SIMULTANEOUS INTEGRATION OF URBAN HEAT ISLAND MITIGATION TECHNOLOGIES IN THE EXISTING URBAN FABRIC IN ATHENS, GREECE

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ABSTRACT

This research studies the possibility of introducing combinations of specific mitigation techniques for the urban heat island effect (UHI) in Athens, Greece. A variety of factors, such as surface cover, dense traffic, anthropogenic heat release and urban characteristics including geographic features and climate conditions interact with one another to create UHI, which is becoming increasingly evident also due to the changing climate, which in this region is expected to increase the duration of hot spells and the frequency of heat waves.

Mitigation techniques can contribute highly to improve the urban thermal environment, decrease the energy consumption of buildings and also decrease urban air temperatures. Proper mitigation technologies involve, among others, new building envelope technologies and the use of highly reflective materials to decrease the absorption of solar radiation by urban surfaces, the use of advanced materials adapted to the local climate, the additional use of urban green spaces and the use of appropriate heat sink technologies. Advanced mitigation techniques have been applied quite recently in many urban rehabilitation projects around the globe and have succeeded in improving the local microclimate significantly. However, each mitigation measure is often being implemented as a unique element. The focus of this research study is on their relationship and the actual feasibility for their simultaneous integration into the urban environment.

To this end this study focuses on urban architectural dynamics and the development of a methodology for the optimal simultaneous architectural integration of high performance heat-island mitigation technologies in the urban fabric. The methodology can be applied at city block or neighbourhood level and is based on the geometric characteristics and the orientation of the site, but also on the microclimatic conditions of the site. In order to achieve the aim of this study, a small typical neighbourhood in Athens, representative in terms of orientation, building height, road width etc, is analyzed as a case study. After recording each feature that describes the urban cityscape, the study presents feedback, regarding the feasibility for the integration of UHI mitigation technologies, as well as their interaction with various smart materials. Mitigation technologies studied in the present research include, but are not limited to, the reduction of anthropogenic heat release, such as the use of cooling towers, the retention of water through materials, the improvement of the reflectivity of urban surfaces, the use of green spaces, the effect of open spaces, the improvement of land usage and orientation, the use of appropriate shading, the use of natural heat sinks etc.

Finally, the study presents whether the above mentioned factors can reduce the air temperature at street level, how they affect the UHI effect and provide good air quality at the neighbourhood scale, whereas at the same time analyze possible problems or merits for their simultaneous integration.

KEYWORDS

Urban heat island, Mitigation Techniques, Thermal comfort, Urban microclimate, Advanced materials

1 INTRODUCTION

Rapidly developed urban areas, such as Athens, have a major negative impact on the outdoor environment. Urban geometry is a major factor in the urban heat island effect (UHI), as it affects airflow and mean radiant temperatures (Oke 1987, Golden 2004). Past research has focused on distinct environmental problems, such as high temperatures, wind distribution and speed in urban canyons (Oke, 1988). There are various physical and climatic factors that affect human thermal comfort in different scales, thus there is a strong need for interdisciplinary work between urban climatology, urban design and architecture (Ali-Toudert, 2005).

Mitigation techniques can contribute highly to improve the urban thermal environment and to decrease urban air temperatures. Advanced mitigation techniques have been applied quite recently in many urban rehabilitation projects around the globe (Ito et al, 2004, Slosberg et al, 2006) and have succeeded in improving the local microclimate significantly. However, each mitigation measure is often being implemented in its own as a unique element. The focus of this research is to study their relationship and the feasibility of their simultaneous integration into the urban environment.

This research studies the possibility of introducing combinations of specific mitigation techniques for the urban heat island effect (UHI) in Athens, Greece. A variety of factors, such as surface cover, traffic density, anthropogenic heat release and urban characteristics including geographic features and climate conditions, interact with each other to create UHI, which is becoming increasingly evident also due to the changing climate, which, in this region, is expected to increase the duration of hot spells and the frequency of heat waves (Climate Change Impacts Study Committee, 2011). The study focuses on urban architectural dynamics and the development of a methodology for the optimal simultaneous integration of high performance heat-island mitigation technologies in the urban fabric.

2 LITERATURE REVIEW

One of the great challenges for cities is the mitigation of the urban heat island effect (UHI). In the last years, interesting research has been presented, recognizing the root of the problem and the effects of the UHI (Golden, 2004, Kartalis, 1999) on the urban environment. The strong relationship between air pollution, anthropogenic heat, urban geometry, urban fabric and UHI density has been analyzed, introducing ways to mitigate the UHI without altering city planning (Che-Ani, 2009, Yamamoto, 2006).

