Effect of urban geometry on surface temperatures of "skin" materials in Greek cities

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ABSTRACT: This paper is an attempt to combine experimental data of materials' surface temperatures recorded by the author during the summer of 2004, with the geometry of the city. The objective of the study is to point out the cases of urban geometric configurations, where the materials that form the horizontal and vertical surfaces are bound to overheat due to increased insolation and lack of shading. These cases are identified through a parametric study that is performed with the Ecotect software. The experimental measurements are used in order to provide data concerning the hours of insolation, as well as the period of the day when the maximum surface temperatures of the materials occur, in conditions of unobstructed solar access. The combination of all the collected data in a series of diagrams leads to the identification of a number of so-called "worst-case scenario" urban configurations, where it is assumed that the surface temperatures of the materials reach their maximum values, and for this reason corrective measures should be implemented.

Keywords: materials, surface temperatures, city geometry

1. INTRODUCTION

The materials, which constitute the outer layer of contemporary cities, play a decisive role on the heat transfer processes that take place between the city and the climatic environment. In cities with warm Mediterranean climate, the long hours of sunshine and the intensity of solar radiation during the summer, result in elevated surface temperatures of the materials. These high temperatures largely affect thermal comfort conditions in both outdoor and indoor spaces. This applies to city surfaces with unobstructed solar access during the summer. However, in densely built urban centres, the insolation of horizontal and vertical surfaces largely depends on the orientation and the geometric characteristics of the urban spaces. The cases of urban open spaces and building facades in which full -or almost full- insolation occurs during the summer months are part of a so-called "worst-case scenario" for thermal comfort in cities. The identification of these cases can be an important tool for architects/designers at the first steps of the design process, as it may rule out certain groups of materials (e.g. dark-coloured ones) or evoke the need for the application of cooling strategies (e.g. shading).

2. INTENTIONS OF THE STUDY

2.1 The surface temperatures of materials in conditions of full insolation

This study forms part of a PhD thesis concerning the thermal behaviour of the materials, which are used in the "skin" of Greek cities. The main experimental part of this thesis includes in-situ measurements in urban open spaces and buildings in various areas of Athens, Greece [1], and of experimental measurements on samples of building materials, which were placed on a flat roof. Samples of building materials used on building facades were also measured in two orientations, southern and western. In both the in-situ and the experimental measurements, the materials had -as far as possible- unobstructed solar access. In this way, their thermal behaviour in conditions of full insolation during the summer was monitored.

2.2 The effect of urban geometry

The surface temperatures of building materials in conditions of unobstructed solar access do not always correspond to those, which develop within the urban fabric, and are influenced by surrounding buildings and other obstacles. The effect of urban geometry became clear during the in-situ experimental measurements: a surface will or will not become overheated, as a direct result of the period of the day during which it receives solar radiation. When the buildings, which surround an open space, prevent the solar radiation from reaching its surface during the hours of maximum solar radiation, then the materials will not overheat. The same applies for building facades, which are shaded by opposite buildings. In other words, the thermal behaviour of the materials, which are used on the external surfaces of the city, largely depends on the orientation and the geometric characteristics of the street sections (urban canyons), of which they form part.

Based on these observations, it is obvious that not all the urban canyon configurations allow the overheating of materials during the summer period. Consequently, the negative effect of the materials on the urban microclimate, and on thermal comfort conditions does not always constrain the decisions of the architect/designer. Therefore, it is of great importance to point out these "worst-case scenario" instances, where the overheating of the materials coincides with the hours when the highest air temperatures and the largest sums of solar radiation occur, and in this way, contribute to the further degradation of microclimatic conditions.

3. PRESENTATION OF THE STUDY

3.1 Description of the computer analysis

The Ecotect software 5.2 [2] was used in order to perform a parametric study of shading and insolation of urban canyon geometric configurations. The study included four (4) basic orientations and seven (7) different height to width (H/W) ratios.

