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Influence of urban morphology on total noise pollution: Multifractal description

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HIGHLIGHTS

- Noise pollution is of a multifractal nature.
- Multifractal analysis supports the correlation between noise and street geometry.
- Urban geometry influences noise pollution spatial distribution.

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ABSTRACT

Exposure to ambient noise levels above 65 dB can cause public health problems. The spatial distribution of this kind of pollution is linked to various elements which make up the urban form, such as construction density, the existence of open spaces and the shape and physical position of buildings. Since urban morphology displays multifractal behaviour, the present research studies for the first time the relationship between total noise pollution and urban features, such as street width and building height by means of a joint multifractal spectrum in two neighbourhoods of the city of Cordoba (Andalusia, Spain). According to the results, the joint multifractal spectrum reveals a positive correlation between the total noise pollution and the street width to building height ratio, this being more evident when urban morphology is regular. The information provided by the multifractal analysis completes the description obtained by using urban indexes and landscape metrics and might be useful for urban planning once the linkage between both frameworks has been done.

1. Introduction

The European Union (EU) Directive 2002/49/EC on the management of environmental noise defines environmental noise as unwanted or harmful outdoor sound created by human activities, including noise from roads, rail, airports and industrial sites. The main health problems occasioned by noise pollution according to the World Health Organization (2012) are cardiovascular diseases, cognitive impairment, sleep disturbance, tinnitus and annoyance. The main exposure which affects human health is road traffic (World Health Organization, 2012). Previous works have related traffic-induced noise to urban morphology (Tang and Wang, 2007; Pathak et al., 2008; Wang and Kang, 2011; Salomons and Pont, 2012) finding a positive correlation between noise pollution and higher density of cities. However, narrower roads, complex road networks and higher density of intersections lead to lower traffic volumes, and thus, lower noise levels. Other studies have also found that various morphological elements in the urban environment can influence noise pollution, such as construction density, existence of open spaces and shape and physical position of buildings (Lucas de Souza and Benutti Giunta, 2011; Oliveiria and Silva, 2011; Montalvão Guedes et al., 2011; Liu et al., 2012).

According to Hillier and Hanson (1984), graphic tools are helpful for quantifying and defining urban morphology characteristics. These authors reproduced and simplified the spatial composition of a city by determining the minimum number of axial lines required to cover all areas of an urban lattice. This approach represents street networks through axial maps graphically and accurately. This procedure has been successfully applied to city modelling (Jiang and Claramunt, 2002), urban design (Jeong and Ban, 2011), spatial distribution of urban pollution (Croxford et al., 1996), prediction of human movement (Jiang, 2007) and road network analysis (Duan and Wang, 2009; Hu et al., 2009).

Urban morphology has also been described by several authors as exhibiting a fractal nature (Batty and Longley, 1987, 1994; Batty, 2008; Benguigui et al., 2000; De Keersmaecker et al., 2003; Feng and Chen, 2010; Frankhauser, 1998). Ariza-Villaverde et al. (2013) reported that urban morphology, described by axial maps, displays multifractal properties, especially for irregular urban patterns. The multifractal formalism has been used as a technique to reveal certain levels of complexities that are overlooked by traditional statistical tools and monofractal analyses (Zeleke and Si, 2004). This formalism proposes that self-similar

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measures can be represented as a combination of intertwined fractal sets, each of which is characterized by its singularity, strength and fractal dimension. This set is called multifractal spectrum and the method of variability characterization, based on the multifractal spectrum, is referred to as a multifractal analysis (Frisch and Parisi, 1985). The main advantage of this formalism is that its parameters are independent over a range of scales and that no assumption is required about the data following any specific distribution. An extension of this procedure is the joint multifractal theory, proposed by Meneveau et al. (1990). This approach analyses the correlations between variables which coexist on the same geometrical support.

The main novelty introduced in this research is the study of the total noise pollution level, L_{den}, and its spatial distribution (Directive 2002/49/EC), and the influence of urban features such as street width and building height by means of a joint multifractal analysis combined with axial maps. The promising results reported by previous works about the urban pattern multifractal description suggest the convenience of exploring city noise pollution by applying this approach.

The paper is organised as follows: Section 2 introduces the Space Syntax algorithm and the multifractal theory required to describe and analyse the relationship between noise pollution and street width and building height. Section 3 details the study areas. Section 4 discusses the main results of the joint multifractal analysis. Finally, Section 5 includes conclusions and recommendations for further research.

2. Methodology

2.1. Axial maps

Space Syntax is a set of tools that describes spatial configuration through connectivity lines covering all areas of a plane. This set of lines comprises an axial map (Peponis et al., 1998; Turner et al., 2005), which is one of the primary tools of Space Syntax. According to Turner (2006), an axial map is an abstraction of the space between buildings, shown through straight lines and drawn following a formal algorithm. The lines are represented as edges and the intersections of lines as junctions or connections between the edges. In accordance with the algorithm, the axial map is the minimal set of axial lines linked in such a way that they completely cover the space.

