microclimatic analysis and simulation SL constructed the meshed 3D CFD domain SD contributed in 3D drawings and proposal interventionAMT contributed in 3D drawings and proposal intervention VS consulted in the bioclimatic implementation ALP contributed in data collection and implementation ED contributed in data collection. All authors read and approved the final manuscript.

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