According to the above, the analysis consisted of:

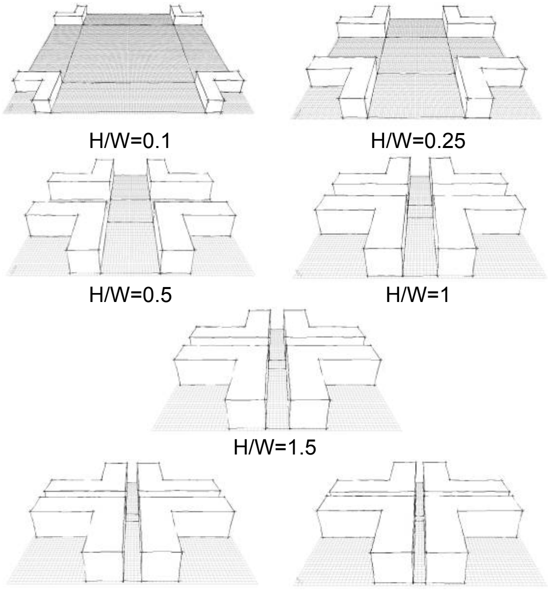
- canyons with their main axis running North to South
- canyons with their main axis running East to West
- canyons with their main axis running North-East to South-West
- canyons with their main axis running North-West to South-East

For the four above-mentioned cases, the following seven H/W ratios, were tested: H/W=0.1, 0.25, 0.5, 1, 1.5, 2 and 3. The aspect ratio H/W=1.5, is the one defined by the Greek General Building Code [3] whereas the H/W=2 and 3 are ratios, which are found quite often in neighbourhoods of Greek cities, which were constructed prior to the existing Building Code.

3.2 Assumptions of the computer analysis

The computer analysis was based on the following assumptions:

- The models, which were constructed, were simplified and did not include a full-scale city area, but a crossroad, comprising of four similar urban blocks (Fig. 1).
- The H/L (height-to-length) ratio for all the urban canyons was equal to 0.34, and close to the typical H/L ratio of the urban blocks in Greek cities.
- The horizontal surfaces between the buildings (urban open spaces) were assumed to be flat (with no inclination).
- The building facades were assumed to be even and continuous, without protrusions and voids, contrary to the real situation.
- The parametric analysis was made for the city of Athens, which, geographically, is situated around the middle of the country.
- The climatic data file (.wea) for Athens, which was used was created with the Weather Tool software [4], based on the weather data file (.epw) available from the Energy Plus web-site [5].
- The solar reflectivity of the vertical building surfaces and the canyon ground was set to a value of 0.75, corresponding to that of light-coloured paint. Nevertheless, this parameter did not influence the insolation analysis, because the inter-reflections between the various canyon surfaces were ignored.
- The insolation of all the surfaces was calculated for direct light only.
- Even though the software can consider the inter-reflections between the various canyon surfaces, these were ignored in this study because the aim was to investigate the primary effect of urban geometry on shading and insolation.
- The shading analysis of the surfaces was made for the whole surfaces and not for a particular part of them. As a result, possible edge effects were ignored.
- The possible effect of the wind on the cooling of the materials through convection, in urban canyons with a H/W ratio between 0 and 0.65 [6] was neglected.
- Flat roofs were assumed to have unobstructed solar access throughout the whole summer period for all the cases. For this reason, neither the shading, nor the insolation of these surfaces were calculated.


H/W=0.1 H/W=0.25

H/W=0.5 H/W=1

H/W=1.5

H/W=2 H/W=3

Figure 1: Models with different H/W ratios, which were used for the parametric study with Ecotect [2].

3.3 Output of the computer analysis

The Ecotect software [2] was used in order to perform shading and insolation analysis for the horizontal (ground) and vertical (building facades) surfaces of the different canyon configurations.

For all the surfaces in question, overshadowing masks were calculated from the "Sun path diagram" command of the software. The percentage of each surface, which is in shade throughout the days of the summer months, and its sky view factor, were calculated with the "Calculate Shading" command.

The analysis of the insolation of the horizontal surfaces was made with the calculation of "Cumulative Incident Solar Radiation" (Wh) from the "Analysis Grid" panel. The insolation of the vertical surfaces was calculated with the "Solar Exposure" command from the "Calculate" Menu. In this way, the total monthly received radiation (Wh/m^2) for direct light only was calculated.

Finally, a qualitative analysis of shading and insolation for June 21st was made for all the cases with the hourly (08:00 - 19:00) calculation of shadows in the OpenGL display.

4. RESULTS OF THE STUDY

4.1 Shading analysis

The results of the shading analysis with the Ecotect software [2] included the calculation of the sky view factors of the horizontal (Table 1) and the vertical (Table 2) surfaces, for the different aspect ratios (H/W). Furthermore, the software was used to generate shading masks, which included the calculation of the percentage (0% - 100%) of the surfaces, which were in shade the different hours of the day during the summer.