The most important formative elements on the urban environment are buildings. Buildings surround urban open spaces, creating urban canyons with high temperatures. Temperature is associated with the UHI, which in turn increases the intensity of heat waves, thus humans are often exposed to extreme thermal conditions within their cities (Tan et al. 2009). There is a strong interest on the quality of open urban spaces and the relationship with various physical and climatic factors, such as surface temperatures, irradiation of canyon surfaces and wind flow at street level, decisive features that affect the microclimate of a neighbourhood. The height-to-width (H/W) ratio and street orientation were found to be the most important factors affecting thermal comfort at street level (Ali-Toudert, 2005). Surface materials were also found to affect the thermal behaviour of an urban canyon (Ali-Toudert, 2005). However, the number of interdisciplinary studies is limited (Pearlmutter et al, 1999).

Thermal sensation has been defined as the Actual Sensation Vote (ASV) (Nikolopoulou et al, 2005). Based on the ASV developed by the RUROS project (CRES, 2005), *ASV=0.034Tair_met +0.0001Sol_met – 0.086V_met – 0.001RH_met – 0.412 (r=0.27), (1)*

there is an indication concerning the contribution of wind and temperature data. Analysing the data, it has been possible to examine correlations between microclimatic parameters and ASV. Through RUROS, it is becoming clear that a purely physiological approach is inadequate to characterise thermal comfort conditions outdoors. ASV has an inverse relation to wind speed. For example a case study area in Athens - which we will focus on paragraph 4 of this paper, - during the summer, records typical values of Tair_met=33^{o}C, Sol_met=1000W/m^2, V_met=1m/s and RH_met=30%. This provides us with the result ASV=0.60, in between the comfortable categories -1=ASV=+1 (varying from «very cold» at -1 to «very hot» at 1). Lack of shading has a -14% impact on this value (CRES, 2005).

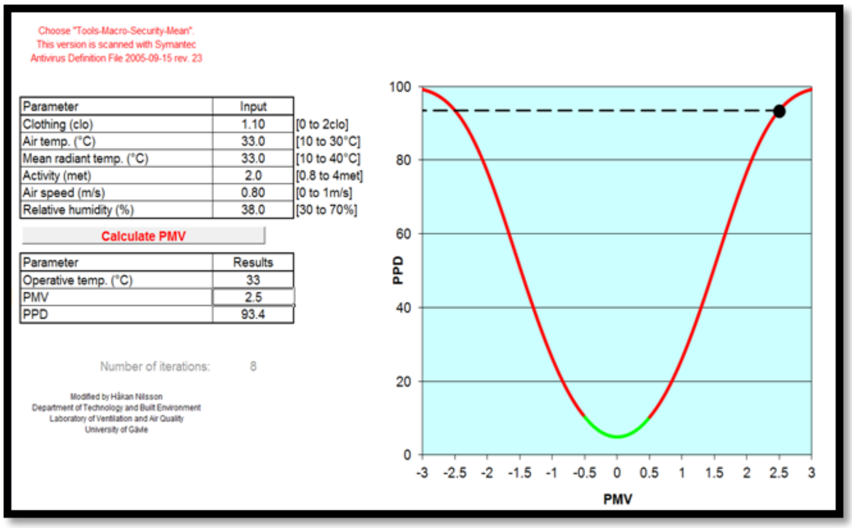

Figure 3: PMV calculation, (PMV calculation programme. Håkan Nilsson, Department of Technology and Built Environment)

The ASV is relevant only to particular meteorological factors. The subjective data collected from interviews can be compared with the thermal index Predicted Mean Vote (PMV), which is another method of predicting thermal comfort. The PMV takes into account the mean objective environmental parameters recorded for the duration of an interview, clothing levels and metabolic rate, using the ASHRAE thermal sensation scale. Comparing the PMV with the corresponding ASV, a great discrepancy was revealed between the two sets of data, since for the same area in Athens the PMV was calculated above 90% (LTPEP, 2013), when the ASV fell within comfortable limits. Therefore, we conclude to the assumption that the prediction of human thermal comfort on the outdoor environment requires a combined model.

