Fat Tailed Distributions of the Spatial Metrics of Urban Organization of Metro Manila, Philippines

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***Abstract*—We investigate the emergent features of urban spatial organization through a statistical analysis of spatial metrics relating to the distribution of the physical structures in the cities and the nature of their interactions. The spatial characterization, which involves the spatial separation of the buildings and the layout of the roads, is employed on two component cities of Metro Manila, the National Capital Region of the Philippines. Our results show fat-tailed distributions that are statistically different from the normal (Gaussian) distribution with the same mean and variance as the data, which is the expected distribution for a null, memoryless condition. The emergence of scale free regimes, therefore, suggests the inherent memory in the spatial organization of urban forms in self-organized cities.**

***Index Terms*—Cities, Scaling phenomena in complex systems, Self-organization of complex systems**

I. Introduction

Self-organization is a phenomenon when a system organizes its structure by itself, independent of external agents [1]. Its common manifestations are in the form of nonlinearity, fractal structures, and possible chaotic behavior, which are observed in many different systems in nature and society [1-4]. Decentralized and organically-grown cities, with their accompanying spatial and temporal elements, are deemed to be examples of complex, self-organizing systems [5,6]. These self-organized cities evolved throughout history to meet the local needs of its inhabitants, unlike completely planned cities that were drawn up for aesthetic purposes and global optimization [7]. This resulted in a non-homogeneous urban layout when viewed in a global scale. However, we believe that the underlying factors that give rise to the development of urban areas for the benefit of the society in general may be deemed to be universal across all regions and periods. We expect, therefore, to still find order and patterns when we characterize the urban elements quantitatively.

Cities become sites of innovation and structural transformation [8]. They are the places where new economic ideas form and crystallize and where cultural, demographic, economic and political changes converge. Increasing urbanization is one of the defining features of cities. The increase in economic activity in highly-urbanized cities lead to a corresponding rise in the population, which in turn, requires the setting up of facilities for services and government regulation. This is especially true for Philippine cities, which are at the forefront of the country's economic development. The Philippines has registered an average of 5.6% GDP growth [9], making it one of the fastest growing economies among major Asian emerging markets. While this scenario has been usually depicted using economic figures and rates, a more important and pressing concern would be on how it will translate into an actual spatial configuration on the ground. The finite spatial extent of the cities has to be accounted for in designing policies aimed at improving or sustaining economic growth.

In this work, we focus on the emergent properties of two cities in the Philippines, Manila and Quezon City, as manifested in the spatial domain. Manila City has been the capital city since the late 1500s, while Quezon City was constructed from a master plan and briefly served as capital from 1948 to 1976. Previous works have shown that urban properties Y such as land area, socioeconomic rates and network properties vary continuously with population size, described by $Y = Y_o N^{\beta}$ [10]. Um et al. [11] have shown that the distribution of these entities follows a positive correlation to population density, described by $D \sim \rho^{\alpha}$. The economic and administrative facilities have been observed to have different distributions: $\alpha = 1$ for the former and $\alpha = 2/3$ for the latter. However, they only consider the relation of population to the facilities and neglect the spatial distribution of the facilities.

On the other hand, the paper of Decreane et al. [12] discussed the mechanism of spreading of facilities in space. They defined three types of entities in urban sprawl - residential, business and industrial - and recovered their spatial distribution using segregation and aggregation mechanisms in a cellular automata model. Makse et. al. [13] recognized that urban growth increases development in nearby areas; they used a percolation-based model with growth centers to recover power-law features of urbanization observed in Berlin and London. However, these works have studied cities in more developed countries, which are dominated by a high degree of centralized planning, unlike urban regions in the developing world that are mostly self-organized [5].

For our work, we analyzed the spatial organization of economic structures in a self-organized setting through statistical description of various spatial metrics. Our

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results show a fat-tailed distribution that are statistically different from null models under memoryless conditions. The actual spatial constraints are being considered which may prove to be useful for understanding the growth and development of these urban metropolitan areas. Moreover, the results may aid in understanding local conditions, for developing better models and more efficient policy measures in building facilities.