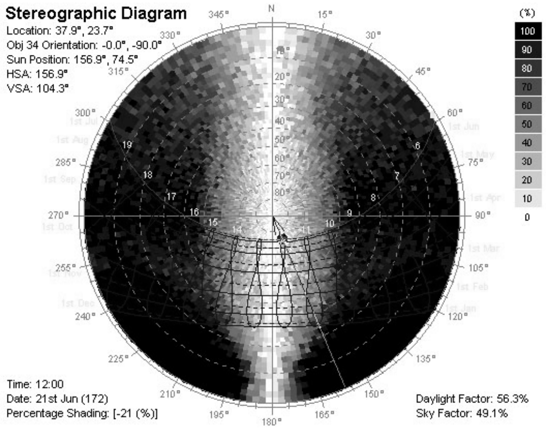


Figure 2: Example of a shading mask, which was generated with Ecotect [2] for the horizontal surface of an urban canyon with H/W =1, running North-to-South.

4.2 Insolation analysis

The insolation analysis produced a series of diagrams and tables comprising of incident solar radiation data for the summer period. An additional series of calculations was performed for all the horizontal and vertical surfaces, assuming an "ideal" aspect ratio of zero value (H/W=0) in order to approximate conditions of unobstructed solar access.

The insolation data for all the cases, which were examined, were compared to the insolation data for surfaces with unobstructed solar access (H/W=0). In this way, it was possible to express solar radiation data in dimensionless form, as percentages of the unobstructed situation for horizontal (Table 1) and vertical (Table 2) surfaces.

Table 1: Sky factor (%) and insolation data for horizontal surfaces according to the different H/W ratios.

H/W	Sky factor	Ratio of solar insolation for H/W=0 to solar insolation H/W=0.1, 0.25, etc.			
		I. N-S	II. E-W	III. NE-SW	IV. NW-SE
0	100%	1	1	1	1
0.1	91.4%	0.95	0.98	0.96	0.96
0.25	80%	0.84	0.92	0.88	0.87
0.5	66.2%	0.68	0.84	0.74	0.73
1	49.3%	0.47	0.69	0.51	0.52
1.5	39.5%	0.35	0.57	0.38	0.39
2	33.1%	0.28	0.47	0.30	0.31
3	25.3%	0.19	0.32	0.21	0.22

Table 2: Sky factors (%) and insolation data for vertical surfaces according to the different H/W ratios.

H/W	Sky factor	I$_1$. E	I$_2$. W	II$_1$. N	II$_2$. S
0	50%	1.00	1.00	1.00	1,00
0.1	49.5%	0.97	0.94	0.96	0,95
0.25	48.6%	0.97	0.94	0.96	0,95
0.5	46.5%	0.89	0.94	0.83	0,95
1	42.2%	0.82	0.83	0.58	0,95
1.5	38.7%	0.70	0.73	0.51	0,95
2	35.7%	0.54	0.62	0.45	0,95
3	31.1%	0.43	0.52	0.32	0,95
Hours		9-11	16-18	-	12-14
Solar azimuth		83.9 -104.4	257.1 -277	-	121.9 -208.4
Solar altitude		32.1 -55.6	54.3 -30.8	-	66.4 -73.8

Table 2: (continued)

H/W	Sky factor	III$_1$. NW	III$_2$. SE	IV$_1$. NE	IV$_2$. SW
0	50%	1.00	1.00	1.00	1.00
0.1	49.5%	0.97	0.98	0.95	0.97
0.25	48.6%	0.97	0.98	0.95	0.97
0.5	46.5%	0.97	0.98	0.92	0.97
1	42.2%	0.97	0.86	0.75	0.97
1.5	38.7%	0.97	0.78	0.65	0.89
2	35.7%	0.89	0.59	0.51	0.81
3	31.1%	0.80	0.55	0.31	0.62
Hours		16-18	9-11	8-10	14-16
Solar azimuth		257.1 -277	83.9 -104.4	75.7 -92.9	208.4 -257
Solar altitude		54.3 -30.8	32.1 -55.6	20.4 -43.9	73.8 -54.3

4.3 Experimental data analysis

The tables and the diagrams of the experimental measurements of the study were examined in order to point out the period of the day when the maximum surface temperatures of the materials occur (Fig. 3). For the majority of building materials in horizontal position, this period was roughly identified to be one and a half-hour (1h30m) before and after the solar noon, namely from 12:00 to 15:00 hours. Based on this examination, those periods were identified for horizontal surfaces and for vertical (northern, southern, eastern and western) surfaces (Table 3).

