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Combining terrestrial laser scanning and computational fluid dynamics for the study of the urban thermal environment

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ABSTRACT

Public spaces located in urban areas constitute a significant vital component of the city's organism, whilst contributing to the mitigation of phenomena such as urban heat island serving as a regulator of urban bioclimatic conditions. In recent years a multiplicity of methodologies have been deployed that enable the 3D modeling of the built environment and the individual study of prevailing bioclimatic conditions in areas such as public spaces, using software and computational techniques.

The aim of the present study is to combine Terrestrial Laser Scanners (TLS) and aerial ortho-photography with computational fluid dynamics (CFD) to study the thermal characteristics of the outdoor space. For the specific analysis a public square in the city of Chania, Crete, Greece, is selected as case study. The TLS are used for the creation of detailed 3D models that are then forwarded to the CFD. The study of the urban environment is based on two scenario analyses in order to evaluate the role of materials to the air temperatures and predict the air flow velocities that influence the thermal comfort conditions in the area of interest. The evaluation of bioclimatic indices showed a significant improvement regarding the thermal comfort conditions prevailing. The TLS method provides a suitable format of the study area while the CFD approach enables a more detailed analysis taking into account more specific parameters that shape the microclimate of the square, such as radiation, turbulence models for the study of the flows, with the aid of a well-defined computation grid.

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1. Introduction and state of the art

The recent years there is a steadily increased interest in the climatic conditions of the outdoor public spaces, its' impact on the energy performance of buildings, as well as the possible mitigation strategies of the urban heat island phenomenon (Kolokotroni & Giridharan, 2008; Krüger, Minella, & Rasia, 2011; Soutullo, Olmedo, Sánchez, & Heras, 2011; Syneffa, Dandou, Santamouris, Tombrou, & Soulakellis, 2008; Thorsson, Honjo, Lindberg, Eliasson, & Lim, 2007).

The microclimatic conditions of the urban public spaces determine to a great extent the prevailing perception of thermal comfort. Thus, it constitutes an influence, either positive or negative, to a variety of factors being involved for the holistic consideration of the urban context, ranging from the energy demand to the quality of living conditions (Kapsomenakis, Kolokotsa, Nikolaou, Santamouris, & Zerefos, 2013; Santamouris et al., 2001). The urban microclimate is affected by several factors such as spatial planning, architectural design, vegetation as well as the anthropogenic activity. It constitutes a vital component of urban deterioration phenomena such as the urban heat island phenomenon (Oke, 1967). The urban heat island has been examined and documented in many cities worldwide leading to a full documentation of the problem and its partial characteristics (Gaitani et al., 2011; Menberg, Bayer, Zosseder, Rumohr, & Blum, 2013; Mirzaei & Haghighat, 2010; Oikonomou et al., 2012; Rizwan, Dennis, & Liu, 2008). In addition there is a significant research effort toward mitigating the urban heat island. In this effort cool materials and cool pavements (Kolokotroni & Kolokotsa, 2013; Santamouris, 2012; Syneffa et al., 2008), as well as green spaces, green roofs and facades (Castleton, Stovin, Beck, & Davison, 2010; Chang, Li, & Chang, 2007; Köhler, 2008; Susca, Gaffin, & Dell'Osso, 2011) play a predominant role.

Individual buildings as well as public spaces serve as "cells" of the complex city's organism and furthermore as a regulator of the balance of bioclimatic conditions. Obviously, the sustainable operation and development of such an organism presupposes the proper cell functioning. Building materials that present high reflectance to solar radiation as well as high emissivity, described as cool materials and cool pavements, can significantly contribute to the reduction of urban surface temperatures to a satisfactory extent (Santamouris, Synnefa, & Karlessi, 2011; Zinzi & Agnoli, 2011). Moreover construction materials for the formulation of the urban

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Fig. 1. The 1866 Square in Chania, Crete, Greece.

texture affect the urban thermal balance. Specifically, they absorb the solar and infrared radiation and dissipate part of the accumulated heat through convection and radiation to the atmosphere, leading to increased ambient temperatures (Doulos, Santamouris, & Livada, 2004; Santamouris et al., 2011). Therefore the detailed definition of building materials is crucial due to the fact that they influence the air temperature of the lowest layers of the urban atmosphere and as a consequence better evaluation can provide a better view of their mitigation potential (Asaeda, Ca, & Wake, 1996; Voogt & Oke, 2003).