3 METHODOLOGY

The outdoor environment is hard to quantify as it includes a multitude of factors that affect thermal comfort at pedestrian level. Critical factors for outdoor comfort include air temperature, relative humidity, air movement and mean radiant temperature. Furthermore, there are numerous unquantifiable factors affecting outdoor comfort, such as the critical importance of urban geometry, vegetation and shading. Therefore, there is a need for a quantitative assessment method for assessing the effects of climate on the urban environment and a proper implementation tool that will guide urban designers evaluate and propose coordinated UHI mitigation techniques.

This research has utilized the research of RUROS (CRES, 2004) and published research (Ali-Toudert et al. 2006, Koutsourakis 2010, Yamamura 2009, Zambrano 2006) on thermal comfort and different factors that affect the UHI, always referring to the street level. Through a combined critical approach, our work uses a simple tool, which takes into consideration climatic and environmental factors, as well as issues and environmental problems, applicable to a wide range of Greek city typologies, adequate to guide designers and architects understand the thermal qualities and measures that create UHI. This tool has been developed through research in the urban characteristics of Greek cities and their potential to include UHI mitigation techniques used in cities around the globe.

Table 1: Site analysis -Meteorological Factors & urban parameters

factors			
meteorological factors		**air temperature** (Tair_met) oC	
		solar radiation (Sol_met) W/m²	
		wind speed (at roof level)(V_h) m/s	
		Relative humidity (RH_met) %	
		ASV (Actual Sensation Vote)	0.034(Tair_met-2)+0.0001(0.2*Sol_met)-0.086(0.4*V_met)-0.001RH_met-0.412
urban parameters	*neighbourhood*	**land use**	mixed use (residential-commercial)
			strictly residential
			strictly commercial
			industrial
			conflicting land use (residential-indastrial)
		Urban geometry	complex
			organised (with a pattern)
			no pattern
		density of built area	<40%
			40%-70%
			>70%
		free space (%)	<5%
			5%-15%
			15%-25%
			25%-50%
			>50%
	building	**characteristics**	pilotis
			atrium
			skylight
		roof type	flat roof
			roof
			terracing
	street	**street orientation**	N-S
			E-W
			NE-SW
			NW-SE
		linear street length	<90
			>90
		road classification	primary
			secondary
			pedestrian area
		height to width ratio (H/W)	<0.5
			0.5-1
			1 to 2
			2 to 3
			>3
		linear street length to height ratio (L/H)	low <3
			medium =5
			high >7
		limit to street	no extra space
			canopy
			gallery
			garden patch
		street canyon	symmetrical
			assymetrical
		sky view factor (0-1)	
		vegetation	low
			high
			linear / individual trees
			group of trees
		wind speed (at street level)(V_h) m/s	
	surface cover	**albedo (solar reflectance)**	<0.1
			0.1-0.3
			0.3-0.5
			>0.5
		thermal emission	<0.30
			0.30-0.50
			0.50-0.70
			>0.70

The referenced tool was created in response to the need for a detailed subjective analysis for case studies. This tool should be easy to use, in contrast to most urban environment simulation programs that require more detailed technical knowledge in order to operate.

Givoni (1998) states that the differences between the urban and the rural temperatures are affected by two types of factors, the meteorological factors, such as humidity and wind speed, and various features of the urban structure, such as the density of the built-up areas, and the ratio of the height of the buildings to the distances between them. Therefore, by simply applying the meteorological factors on a site and recording the urban elements as shown in table 1, one can inspect the general characteristics for the corresponding area. All possible features can react or contradict with the restrictions of the urban geometry, thus a complete site analysis is able to provide us with the information we need to proceed with the proposal of appropriate UHI mitigation techniques.

The tool proposed in this paper is based on a database that we have developed through past research on specific UHI mitigation techniques and their implementation within the urban environment in relation to specific meteorological factors. This database is an attempt to record all possible UHI mitigation techniques and their relation to most possible urban parameters. The critical approach on their interaction, is the step towards their optimal simultaneous architectural integration in the urban fabric of Greek cities. All available mitigation techniques collected in the database have been decoded and categorized, creating an up-to-date model that suggests a 5 point scale of importance, from 1 (not important) to 5 (very important), combining urban parameters and meteorological factors and considering the analytical sensation of thermal comfort. Table 2 shows the outline of the tool, which has a tree structure that concludes to the scale of its implementation and a subjective account on the degree of effect, all considering the properties of Greek cities.

