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# Microclimate design for open spaces: Ranking urban design effects on pedestrian thermal comfort in summer

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ABSTRACT

The paper presents a study on the influence of urban morphology and urban design parameters such as street and building geometry, landscape elements including vegetation types, water surfaces and material properties and their effects on pedestrian thermal comfort in cities. The data provided by the paper are based on simulations using selected computational tools (ENVI-met, RadTherm and Fluent) and performed for two typical urban spaces, a square and a courtyard. The paper focuses on summer conditions which include increasingly uncomfortable periods. It draws upon studies initiated in the city of Thessaloniki in northern Greece. However, the findings apply to many other cities with similar morphological characteristics and summer design conditions. The results are ranked according to the influence each of the design parameters considered can have on pedestrian thermal comfort. Spatial and temporal variations are highlighted. Special mention is given to the high impact of trees and soil humidity and the contrasting effects of pavement albedo. The paper provides data for use by urban designers in specifying appropriate microclimatic interventions to improve pedestrian comfort.



## 1. Introduction

The microclimates of cities depend significantly on their geographical location and local climate, but are also products of human activity modifying the built environment. The influence that urban design parameters can have on the microclimate of open spaces has been studied in many different urban contexts and climates. However, in most studies the effects of individual parameters are discussed separately, lacking a comparative basis to assess their relative importance as possible design options for a specific urban space. Geometric features of streets and courtyards such as aspect ratios, orientation, openings and canopies, have been examined in terms of their effects on comfort, energy fluxes and wind field in the urban environment (Andrade & Alcoforado, 2008; Ali-Toudert & Mayer, 2007; Bottillo, De Lieto Vollaro, Galli, & Vallati, 2014; Chen et al., 2012; Sharmin & Steemers, 2013). Other studies report on the effects of building and pavement materials based on their physical properties (Santamouris et al., 2012; Bougiatioti, Evangelinos, Poulakos, & Zacharopoulos, 2008; Doulos, Santamouris, & Livada, 2004; Asaeda & Ca, 2000; Erell, Pearlmutter, Boneh, & Kutiel, 2014). The influence of vegetation has been studied in urban parks, street trees, courtyards, roofs and walls (Shashua-Bar, Pearlmutter, & Erell, 2011; Ca, Asaeda, & Abu, 1998; Wong & Chen, 2004; Kumakura, Nakaohkubo, & Hoyano, 2013). The studies that consider more than one parameters influencing microclimate and comfort conditions focus mostly on geometric variations in combination with the presence of trees, "green" roofs and walls or with varying surface albedo (Berkovic, Yezioro, & Bitan, 2012; Lee, Holst, & Mayer, 2013; Alexandri & Jones, 2008; Emmanuel, Rosenlund, & Johansson, 2007; Shashua-Bar, Tsiros, & Hoffman, 2012; Santamouris, 2014).

This paper provides a comparative assessment that takes account of the effects of multiple parameters on the urban microclimate in order to allow an evaluation of the relative influence of each design measure on a specific open space case. The analysis is based on simulations performed with various tools that focus on different aspects of the urban microclimate. Simulations are not expected to fully represent the complexity of the actual urban environment, which is integrated in monitoring studies; however they can provide comparable results for examining microclimate development in relation to design parameters. The choice of design parameters to consider depends on their expected effects on the environmental variables and on pedestrian comfort.

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There is a substantial literature on computational tools used by researchers to study microclimate conditions at different scales. CFD software has been used by Yuan and Ng (2014), Robitu, Musy, Inard, and Groleau (2006), Skote, Sandberg, Westerberg, Claesson, and Johansson (2005) and Santamouris et al. (2012) among others. Other studies have reported using models such as SkyHelios (Matzarakis, Frohlich, Gangwisch, Ketterer, & Peer, 2015), SOLWEIG (Lindberg, Holmer, & Thorsson, 2008), Urban Canyon (Sánchez de la Flor & Alvarez Domínguez, 2004), Town Energy Balance model (Lemonsu, Masson, Shashua-Bar, Erell, & Pearlmutter, 2012), CAT (Erell & Williamson, 2006), TOWNSCOPE (Katzshner, Bosch, & Rottgen, 2003), as well as empirical models (Cadima, 2005). The software used in this study included the microclimate simulation software ENVI-met (www.envi-met.com; Bruse, 2004), the CFD software Fluent (http://www.ansys.com/), the thermal transfer simulation model RadTherm (http://www.thermoanalytics.com) and the RayMan model (http://www.urbanclimate.net/rayman/; Matzarakis, Rutz, & Mayer, 2007) for the calculation of thermal indices.

Open spaces are vital constituents of the urban environment, hosting functions and activities that are essential to the character of a city and the quality of life it can provide to its inhabitants. The geometric proportions and materiality of open spaces affect their microclimates and functionality leading to significant social, economic and environmental outcomes. This paper presents the findings of a study that looked at the different design strategies for improving environmental conditions and pedestrian thermal comfort in outdoor spaces in summer. Trees and canopies, grass and water, spatial proportions and material properties were among the design strategies considered. The findings show that each of these design measures can have specific environmental effects that are both measurable and predictable; knowledge of these can help improve decision-making on the design of open spaces in the urban environment.

