Ecological Indicators 67 (2016) 183–192

Contents lists available at ScienceDirect

Ecological Indicators

journal homepage: www.elsevier.com/locate/ecolind

Scaling indicator and planning plane: An indicator and a visual tool for exploring the relationship between urban form, energy efficiency and carbon emissions

Fouad Khan[a,*], Laszlo Pinter[b,c]

[a] Central European University and WWF Luc Hoffmann Institute, A-202, Block 7, Gulistan-e-Johar, Karachi, Pakistan
[b] Department of Environmental Sciences and Policy, Central European University, Nador 9, 1051 Budapest, Hungary
[c] International Institute for Sustainable Development, Winnipeg, Canada

ARTICLE INFO

Article history:
Received 4 December 2015
Received in revised form 13 February 2016
Accepted 17 February 2016
Available online 25 April 2016

Keywords:
Urban sustainable development
Complex systems
Scaling indicator
Fractal dimension
Energy consumption
Sustainable development indicator

ABSTRACT

Ecosystems and other naturally resilient systems exhibit allometric scaling in the distribution of sizes of their elements. In this paper we define an allometry inspired scaling indicator for cities that is a first step toward quantifying the stability borne of a complex systems' hierarchical structural composition. The scaling indicator is calculated using large census datasets and is analogous to fractal dimension in spatial analysis. Lack of numerical rigor and the resulting variation in scaling indicators – inherent in the use of box counting mechanism for fractal dimension calculation for cities – has been one of the hindrances in the adoption of fractal dimension as an urban indicator of note. The intra-urban indicator of scaling in population density distribution developed here is calculated for 58 US cities using a methodology that produces replicable results, employing large census-block wise population datasets from the 2010 US Census and the 2007 US Economic Census. We show that rising disparity – as measured by the proposed indicator of population density distribution in census blocks in Metropolitan Statistical Areas adversely affects energy consumption efficiency and carbon emissions in cities and leads to a higher urban carbon footprint. We then define a planning plane as a visual and analytic tool for incorporation of scaling indicator analysis into policy and decision-making.

1. Introduction

It has been shown that the hierarchical organization in ecosystems makes them more stable and less sensitive to damage from environmental disturbances (Jørgensen and Nielsen, 2013). The mechanisms underlying this 'stability' that originates from the system 'form' have been a subject of study since the earliest analyses of systemic risk were undertaken for anthropogenic complex systems (Perrow, 1984). Higher de-coupling between system elements (or niches for ecosystems) and higher functional redundancy have been identified as factors that contribute toward making a system more adaptable and hence more resilient to shocks. Post 2008, a growing body of literature has also explored the role of these factors in making economic systems more or less resilient (Taleb, 2012). This paper explores how the city as another anthropogenic complex system can be analyzed for the presence, absence or degree of this stability within its structure. The hierarchical organization that lends ecosystems their stability expresses itself structurally in the form of very specific scaling. What this means is that in such systems, the design elements are distributed at various scales such that the number of elements p, at each scale x are related according to the equation $px^m = \text{constant}$ (Salingaros and West, 1999) where m is the exponent of the power law, also called the fractal dimension. Like the teeth along the edge of a toothed leaf or the orbits of moons and planets, similar design elements repeat themselves at different scales and also on the same scale. Natural complexity emerges out of a repetition of design algorithms with slight variations or anomalies or mutations for each repetition and at each varying scale. In other words, typically these systems are not naturally inclined to have aberrantly sized elements and the number of component elements decreases as the scale to which the element belongs increases in size. The bigger an element is, the lesser its population in the system (Parrott, 2010; Salingaros and West, 1999; West and Brown, 1997, 2004; West et al., 1999).

In architecture and urban planning there has been an emerging body of work rediscovering the significance of form and scaling in urban planning especially within the new urbanism movement (Batty and Longley, 1994; Benguigui and Czamanski, 2004;

* Corresponding author. Tel.: +45 91626381; fax: +36 1 327 3031.
E-mail addresses: fouadmkhan@gmail.com (F. Khan), lpinter@iisd.ca (L. Pinter).

http://dx.doi.org/10.1016/j.ecolind.2016.02.046
1470-160X/

Bettencourt et al., 2010; Coward and Salingaros, 2004; Salingaros and West, 1999; Shen, 2002). These form analyses have taken into account the complex nature of urban systems and identified fractal dimension as an indicator of note, both as a measure of scaling and space filling within the city. It has also been shown that on a greater scale, similar scaling characteristics can be attributed to the distribution of human population in general, with cities having predictable socioeconomic and infrastructural parameter values based on their size (Bettencourt et al., 2010; Hern, 2008).