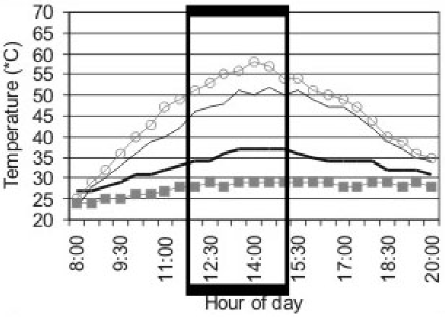


Figure 3: Example of daily surface temperature fluctuation of samples of building materials (in this case concrete slabs). The hours where the maximum surface temperatures occur are marked with a square frame.

Table 3: Period of the day when the maximum surface temperatures of materials with unobstructed solar access occur (based on unpublished experimental data).

	Local Time (summer)	Solar Time
Horizontal surfaces	14:00-17:00	12:30-15:30
Vertical surfaces	-	-
- North	-	-
- South	13:00-15:00	11:30-13:30
- East	9:00-11:00	7:30-9:30
- West	16:00-18:00	14:30-16:30

where: LCT (summer) = TST + 1h 30min (approximately) as a result of daylight savings for latitude 38° (Athens, Greece).

4.4 Combination of parametric study with experimental data and identification of the "worst-case scenario" instances for horizontal and vertical surfaces

All the available data of the parametric and the experimental study is combined in a series of diagrams (Figs. 4 to 15). Twelve diagrams are constructed. Three diagrams (one for the horizontal and two for the vertical surfaces) correspond to each one of the four basic orientations, which were examined. In these diagrams, on the y-axis the examined H/W ratios are represented, whereas the x-axis comprises a timeline. The upper timeline corresponds to the winter local clock time (Wt.), while the lower timeline corresponds to the summer local clock time (St.).

The combination of the parametric study with the experimental data in the above-mentioned diagrams is based on the following logical sequence:

1. Definition of the hours of the summer days during which the different surfaces receive full insolation and those, during which they are shaded, These are presented in the diagrams with blank cells and with cells with different shades of grey.
2. Note of the hours of the days when the surfaces receive the maximum solar radiation. These are presented in the diagrams with light grey shaded cells below the lower timeline.
3. Identification, from the analysis of the experimental measurements, of the period of the day when the materials attain their maximum surface temperatures. This is presented in the diagrams with a grey, heavy-weight line frame.

It is assumed that when the hours of overheating of the materials coincide with the hours of full insolation, and the surfaces are not in the shade, the materials will overheat during the summer. In this way, the "worst-case scenario" instances for horizontal and vertical surfaces are defined. These are marked in the diagrams (Figs. 4 to 15) with a black, heavy-weight, horizontal line and frame, and are presented in Tables 4 and 5.

Legend for Figures 4-15:

□ Shading percentage 0-10%
▒ Shading percentage 10-30%
▓ Shading percentage 30-50%
■ Shading percentage 50-100%
▯ Period of highest surface temperatures
░ Period of largest sums of solar radiation

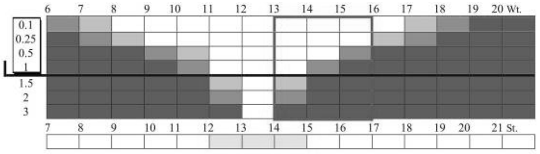


Figure 4: Streets with North-South orientation with different H/W ratios.

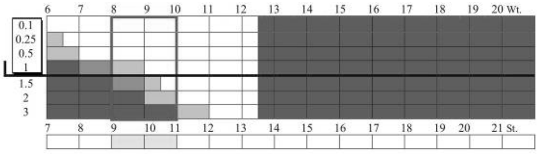


Figure 5: Eastern facades with different H/W ratios.

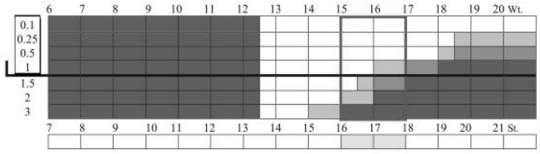


Figure 6: Western facades with different H/W ratios.