Table 2: Mitigation technique model outline

<table>
<tr><th colspan="5"></th><th>scale of implementation</th><th>degree of effect</th></tr>
<tr><td rowspan="14">MITIGATION TECHNIQUE</td><td rowspan="7">reduction in anthropogenic heat release</td><td colspan="3">control of land use</td><td>neighbourhood</td><td>1</td></tr>
<tr><td rowspan="2">improvement control of air conditioning systems</td><td colspan="2">optimal operation of air conditioning systems</td><td>buildings</td><td>1</td></tr>
<tr><td colspan="2">proper placing of outdor units</td><td>buildings</td><td>2</td></tr>
<tr><td colspan="3">use of cooling towers</td><td>buildings</td><td>5</td></tr>
<tr><td colspan="3">greening of building surfaces and adoption of water-retentive materials</td><td>buildings/street</td><td>5</td></tr>
<tr><td colspan="3">improvement in the reflectivity of walls and roofing materials</td><td>buildings</td><td>5</td></tr>
<tr><td colspan="3">traffic management</td><td>streets /neighbourhood</td><td>4</td></tr>
<tr><td rowspan="7">improvement of artificial surface covers</td><td rowspan="3">use of cool materials</td><td colspan="2">improve reflectivity of walls and roofing</td><td></td><td></td></tr>
<tr><td colspan="2">improve reflectivity of paving materials</td><td>streets /neighbourhood</td><td>5</td></tr>
<tr><td colspan="2">water retentive pavement</td><td>streets /neighbourhood</td><td>5</td></tr>
<tr><td colspan="3">PCM Phase change materials</td><td>buildings & streets</td><td>1</td></tr>
<tr><td rowspan="3">greening</td><td rowspan="2">street greenery</td><td>low vegetation</td><td rowspan="2">streets /neighbourhood</td><td>4</td></tr>
<tr><td>row of trees</td><td>2</td></tr>
<tr><td colspan="2">green roof</td><td>buildings</td><td>5</td></tr>
</table>

			green walls	buildings	3
		pockets parks		neighbourhood	3
	improvement of city air ventilation	shading	artificial	street	1
			greenery		3
		use of cooling towers		buildings	5
		cold sinks		city	3
		water & green areas		neighbourhood	3
		windbreaks	artificial	neighbourhood	1
			greenery		1

The outcome of the process can inform architects and urban designers on the feasibility for applying each proposed mitigation technique at a certain site or neighbourhood, in terms of thermal comfort at street level. To this end the methodology proposed consists of five stages as shown in Figure 1:

Figure 1: Outline of analysis

4 CASE STUDY

The city of Athens, is dealing with the lack of green spaces and pedestrian activities, as the city centre is a vehicular environment with exposed concrete sidewalks. The present study focuses on the relation between street design, building characteristics and outdoor thermal comfort. In order to achieve the aim of the study, five city blocks representative to the city centre in terms of orientation, building height, road width etc were selected, The case study covers the district area of approximately 20.000 square meters. This district is a high density area (>70%) of mainly residential and office use. Most of the buildings are multi-storey concrete volumes (>6 floors) with flat roofs and recesses, built during the '60s, presenting high height-to-width ratio (>3), with no inner patios or an internal atrium.

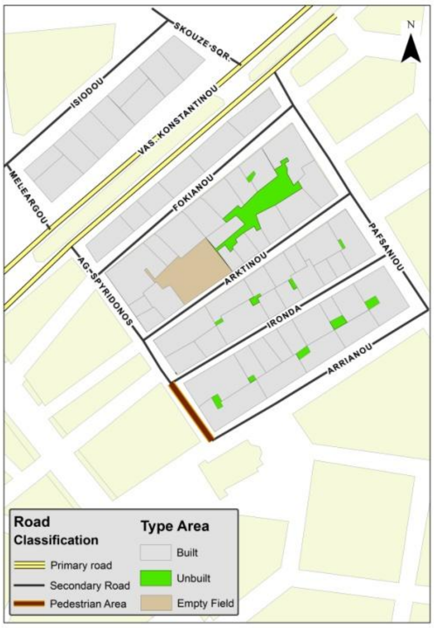

Figure 2: Area type / Road classification

The street materials are porous asphalt, concrete pavement tiles and old dirty stucco for the vertical building surfaces. Those low reflectance and high thermal emitance materials are common to the Greek urban fabric. Furthermore, the case study area consists of a sequence of urban canyons (Koutsourakis 2010), resulting to inadequate street ventilation.