II. Methodology

In this work, we investigated the spatial characterization of economic structures present in the city to have a description of the urban fabric. Different spatial metrics were employed to develop indicators of urban form.

A. GIS Data

We gathered data on the positions of various structures in two representative Metro Manila cities: Manila and Quezon City, two of the largest cities in the Philippines' capital region in terms of population and land area. For both cities, the political boundary, structure and road network shapefiles are taken from Open Street Map (OSM) Philippines and are processed using Quantum GIS (QGIS) software to extract important parameters needed in the characterization.

Upon obtaining the map and the GIS data, each structure is made up of a node, containing attributes such as the corresponding latitude ϕ and longitude θ coordinates and an ID. For our work, economic buildings are locations for business establishments. The tags in OSM data allowed us to manually classify structures under economic classification.

B. k-nearest-neighbor

The k-nearest-neighbor (kNN) is used in statistical estimation and pattern recognition as a non-parametric technique. kNN is an algorithm that stores all available cases and classifies new cases based on similarity measure; for our case, it is the distance function.

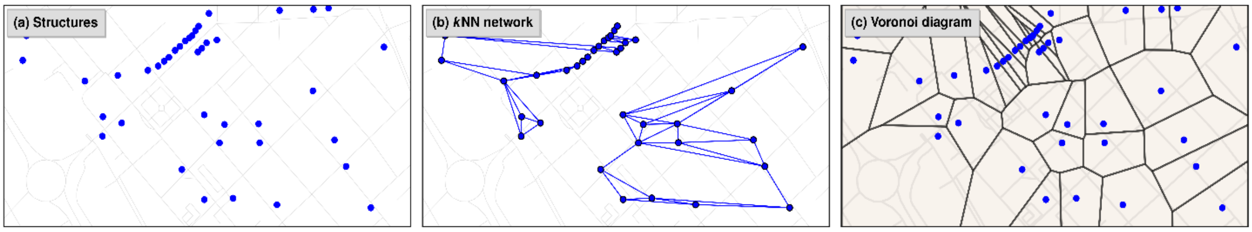

Figure 1. A zoomed-in portion of Quezon City which shows the (a) location of economic structures and the road networks, the (b) k-nearest-neighbor scheme for k = 3, and the (c) Voronoi diagram.

For our work, a k-nearest-neighbor networks of similar categorized structures are constructed. Each structure has location and is denoted by the latitude-longitude pair $(\phi_i,\ \theta_i)$ are connected to its k_{nn} nearest neighbors in space, $(\phi_{nn},\ \theta_{nn})$, as a gauged using the distance formula for points on a sphere,

$$d = R_E \arccos(\sin\phi_i - \sin\phi_{nn} + \cos\phi_i \cos\phi_{nn} \cos|\theta_i - \theta_{nn}|) \tag{1}$$

where R_E denotes the radius of the Earth; i.e. the k_{nn} locations with lowest d values relative to i are chosen. The point-to-point distance given by (1) is better at capturing better distances, for adjacent structures or those that are on opposite sides of the road. We opted to use the geodesic distance, as it better reflects clustering, especially for economic structures. The k_{nn} that ensures full network connectivity while ensuring minimal complexity for the cities is explored. The metric is illustrated schematically in Fig. 1(b). The network is characterized by looking at the distributions of the degree k, the number of links that a location has, and the distances d of all connections.

C. Voronoi Diagram

Given a finite set of distinct points in Euclidean space, we associate all locations in that space with the closest members of the point set with respect to the Euclidean distance. This yields a tessellation of a plane into a set of regions. The tessellation is called a Voronoi diagram while the regions which comprise the diagram are called Voronoi polygons [14].

Let the number of points, n, in the Euclidean plane be bounded by $2 \le n < \infty$. The n points are each labeled as $p_1, \ldots, p_n$ with corresponding Euclidean coordinates (x, y). The planar ordinary Voronoi diagram is given by

$$\mathcal{V} = \{V(p_1), \ldots, V(p_n)\} \tag{2}$$

where $V(p_1), \ldots, V(p_n)$ are the Voronoi polygons associated with $P = \{p_1, \ldots, p_n\}$. We call p_n of $V(p_n)$ the generator point or generator of the nth polygon, where P is the generator set of the Voronoi diagram [14].