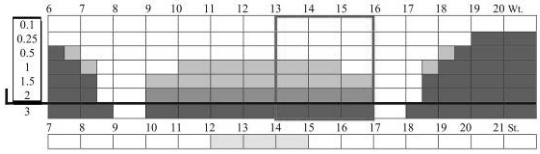


Figure 7: Streets with East-West orientation with different H/W ratios.

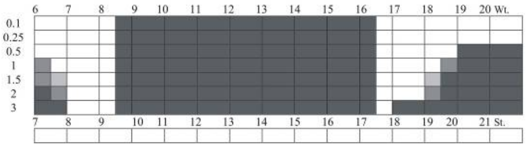


Figure 8: Northern facades with different H/W ratios.

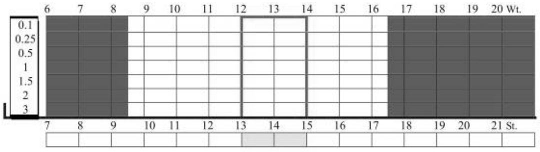


Figure 9: Southern facades with different H/W ratios.

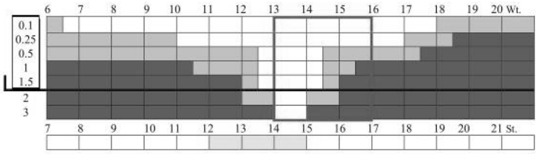


Figure 10: Streets with NEast-SWest orientation with different H/W ratios.

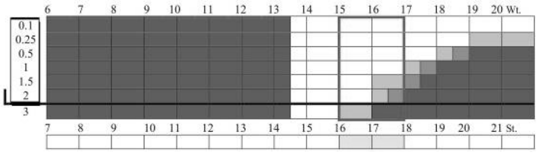


Figure 11: North-western facades with different H/W ratios.

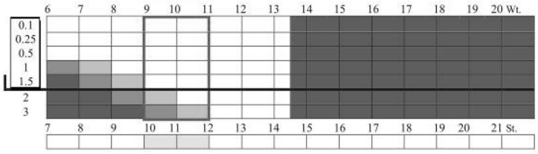


Figure 12: South-eastern facades with different H/W ratios.

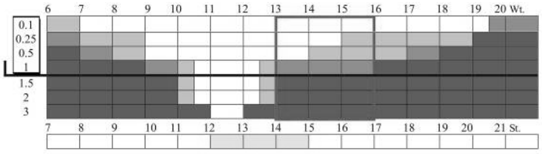


Figure 13: Streets with NWest-SEast orientation with different H/W ratios.

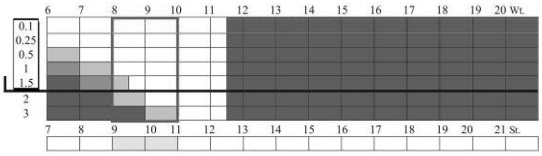


Figure 14: North-eastern facades with different H/W ratios.

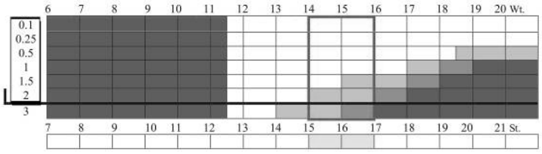


Figure 15: South-western facades with different H/W ratios.

Legend for Figures 4-15:

□	Shading percentage 0-10%	▒	Shading percentage 10-30%
▓	Shading percentage 30-50%	█	Shading percentage 50-100%
▯	Period of highest surface temperatures	░	Period of largest sums of solar radiation

Table 4: Horizontal surfaces. "Worst-case scenario" urban configurations for four different orientations, according to their aspect ratio (H/W).

	"worst-case scenario" urban configurations (H/W)							
	0	.1	.25	.5	1	1.5	2	3
N-S	x	x	x	x	(x)			
E-W	x	x	x	x	x	x	(x)	
NE-SW	x	x	x	x	x	(x)		
NW-SE	x	x	x	x	(x)			

Table 5: Vertical surfaces. "Worst-case scenario" urban configurations for eight different orientations, according to their aspect ratio (H/W).