## 2. Research methods

The paper draws upon measurements that were reported previously (Chatzidimitriou & Yannas, 2015), taken in Thessaloniki in northern Greece, a coastal city with deep street canyons and scarce open spaces. Table 1 and Fig. 1 provide key data for the city's temperate climate and dense urban environment. Data from these measurements were used for adjusting and testing the selected simulation software. The software were then used to perform the calculations reported in the present paper. The cases for which each software was used, the output produced and the manner in which these were combined for this study are shown in Fig. 2.

The software selected for the study included ENVI-met for overall microclimate simulation of urban areas, Fluent for detailed characterisation of morphological parameters and air movement and RadTherm for the calculation of surface and mean radiant temperatures. The output of these tools is used as input in RayMan for the calculation of Physiological Equivalent Temperature PET (Hoppe, 1999). PET values are used as the thermal indices for the assessment of pedestrian comfort in the studied open spaces, and are calculated based on environmental parameters such as air temperature and humidity, wind velocity, and short and longwave radiation fluxes summarised as the mean radiant temperature.

### 2.1. Base case

Two typical forms of open space that are encountered in many cities were taken as generic cases for the study (Fig. 3). One represents an urban square of 20 m by 20 m dimensions in plan, surrounded by streets 10 m wide and buildings 20 m high (H/W = 2.0). The other represents the internal courtyard of an urban block, and is also 20 m by 20 m in plan and surrounded by buildings 20 m high. The external surfaces of buildings and ground materials are assumed to have typical values as listed in Table 2, corresponding to materials such as medium density concrete, cement render, clay tiles, soft limestone etc (EN ISO 10456, 2007). These two urban elements were taken as representing realistic morphological configurations for Thessaloniki in Northern Greece (Fig. 1). Earlier studies (Chrisomallidou, Tsikaloudaki, & Theodosiou, 2002; Chatzidimitriou, Liveris, Bruse, & Topli, 2013) have reported on similar dimensions of urban areas where building heights vary between 2 and 8 storeys and most commonly in the range of 15–25 m. Squares and courtyards can take many different shapes with areas ranging from 400 $m^2$ to well over 2000 $m^2$. The spaces discussed here represent the smaller range in terms of floor area, but are quite typical in their geometries with common proportions and height to width ratios.

### 2.2. Study of design parameters

Nine fundamental design parameters were studied as relating to morphology, material properties and the presence of trees, grass and water. The numerical values associated with each parameter are listed in Table 3. The morphological parameters are the aspect ratio (the ratio of building height H to the width W of street or open space) and the size and position of shading canopies (if any). Two additional cases of aspect ratio were considered for the square and the courtyard as variations of the base case: a wide square with H = 10 m and W = 40 m (H20W40), a deep square with H = 20 m and W = 20 m (H20W20), a wide courtyard with H = 10 m and W = 20 m (H10W20) and a deep courtyard with H = 20 m and W = 10 m (H20W10). Three canopy variants were examined as applicable to both the square and the courtyard: canopy covering of the North-West quarter of the spaces (indicated as 25% cover), canopy covering both NW and NE quarters (indicated as 50% cover), and canopy covering all four quarters (indicated as 100% cover). Canopies were considered as solid timber horizontal planes at 3 m above ground level. The material properties include the albedo and emissivity of the pavement surface, the thermal capacity of the pavement material, and the moisture content of the soil. The presence of vegetation and water is indicated as a replacing 25%, 50% or 100% of pavement material by trees, grass or water surfaces (Fig. 4). Leaf area density (LAD) profiles for trees and grass are listed in Table 4. The values assumed for material properties have been chosen to represent the range of common urban construction materials such as asphalt, concrete, bricks, marble, granite and stone.

### 2.3. Simulation tools assessment

The software tools listed in Fig. 2 were assessed against measured data taken in the summer period in open spaces in Thessaloniki (Chatzidimitriou & Yannas, 2015). Simulations of the monitored spaces revealed a good agreement between measured and simulated results (Appendix A; Chatzidimitriou, 2012). For Fluent and ENVI-met the differences between measured and simulated results did not exceed 20% for most of the variables tested. With ENVI-met the average differences were of 0.6 °C and 3.6 °C for air and surface temperatures respectively with highest differences of 2 °C and 10 °C. With Fluent the average differences for air temperature and velocity were of 3.7 °C and 0.1 m/s respectively, with highest differences of up to 7 °C and 0.2 m/s. With RadTherm the differences were of no more than 10% for surface and globe temperatures. These correspond to averages of 1.6 °C and 0.3 °C respectively and highest differences of 7 °C and 5 °C. These comparisons underlined the specific advantages and drawbacks of each tool (Chatzidimitriou, Chrisomallidou, & Yannas, 2006;