Several authors have developed different software programmes for the construction of axial maps based on the initial proposal of Hillier and Hanson (1984). Software, such as Axman, created by Nick Dalton at University College London (Major et al., 1997), and Axwoman developed by Jiang et al. (1999) have been implemented in GIS. Both are used to draw axial lines from a computer and analyse axial maps of urban and interior space; the main difference between them is that Axman is based on Mac-based applications and Axwoman on Windows-based applications.

Other software has recently been designed to generate axial maps automatically. Turner et al. (2005) introduced a universal platform software called Depthmap to perform a set of spatial network analyses designed to understand social processes within a built-up environment. AxialGen, developed by Jiang and Liu (2009), is a research prototype for automatically generating axial maps to demonstrate that axial lines constitute a true skeleton of the urban space. Although it is a good approximation of the axial map proposed by Hillier and Hanson (1984), this prototype has not been tested by a significant number of studies.

This research follows the method proposed by Turner et al. (2005) to extract axial maps. These authors succeeded in demonstrating and implementing the algorithm proposed by Hillier and Hanson (1984) in Depthmap with accurate results. To translate from formal language to algorithmic implementation, the definition of axial maps given by Hillier and Hanson (1984) was clarified and rewritten as “An axial map is the minimal set of lines such that the set taken together fully surveils the system and that every axial line that may connect two otherwise-unconnected lines is included”. To create the axial map, Turner et al. (2005) establish two conditions: i) the reduction from the all-lines map to a unique minimal axial graph of the system, and ii) the ability to surveil the whole system by axial lines and the preservation of topological rings.

Any possible axial lines are calculated from a map where all the streets and blocks (polygons) are displayed. Every axial line is defined by joining two intervisible vertices. There are three different possibilities (Fig. 1): i) both of the vertices are convex, ii) one vertex is convex and one is concave or iii) both vertices are concave.

The reduction to a single minimal axial line map is based on the rule that if any line connects to a line, its neighbours do not join the two; the single line is retained, or otherwise, removed. In the case of two lines having the same connection, the longest line is chosen and the other one is removed. A second condition needs to be applied to obtain the preservation of topological rings and surveillance of the whole system. To surveil the system, the algorithm chooses those lines from which every point of the system is visible. Therefore, this new condition is added to the last criterion. To complete the topological rings, the algorithm executes a triangulation around a polygon edge to be visible from the three axial lines around the geometry (Fig. 2).

2.2. Joint multifractal analysis

The procedure proposed by Meneveau et al. (1990) to perform a joint multifractal analysis for two measures coexisting on the same geometrical support has been applied here to determine the relationship between the total noise pollution (L_{den}) and two morphological features (MF), street width (SW) and building height (H). This procedure is based on the strange attractor (Hentschel and Procaccia, 1983; Grassberger, 1983; Halsey et al., 1986) formalism that deals with the fractal dimensions of the geometric sets associated with singularities of the measures. In order to apply this formalism, the urban morphology image is divided into n_{ini} non-overlapping intervals of an initial grid size, δ_{ini}, in such a way that all of them contain at least one sample of the measure. Thus, the measures $\left(L_{den_{ini}}\right)_j$ and $(MF_{ini})_j$ in any initial grid j are set to be equal to the sample measurement or to the average, if there is more than one sample. When the analysed whole image is split into n non-overlapping grids size $\delta > \delta_{ini}$, the probability mass functions $c_{iL_{den}}(\delta)$ and $c_{iMF}(\delta)$ are defined in each grid size i as

$$c_{i[L_{den}]}(\delta) = \frac{L_{den_i}}{\sum_{j=1}^{n_{ini}} \left(L_{den_{ini}}\right)_j} \qquad c_{i[MF]}(\delta) = \frac{MF_i}{\sum_{j=1}^{n_{ini}} (MF_{ini})_j} \tag{1}$$

where L_{den_i} and MF_i are calculated as the sum of the $\left(L_{den_{ini}}\right)_j$ and $(MF_{ini})_j$ values, respectively, included in that interval i. The distribution of the probability mass function is analysed by using the method of moments (Evertsz and Mandelbrot, 1992), in which the joint partition function $\chi\left(q_{L_{den}}, q_{MF}, \delta\right)$ is calculated from $c_{iL_{den}}(\delta)$ and $c_{iMF}(\delta)$:

$$\chi\left(q_{L_{den}}, q_{MF}, \delta\right) = \sum_{i=1}^{n} \left[c_{i_{L_{den}}}(\delta)\right]^{q_{L_{den}}} \left[c_{i_{MF}}(\delta)\right]^{q_{MF}} \tag{2}$$

with $q_k \in\,]-\infty,\infty[$, with k standing for $[L_{den}]$ and $[MF]$. The joint partition function has the following scaling property for multifractal measures:

$$\chi\left(q_{L_{den}}, q_{MF}, \delta\right) \approx \delta^{\tau\left(q_{Lden}, q_{MF}\right)} \tag{3}$$

where $\tau\left(q_{L_{den}}, q_{MF}\right)$ is known as the joint mass exponent function of order $q_{L_{den}}/q_{MF}$.