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Using street based metrics to characterize urban typologies

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ABSTRACT

Urban spatial structures reflect local particularities produced during the development of a city. High spatial resolution imagery and LiDAR data are currently used to derive numerical attributes to describe in detail intra-urban structures and morphologies. Urban block boundaries have been frequently used to define the units for extracting metrics from remotely sensed data. In this paper, we propose to complement these metrics with a set of novel descriptors of the streets surrounding the urban blocks under consideration. These metrics numerically describe geometrical properties in addition to other distinctive aspects, such as presence and properties of vegetation and the relationship between the streets and buildings. For this purpose, we also introduce a methodology for partitioning the street area related to an urban block into polygons from which the street urban metrics are derived. We achieve the assessment of these metrics through application of a one-way ANOVA procedure, the winnowing technique, and a decision tree classifier. Our results suggest that street metrics, and particularly those describing the street geometry, are suitable for enhancing the discrimination of complex urban typologies and help to reduce the confusion between certain typologies. The overall classification accuracy increased from 72.7% to 81.1% after the addition street of descriptors. The results of this study demonstrate the usefulness of these metrics for describing street properties and complementing information derived from urban blocks to improve the description of urban areas. Street metrics are of particular use for the characterization of urban typologies and to study the dynamics of cities.

1. Introduction

Landscape metrics are defined as measurements that enable numerical quantification and summarise the spatial patterns of the land-use/land-cover (LULC) classes of a geographical area (McGarigal & Marks, 1995; Uuemaa, Antrop, Roosaare, Marja, & Mander, 2009). Urban spatial structure reflects the processes that occur during a city's development, and thus urban districts show significant differences in building density and structural characteristics related to their development period (Anas, Arnott, & Small, 1998; Yu, Liu, Wu, Hu, & Zhang, 2010). The appearance of urban environments is strongly influenced by the geometry of open spaces and built-up areas; the topological relationships between such spaces determine, to a large extent, local particularities related to spatial identities (Laskari, Hanna, & Derix, 2008). Therefore, various urban structural typologies can be depicted through metric attributes quantifying characteristics such as shape, land cover composition, spatial arrangement, and/or contextual relationships, and the use of those urban metrics has become a trend in a wide range of studies and applications (Ji, Ma, Twibell, & Underhill, 2006), including environmental monitoring (Edussuriya, Chan, & Ye, 2011; Yu, Liu, Wu, & Lin, 2009); energy efficiency assessment (Neidhart & Sester, 2004; Geiß et al., 2011; Kellett et al., 2013; Tooke, Coops, & Webster, 2014; Tooke, vanderLaan, Coops, Christen, & Kellett, 2011); socio-economic analysis (Jensen & Cowen, 1999; Lu, Im, Quackenbush, & Halligan, 2010; Patino and Duque, 2013; Tompalski and Wężyk, 2012; Gong, Yu, Joesting, & Chen, 2013); hydrological studies (Canters et al., 2007); or, importantly, in LULC mapping and change detection (Furberg & Ban 2008; Hermosilla, Ruiz, Recio, & Cambra-López, 2012a; Malinverni, 2011; Novack, Kux, Feitosa, & Costa, 2010; Hermosilla, Gil-Yepes, Recio, & Ruiz, 2012b; Peeters & Etzion, 2012).

Remote sensing data have a relevant role in providing automatic and massive structural descriptions of urban areas (Puissant, Zhang, & Skupinski, 2012). Early attempts at using remote sensing

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data for urban planning failed due to the limited spatial resolution of sensors used, contributing to a considerable lack of precision and level of detail, both of which are requirements for such activities (Zhan, Molenaar, & Gorte, 2000; Sohn and Dowman, 2007). In contrast, high spatial-resolution multi-spectral information acquired from satellites or airborne sensors enables a detailed characterisation of urban areas. Airborne LiDAR (Light Detection and Ranging) systems facilitate an accurate three-dimensional description of the landscape by providing point clouds representing the height distribution of observed terrain and aboveground elements. When working with remotely sensed data, urban areas are commonly described by applying two-stage approximation methods (Bauer & Steinnocher, 2001). Initially, the principal LULC or basic elements (e.g., buildings, vegetation) are identified. This information is then analysed in a spatial context to define urban metrics describing aspects such as the geometry, dimensions, or the area covered by buildings, vegetation, or other construction materials.