Despite progress at the conceptual level, the role of scaling characteristics in understanding the role of urban form has not been universally recognized. Continued skepticism toward the significance of form in urban planning (Echenique et al., 2012) however, often fails to take into account the complexity of urban systems while analyzing form. One of the reasons for that is because scaling indicators, such as fractal dimension, are often not easy to calculate with replicability and reliability. A case in point is the box counting method that has been traditionally used for estimating scaling indicators for cities (Batty and Longley, 1994; Benguigui et al., 2000; Hern, 2008; Shen, 2002). This usually involves overlaying a grid on a digitized map of the city and then counting or estimating the covered or relevant populated area within each box of the grid. The count is then binned into classes according to increasing size or increasing number of boxes (having count within the class range) within each class. The scaling indicator is estimated by plotting a log–log graph of the count range against the number of boxes falling within that count range; the slope of the resulting trend-line is the exponent of the power law or our scaling indicator of concern for the distribution of sizes of elements. The method is prone to varying results given the size of the box and the resolution of the map or image. Of course this lack of replicability means that the indicator does not meet a fundamental criterion for good indicator development and represents a constraint on its usefulness for policy (Kandziora et al., 2013; Pintér et al., 2012).

In this paper, we present a more rigorous method for estimating a scaling indicator for cities that can produce replicable results. The new method would allow a more reliable representation and analysis of urban form, and an indicator of space filling within the city can be developed that is cognizant of the complex nature of the city. The paper goes on to show how urban form, once analyzed in this manner, does indeed influence sustainability attributes such as gasoline consumption within the city. We also suggest that further research into more reliable scaling-based indicators such as the one proposed is warranted and could result in discovering new relationships between spatial structure and environmental performance with significant relevance for policy. Finally we propose a visual representation of the new indicator called planning plane to incorporate analysis of scaling into policy for urban sustainable development.

2. Materials and methods

To implement our data intensive method for the estimation of a fractal dimension based scaling indicator, data on US population by census blocks is downloaded from the US Census Bureau website (US Census Bureau, 2010). A census block is a small unit roughly congruent to a neighborhood block. As such, the assumption that the housing type within the census block is largely homogenous should hold. The data is downloaded for Metropolitan Statistical Areas (MSAs) which are census designated places that take into account the network of economic, industrial and commercial activity. So if a suburb has most of its financial linkages to a metropolitan area, the corresponding MSA would include the suburb as part of the MSA. The MSA is selected as the smallest unit of analysis for the study.

MSAs are composed of counties. Every county is then divided into census tracts. The census tracts are then split into block groups, which are made up of census blocks. The census block is the smallest census designated geography. An MSA or city maybe composed of anywhere from hundreds to hundreds of thousands of census blocks.

The census blocks for each city are first sorted according to increasing population density and then binned in ten classes using *k*-means clustering (Lloyd's algorithm) along the population density spectrum (Khan, 2012). The population density and area covered are then calculated for the ten classes. The fractal dimension based scaling indicator is calculated by plotting the inverse of population density against the area covered by housing of that density. Once plotted on log–log scales the resulting slope of the trend-line would be the exponent of power law or the proposed fractal dimension based scaling indicator of the distribution of population densities within the city.

To derive our exponent we first start with the formula for the box-counting dimension, as expressed by Eq. (1) (Salingaros and West, 1999). According to the box-counting method a grid of 'boxes' is layered on a map of the city, that divides the spatial spread of the city into different populated areas, each with a different land use coverage.

$$D = \frac{\log N_x}{\log\left(\frac{1}{x}\right)} \tag{1}$$

where

D = box counting dimension
x = certain percentage (or range of percentages) of area of the box covered by land use
N_x = number of boxes falling within range x

Instead of a map we have an extensive dataset of the distribution of urban population by census-blocks. Accordingly, instead of overlaying a grid of 'boxes' on a map, we will split the population into virtual boxes, each covering an area of 1 km^2. So in our methodology the 'box' of the box-counting method is any given 1-km^2 region of the city.

The next step is to establish the frequency distribution of population intensity across the boxes. In box counting method this is done by counting all the boxes that fall within a certain range of land use coverage; say 2 out of 20 boxes have between 40% and 50% of their area covered by urban land use. This is designated by the term N_x in Eq. (1). For our methodology the congruent count will be the number of km^2 boxes that fall within a certain population density range; say 8 km^2 of the city has population density between 100 and 200 people per km^2. The comparison of these two methodologies is shown in Fig. 1. In the proposed method, an area of 1 km^2 is analogous to what is defined as the 'box' in box counting method and clustering is on the basis of population density instead of percentage of area of box covered by land use.

So if, a_i = area of block i, where i = 1 to n, and n = no. of blocks, and p_i = population in block i, then population density in block i can be given as:

$$\rho_i = \frac{p_i}{a_i}$$

Now if the list of blocks is sorted according to increasing population density ρ_i such that increasing index i indicates blocks of increasing density and blocks are clustered in c number of classes such that the blocks falling within each class j have the population density range $\rho_{il} \le \rho_i < \rho_{iu}$, where ρ_{il} = lower population density bound of