The neighbourhood is facing the prevailing northeast winds on roof level. There is lack of empty space, greenery or air circulation areas in a site of flat organised topography. Being close to the city centre, dense traffic fortifies the concentration of air pollution, which combined with encapsulated high temperatures, can be stressful and indirectly dangerous to the urban environment. Considering all of the above features and the recorded low surface reflectivity, the region, on street level, faces high temperatures.

Using Tables 3 and 4 shown below, one is able to understand specific features concerning the district of this study. While Table 3 shows the metrological factors in the area of the case study, Table 4 analyses the street characteristics, in terms of orientation, H/W ratio, material reflectance factor and surface temperature.

Table 3: Meteorological Factors – case study
(Sunday 21/07/2013, 12:00 www.airquality.gr)

meteorological factors	**PMV=4.8**	**air temperature** (Tair_met) oC	**33°C**
		solar radiation (Sol_met) W/m²	**1000W/m²**
		wind speed (at roof level)(V_h) m/s	**2.1m/s**
		Relative humidity (RH_met) %	**38%**
		ASV (Actual Sensation Vote)	0.034(Tair_met-2)+0.0001(0.2*Sol_met)-0.086(0.4*V_met)-0.001RH_met-0.412

Through recording urban parameters, it is becoming clear that there are many restrictions in terms of geometry, materials and meteorological quantities. The above, set the immediate challenge to improve the qualities of artificial surfaces and the simultaneous improvement of the ventilation of the city, both without changing the urban geometry.

The most important factor is urban geometry. It is very important to analyse the urban volume (buildings) in relation to the unbuilt areas, such as streets and empty fields (which are very limited), and understand the importance of orientation. The case study area faces intermediate street orientations of NE-SW and NW-SE, which translate to short periods of thermal discomfort, as the streets are always partially in the shade (Ali-Toudert, F. et al 2006).

Table 4: Case study Street analysis

STREET ANALYSIS (air Temperature 33°C)								
	Road Name	**Orientation**	**H/W**	**Materials**	**Solar reflectance/ Thermal emmitance**	**Surface T (ASTM E1980)**	**Direct Sunlight**	**Wind Speed**
1	Vas.Kon/nou	NE-SW	<1	Porous asphalt, cement pavement tiles	0.05/0.93(asphalt) 0.1/0.63(tiles)	**81.2** (asphalt) **86.3**(tiles)	Yes	**0.4*2.1=0.84m/s** (depending on the direction)
2	Fokianou	NE-SW	>3				No	
3	Arktinou	NE-SW	>3				Yes	
4	Ironda	NE-SW	>3				Yes	
5	Agiou Spiridonos	NW-SE	>3	Porous asphalt, cement pavement tiles, row of trees	0.05/0.93(asphalt) 0.1/0.63(tiles) 0.25/0.75 (trees)	**81.2** (asphalt) **86.3**(tiles) **75.6** (trees)	Yes	
6	Pausaniou	NW-SE	1-2				Yes	

The area experiences dense street canyons (H/W>3), so it is critical to understand the air movement through the canyon and the various whirls that are created near the buildings and through the vertical development of the canyons. Those whirls block the air circulation and create a heat sink, while constantly interacting with high surface temperatures. Discomfort can extend under balconies when sidewalks in the open street area already experience thermal stress (Ali-Toudert, F. Et al 2006) because of the direct irradiation, especially in wide canyons.

In the study area, there are tall building with roofs and many recesses that modify the H/W ratio. Asymmetries of street canyons tend to cause thermal stress because of direct exposure. Nevertheless, when H/W>2 (as most cases of the district), an asymmetrical canyon shows better thermal behaviour than a symmetrical (Ali-Toudert, F. Et al 2006). The use of rows of trees improves thermal comfort within a street canyon only where direct solar radiation appears. In other cases, the use of low vegetation is ideal. Furthermore, the use of water has been found very effective at the street level, as air temperature was found to be a secondary factor in influencing thermal comfort (Ali-Toudert, F., 2005). If buildings are coated with high albedo materials or vegetation then temperatures could decrease and balance thermal comfort. The street surface temperature (table 3 surface T) can decrease up to 21.2 ^{o}C, with the implementation of >0.50 albedo street material (calculated by using the ASTM standard E1980).