In this analysis of urban morphology, remote sensing may take advantage of the physical explicitness represented by urban blocks, since roads and/or cadastral maps delimit these blocks (Yoshida & Omae, 2005). An urban block is defined as a group of private or public buildings and open spaces composing an island surrounded by public roads or streets (Gil, Beirão, Montenegro, & Duarte, 2009). Using urban blocks facilitates the use of multiple datasets to analyse and describe urban areas while also integrating the information derived from remotely sensed data into GIS (Geographic Information Systems) (Gamba, Dell'Acqua, & Dasarathy, 2005). Hence numerous authors have employed urban blocks – or occasionally plots – to define units from which they can extract metrics. When working with high spatial-resolution imagery, urban metrics are generally based on the description of the spectral response of the diverse materials composing an urban block, and the presence and distribution of different land covers, with particular attention to buildings (Bauer & Steinnocher, 2001; Kressler, Bauer, & Steinnocher, 2001; Wijnant & Steenberghen, 2004; Zhan et al., 2000; Banzhaf and Höfer, 2008; Huck, Hese, & Banzhaf, 2011; Novack et al., 2010; Pan, Zhao, Chen, Liang, & Sun, 2008; Vanderhaegen & Canters, 2010; Wu, Qiu, Usery, & Wang, 2009). LiDAR and three-dimensional information complement the image-derived metrics with height and volumetric descriptor sets, which are primarily focused on describing the structure of buildings but also describe vegetation (Hermosilla et al., 2012a; Neidhart & Sester, 2004; Wu et al., 2009; Yoshida & Omae, 2005; Yu et al., 2010; Berger et al., 2013; González-Aguilera, Crespo-Matellan, Hernández-López, & Rodríguez-Gonzálvez, 2013; Heiden et al., 2012; Hu & Wang, 2013; Taubenböck et al., 2013).

In addition to bounding the blocks, urban-block cartography enables public streets to be delimited as a complementary area. Street properties such as shape and geometry, or the presence of diverse vegetation, are also factors determining the appearance of the urban space (Lillebye, 1996)). Hence, the description of streets surrounding an urban block may provide a contextual frame to highlight the differences between urban structural typologies. Although urban metrics describing street properties have been profusely employed for a variety of studies related to urban climates (Voogt & Oke, 2003), such as wind flow modelling (Cionco & Ellefsen, 1998), sun radiation estimation (Robinson, 2006), or urban heat island analysis (Chang & Goh, 1999), the potential of street-based attributes to discriminate between urban typologies has scarcely been explored in the literature. Louw and Sithole (2011) describe urban blocks with a set of street-based descriptors (e.g., street width, building-street distances) while Gil et al. (2009) use other properties for description (e.g., dimensions, orientation, accessibility, connectivity). Both works consider streets to be linear features representing the edge of roads. We propose to complete and complement the geometric description of streets with information computed from remote sensing data. This would enable a novel and profound description of the urban landscape using additional characteristics derived from the streets (considering these as polygon features) such as the presence and distribution of vegetation and the relationship between street geometry and surrounding buildings. This requires an initial process to partition the street space and determine dependencies with urban blocks.

This paper aims to: (i) propose a methodology for partitioning public street space and relate it to each urban block; (ii) define a set of urban metrics based on the streets surrounding urban blocks; and (iii) perform a comprehensive statistical analysis of the usefulness of the proposed metrics. This is achieved by studying the degree to which street metrics complement urban block metrics in discriminating among several urban typologies in the metropolitan area of Valencia, Spain.

The paper is structured as follows. Section 2 presents the study area. In Section 3, high-spatial resolution images and LiDAR data are described. Section 4 describes the methodology followed: definition of urban typologies within the studied area; procedure for deriving the street area related to the urban block; compilation of the urban block based metrics; definition of street-based descriptors; and finally, the methodology adopted to assess the metrics. The statistics and classification results are presented and discussed in Section 5. Section 6 provides conclusions.

2. Study area

We performed this study in the city of Valencia, Spain's third largest city. The demolition of the medieval city wall and the subsequent process of annexing nearby villages in the second half of the nineteenth century led to a process of urban expansion relatively concentric to the old city. Major industrialisation in the 1950s–1960s and the rapid increase in population produced by urban exodus disturbed the planned model. The subsequent processes to connect the city to the sea directed the urban sprawl eastwards, engendering the integration of former satellite settlements within the new and expanding city (Balsa-Barreiro and Lois-González, 2009).

3. Data

Remotely sensed data – high spatial-resolution imagery and LiDAR – were acquired in the frame of the Spanish National Plan of Aerial Orthophotography (PNOA). The images were collected in August 2008, with 0.5 m/pixel spatial resolution, 8-bit radiometric resolution, and four spectral bands: infrared, red, green, and blue. The images are distributed orthorectified and georreferenced, with fused panchromatic and multispectral bands and also include mosaicking and radiometric adjustments. LiDAR data were collected in September 2009 using a RIEGL LMS-Q680 laser scanner with a 46 Hz scan frequency, 70 kHz pulse repetition rate, and a scanning angle of 60°. The mean flying height was 1300 m with a nominal density of 0.5 points/m^2 and an average density value of 0.7 points/m^2. A normalised digital surface model (nDSM), i.e., the difference between the digital surface model (DSM) and the digital terrain model (DTM), representing the physical heights of the elements present over the terrain, was generated from the LiDAR data. The DTM was computed using an algorithm that iteratively selects minimum elevation points and eliminates points belonging to any aboveground elements, such as vegetation or buildings (Estornell, Ruiz, Velázquez-Martí, & Hermosilla, 2012).

Urban block boundaries were provided in vector-format cadastral cartography at a scale of 1:1000. These maps are produced by the Spanish General Directorate for Cadastre (Dirección General de Catastro).