	"worst-case scenario" urban configurations (H/W)							
	0	.1	.25	.5	1	1.5	2	3
E	x	x	x	x	(x)			
W	x	x	x	x	(x)			
N								
S	x	x	x	x	x	x	x	x
NW	x	x	x	x	x	x	x	(x)
SE	x	x	x	x	x	x		
NE	x	x	x	x	x	(x)		
SW	x	x	x	x	x	x	(x)	

Note for Tables 4, 5: In the cases, which are denoted with (x), the overheating of the materials may not be as critical, because the surfaces are partly shaded (by 10-30%) before or during the period when the maximum surface temperatures occur.

It can be seen that for urban canyons with a North-to-South direction and with a Northwest-to-Southeast direction, the cases where the materials of the horizontal surfaces are bound to overheat during the summer include H/W ratios from 0 to 0.5 (or 1). For canyons with a direction Northeast-to-Southwest, these cases also include more narrow cases, with an aspect ratio of 1 (or 1.5). Finally, the horizontal surfaces of urban configurations, of which the main axis runs East-to-West are probable to overheat in the summer, even in the case of an aspect ratio equal to 2.

In all the above-mentioned cases of horizontal surfaces, the overheating of the materials during the noon and afternoon of the summer days can contribute to the degradation of microclimatic and thermal comfort conditions in the urban open spaces of the city. For this reason, it should be taken seriously into consideration by the architect/designer.

For the vertical surfaces with eastern and western orientation, the "worst-case scenario" urban configurations include aspect ratios from 0 to 0.5 (or 1). Northern facades do not overheat, because of the few hours of insolation and of the sun altitude and azimuth angles during their insolation. On the other hand, the southern facades of buildings are never shaded during the summer in Greece, even in narrow urban canyons of an aspect ratio equal to 3. North-western facades may overheat in urban canyon with H/W ratios ranging from 0 to 2 (or 3), whereas for South-eastern ones the effect of the aspect ratio is more pronounced and overheating may occur for H/W up to 1.5. Finally, the materials that constitute North-eastern facades may reach their maximum surface temperatures when the urban canyon of which the building forms part has an aspect ratio from 0 to 1 (or 1.5). For South-western facades, these cases include narrower canyons of 1.5 (or 2).

In all the above-mentioned cases of building facades, the overheating of the materials in different parts of the day, according to their orientation, during the summer, can have a negative effect on the urban microclimate and thermal comfort. Furthermore, the appearance of high surface temperature on the facades and the roofs of buildings can have a negative effect on the internal conditions, in the cases of poorly insulated buildings.

5. CONCLUSIONS

5.1 General conclusions

The role of materials (along with the use of vegetation) has been pronounced by many researchers [7], [8] as the most important among all heat island mitigation strategies. For this reason, it is essential to identify the cases of urban open spaces and of building facades, where the urban geometry may result in the overheating of the materials, due to increased insolation and lack of shading.

In all the cases, which were identified in the previous section (Table 4, 5), the thermal behaviour of the building materials, and namely their surface temperatures during the hot summer period, should constitute one of the definitive parameters for their selection. The aim of reducing the maximum temperatures of a horizontal or a vertical surface could be a purely architectural decision, with which the architect/designer has to deal from the first stages of the design process. The choice of the colour of the surfaces, which basically defines their behaviour towards solar radiation, as well as the intention to apply cooling strategies (e.g. shading [9] or water-sprinkling [10]) in order to reduce their maximum surface temperatures, are factors that should shape architectural design. This is why, the identification of these "worst-case scenario" urban canyon configurations is considered to be a useful starting point for the choice of the materials, which are used in the urban open spaces and in the facades of buildings.

5.2 Issues under consideration and further research

It is obvious that the proposed approach is over-simplified, as it ignores aspects of inter-reflections, which always occur in actual situations, as well as of the complexity of the urban fabric (e.g. voids, extrusions, such as balconies, etc.). The magnitude of the approximations, which were made, is considerable. Nevertheless, it is believed that this approach could function as an easy-to-use general guide for architects and designers during the very first stages of the design process.

The present study has revealed the need for further development of this methodology with the use of appropriate urban climate software. In this case, the experimental measurements could be used to calibrate the software, which would then be used in order to simulate the surface temperatures of given materials in a series of detailed and complex urban canyon configurations. Finally, a more detailed analysis should also take into consideration the possible effect of wind circulation on the cooling of materials through convection, as well as the effect of the urban geometry on the radiant cooling of the materials during the night through long-wave radiation.

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