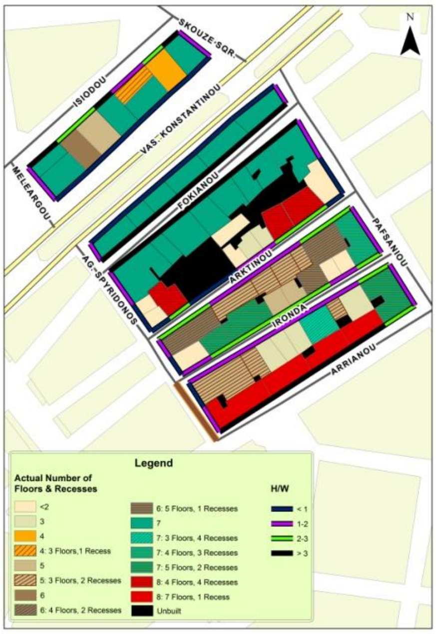

Figure 3: Actual number of floor & recesses & H/W ratio

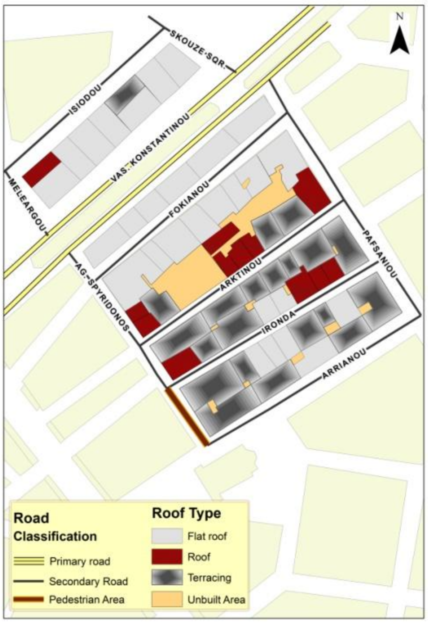

Figure 4: Road classification & roof type

5 RECOMMENDATIONS

Using the developed model (tables 2, 3 and 4), the following recommendations are suggested for improving thermal comfort in street level for the case study area by the simultaneous combination of UHI mitigation techniques:

I. Reduction in anthropogenic heat release:
   - *i. Make pedestrian paths more pleasant for walking and social interaction by eliminating traffic at NE-SW oriented streets with H/W>3*
   - *ii. Using permeable pavements*
   - *iii. Row of trees at the NW facade of the street for shading*
   - *iv. Low vegetation on the SE facade of the street to prevent whirls*

II. Improvement of artificial surface covers:
   - *i. High albedo and light colour materials for facades and building covers in order to decrease the ambient air temperature and contribute to better urban thermal comfort (as above)*
   - *ii. Creating a pocket park utilizing the only empty field of the neighbourhood connected with the private empty forgotten spaces, adjacent to the unbuilt land*
   - *iii. Permeable pavements (transpiring surfaces)*
   - *iv. Green roofs where flat roofs*
   - *v. Green walls where direct solar radiation occurs (otherwise, lack of sun implies discomfort)*
   - *vi. Canopies (shade) & vegetation where direct solar radiation occurs*

III. Improvement of city air ventilation:

i. *No windbreaks needed*

ii. *Increasing wind speed: Warm air stagnates in the urban canyons unless ventilated with the use of water and evapotranspiration by greenery (as above)*

iii. *Using urban geometry vertical voids (building skylights) to create a cool tower to ventilate the existing canyon*

The method applied in this study is recommended for existing locations, as it uses the real vote of the users, registered in questionnaires, making it possible to evaluate situations were inadequacies of the urban space are observed.

6 CONCLUSIONS

This paper has shown that there are ways to improve the outdoor environment in Athens, without altering the city planning by the simultaneous integration of various UHI mitigation techniques. If implemented, the recommendations gained through the model developed, have the potential to influence human thermal comfort within urban canyons.

Shading might be the key strategy in a hot and dry climate like Athens, but various urban parameters, site restriction and possibilities must be considered in the design process. Microclimatic conditions differ in the aspect ratio H/W, street orientation and a number of design details. Symmetrical and asymmetrical urban canyons with different sky view factors may occur, interacting with the same meteorological factors, requiring different implementation techniques in terms of thermal comfort. The disconnection observed so far between urban climatology on the one hand and urban geometry on the other hand, is inadequate towards the integrated sustainable urban design. This paper presented a subjective quantitative tool in the form of a computer program, that has been developed and is constantly improving (since it is under evaluation). This tool integrates climatic and environmental factors, as well as issues and environmental problems in Greece, while providing a simple design guideline understandable by practitioners, adequate for large scale implementation.

Future work can focus on the simulation of this quantitative analysis for establishing this implementation model into a simple tool for street design assessment and design guide.

7 ACKNOWLEDGEMENTS

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