Based on the above, in order to improve the bioclimatic conditions in a specific urban region, optimal considerations among all the preconditions that determine the microclimate as well as the application of appropriate technological tools, which will provide not only an easier but also an accurate approach, should be considered.

Toward this direction, Terrestrial Laser Scanners (TLS) have been introduced in order to enhance the development of 3D models for the built environment (Maravelakis, Bilalis, Mantzorou, Konstantaras, & Antoniadis, 2012; Tang, Huber, Akinci, Lipman, & Lytle, 2010). Terrestrial laser scanning provides highly accurate 3D images enabling designers to experience and work directly with real-world conditions by viewing and manipulating rich point-clouds in Computational Aided Design (CAD) and Reverse Engineering software. There are many possible outputs available from point-clouds and basic measurements to ortho-photographs, derived 2D/3D drawings, 3D surfaces and solid models (Maravelakis, Konstantaras, Kritsotaki, Angelakis, & Xinogalos, 2013; Elshehaby & El-Deen Taha, 2009; Haala & Brenner, 1999; Isikdag & Zlatanova, 2010; Teo, Rau, Chen, Liu, & Hsu, 2006). This method enables users to develop detailed approach of the study objects in a more duly short yet accurate way and is very essential for the implementation of building modeling purposes.

Simultaneously, the computational fluid dynamics modeling constitutes a significant research tool for the detailed analysis of the built environment. The CFD method is mainly employed for its ability to produce a detailed description of the different flows within the building context. More specifically, the CFD method is increasingly used for the evaluation of thermal comfort conditions and air quality in the urban contexts (Fintikakis et al., 2011; Santamouris et al., 2012). The decomposition of the study area in a large number of control volumes with homogeneous or heterogeneous global mesh allow the detailing of the flow field. Therefore, the CFD technique is recognized as a three-dimensional approach (Foucquier, Robert, Suard, Stéphan, & Jay, 2013).

In the present study the case of a public square located in the city of Chania, Crete, Greece, is examined (see Fig. 1). Chania represents a small scale city with a total population of 108,000 inhabitants with typical Mediterranean climatic conditions. Concerning population dispersion, the major amount of people lives within the urban center, while the rural areas and suburbs are sparsely populated (Maragogiannis, Kolokotsa, & Maria, 2011). Such a distribution of the population leads to the analogous structure of the urban context and its individual parts such as the public spaces which influence the albedo and the total energy balance of the city. This fact becomes more significant if considering the urban heat island phenomenon that is already reported for the specific city while in the region under study the highest temperatures are measured during the summer period (Kolokotsa, Psomas, & Karapidakis, 2009; Maragogiannis et al., 2011).

To this end the aim of the present paper is to combine the terrestrial laser scanning and the computational fluid dynamics for the outdoor conditions analysis of the area under study The development of the 3D model is described in Section 2 while the modeling procedures of computational fluid dynamics in Section 3. Following the development of the model an analysis of the impact of materials is examined. Two separate scenarios are studied in Section 4 in order to highlight and depict the differences in bioclimatic conditions among them, as well as to evaluate the microclimatic improvements arranging from the application of cool materials. Finally conclusions and prospects are discussed in Section 5.

2. 3D modeling combining TLS and aerial ortho-photography

In the present section the creation of the 3D model is described. Latest methods for 3D city modeling include the usage of raw laser scanning data, which are used for various applications such as creation of photorealistic models in a mobile phone for personal navigation (Zhu, Hyyppä, Kukko, Kaartinen, & Chen, 2011), classification of buildings, ground and vegetation (Forlani, Nardinocchi, Scaioni, & Zingaretti, 2006), historical study (Ergun, Sahin, Baz, & Ustuntas, 2010) and many other applications (Al-Durgham, Fotopoulos, & Glennie, 2010; Lwin & Yuji, 2011).

In this study light detection and ranging (LiDAR) technology has been applied using an Optech-ILRIS3D laser scanner in order to develop a 3D model of the Chania 1866 Square (see Fig. 2), suitable for further processing using computational fluid dynamics (CFD). For this purpose five different scanning positions have been used (Fig. 2) and the produced scans are merged to create a unified point cloud of the examined area. In each position, 2500 laser pulses per second across a 360° horizontal and 40° vertical field of view are emitted, under the following laser specification parameters: *wavelength* 1535 nm, *pulse width* <10 ns, *pulse energy* <10 μJ, *average power* < 100 mW. Since the focal point of this study is the location and dimensions of individual building blocks and not greater details requiring enhanced resolution, such as the presence of a window or

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