ABSTRACT

The difficulty to obtain a stable estimate of fractal dimension for stochastic fractal (e.g., urban form) is an unsolved issue in fractal analysis. The widely used box-counting method has three main issues: 1) ambiguities in setting up a proper box cover of the object of interest; 2) problems of limited data points for box sizes; 3) difficulty in determining the scaling range. These issues lead to unreliable estimates of fractal dimensions for urban forms, and thus cast doubt on further analysis. This paper presents a detailed discussion of these issues in the case of Beijing City. The authors propose corresponding improved techniques with modified measurement design to address these issues: 1) rectangular grids and boxes setting up a proper box cover of the object; 2) pseudo-geometric sequence of box sizes providing adequate data points to study the properties of the dimension profile; 3) generalized sliding window method helping to determine the scaling range. The authors’ method is tested on a fractal image (the Vicsek prefractal) with known fractal dimension and then applied to real city data. The results show that a reliable estimate of box dimension for urban form can be obtained using their method.

Keywords: Box-Counting Method, Fractal Dimension, Pseudo-Geometric Sequence, Scaling Range, Sliding Window Method, Urban Form

1. INTRODUCTION

Fractal dimension is a useful landscape metric in that it can capture the irregularity and complexity of landscape patterns (Hargis et al., 1998; Herold et al., 2005; Imre & Bogaert, 2004; Pincheira-Ulbrich et al., 2009). The usefulness of fractal in characterizing urban form is shown by various researchers (Batty, 1985; Batty & Longley, 1994; Benguigui et al., 2000; Frankhauser, 1994; Thomas et al., 2008; Thomas et al., 2007). Mostly inspired by the studies on coast line (Mandelbrot, 1967; Richardson, 1961), early studies of urban form mainly focus on city boundaries (Batty & Longley, 1987; Batty & Longley, 1988; Longley & Batty, 1989a, 1989b). Later fractal urban form studies extend to urban surface, i.e., urban land use (Batty & Longley, 1994; Benguigui et al., 2000; Shen, 2002; Thomas et al., 2008; White &
Engelen, 1993). It seems to be widely accepted that urban boundary as well as urban surface are both fractals at least in certain stages (Batty & Longley, 1994; Batty & Xie, 1996; Benguigui et al., 2000).

Fractal analysis of urban form relies heavily on the calculation of fractal dimension—the main scaling exponent to describe a fractal set. The fractal dimension of a deterministic fractal (e.g., the Vicsek fractal) can usually be estimated analytically. However, the dimension of a stochastic fractal (e.g., urban form) needs to be estimated numerically. Three numerical methods are popular in the research community: the perimeter-area relation method (Batty & Longley, 1988; Batty & Longley, 1994), the area-radius method (Frankhauser, 1994; White & Engelen, 1993), and the box-counting method (Benguigui et al., 2000; Lu & Tang, 2004; Shen, 2002). Due to its simple algorithm and equal effectiveness to point sets, linear features, areas, and volumes, the box-counting method enjoys a wide popularity across various disciplines such as physics (Lovejoy et al., 1987), earth sciences (Walsh and Watterson 1993), biology (Foroutan-pour et al., 1999), ecology (Halley et al., 2004), and urban studies (Benguigui et al., 2000; Feng & Chen, 2010; Lu & Tang, 2004; Shen, 2002; Verbovsek, 2009). In the case of urban studies, box-counting dimension is an indicator of compactness for the distribution of built-up areas. Despite its popularity in the research community, several issues of the box-counting method remain unsolved.

The first issue is concerned with the ambiguities in setting up a proper box cover of the object. This issue has two aspects. The first aspect is related to the shape of the grids and boxes in the box-counting method. Theoretically, the shape of the grid and box does not influence the estimate of the box dimension. However, in practice, the object does not have infinite detail, thus different covering schemes may lead to different estimates. For simplicity of practical calculation, the conventional box-counting method is performed based on square boxes (Shen, 2002; Verbovsek, 2009). Although the square box is widely used, it is not necessarily the only caliber. The choosing of square boxes cannot always efficiently cover the object. The second aspect is more related to the analysis of urban form. Due to the scale-free characteristics of urban form, it is difficult to find the exact boundary of a city and there is no agreement on a theoretically correct definition of urban boundary (Benguigui et al., 2000; Berry et al., 1968). In urban studies, we often need to make a subjective decision about the city boundary. As we will illustrate later, the fractal dimension of the same city changes with the study area. Therefore, the box dimension of a city should be given along with the study area. We should be cautious in comparing the fractal dimension of different cities as the calculated dimension may not be comparable.

The second issue in the box-counting method is the problem of dimension estimation due to the limited number of data points for regression (Pruess, 1995). The issue comes from the use of a dyadic sequence. Box size approaches zero quickly and thus provides only a few data points for regression. Take the unit box size as level one, and the box size changes as 1/2, 1/4… In the 10th level of box division, the box size is $1/2^9$, and the total number of boxes is $2^{18}$. This is the lower bound for box division in most literature, which provides 10 data points of box size (Benguigui et al., 2000; Grau et al., 2006; Lu & Tang, 2004). Besides the dyadic sequence, other choices have been proposed, such as the odd number sequence (Bisoi and Mishra 2001; Chen et al., 1993), modified arithmetic sequence (Buczkowski et al., 1998; Foroutan-pour et al., 1999), and modified dyadic sequence (Shen, 2002).

The third issue is the difficulty in determining the scaling range of box sizes over which the fractal analysis is applied (Saucier & Muller, 1998). It is widely accepted that fractal properties only exist on a certain scaling range for stochastic fractals (Goodchild, 1980; Lam & Quattrochi, 1992; Roy et al., 2007). However, there is no generally agreed method to specify the upper and lower bounds of the scaling range (Foroutan-pour et al., 1999; Huang et al., 1994; Liebovitch & Toth, 1989). Most studies suggest...
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