Voronoi diagrams can be generalized to incorporate a network [15], weights [16], and line and area generators [17]. In this work, we solely focus on an ordinary Voronoi diagram. The locations of the economic structures are used as generators to create a planar ordinary Voronoi diagram for ease of construction. The Voronoi polygons represent the land areas A partially covered by and partially surrounding each of the structures, as shown in Fig. 1(c). We define a polygon to be a structure's "area of influence". The network is characterized by relating the road length enclosed by the polygon to the Voronoi area.

III. Results and Discussion

Fig. 2 shows the probability density functions $p(d)$ of the actual distance between kNN connected locations across the two cities considered, (a) Manila and (b) Quezon City. The distance distributions follow a relation that is best represented by the log-normal distribution regardless of the location of the cites. For both cities, we observe that the characteristic modal values between economic buildings are small in magnitude: for Manila, the $p(d)$ for economic buildings is at $79\,m$ while for Quezon City, the economic buildings have characteristic separation distance of $103\,m$. This result validates our claims economic buildings cluster around economic hubs where conditions are suitable for business. The distribution of economic centers have similar distance distributions, suggesting that the mechanisms for the formation of economic buildings must be the same, and is dependent only on the viability of certain locations.

We then compare the data to a synthetic null model which has a Gaussian distribution. The null model is created by using the same total number of structures and the same administrative boundary and distributing it as a Gaussian. As expected, the data does not have the same shape as the null model either at the tail or at the head. The spacing of the structures in the null model is uniform and it fails to take into consideration the geographical features and road networks of the city. This goes to show that the data is in fact non-trivial. The empirical results show a fat-tailed distribution that are statistically different from the null model under memoryless conditions. This means that regularity is present in the spatial organization of economic structures.

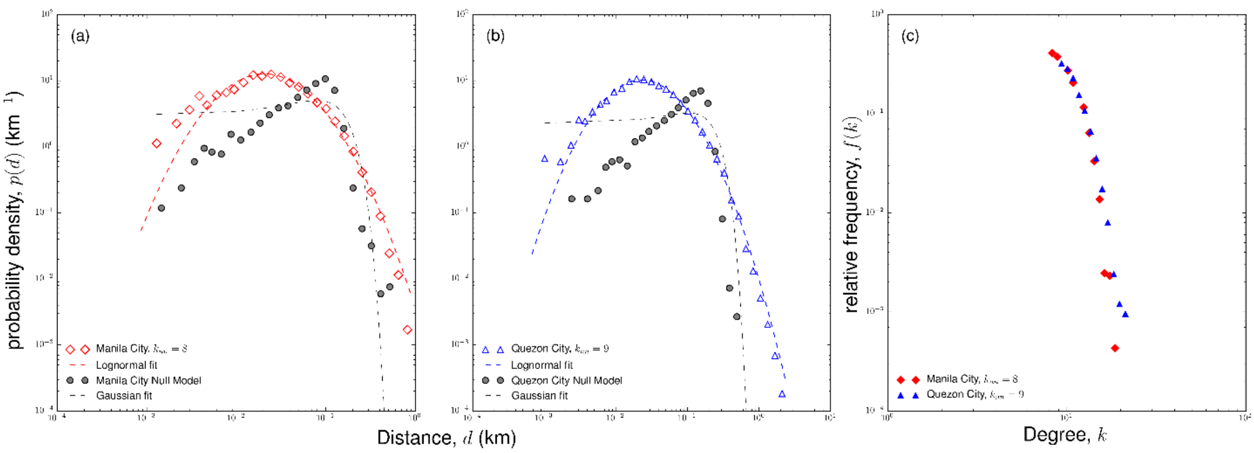

Figure 2. (a) and (b) Distance distributions p(d) of economic nearest-neighbor buildings in Manila and Quezon City. Both cities have distance distribution that follows a lognormal distribution. (c) Degree distributions f(k) of economic nearest-neighbor buildings in Manila and Quezon City. There is no significant difference observed between the two cities. [symbols and colors denote different cities, hollow (filled) symbols for economic (null model) building]

Fig. 2(c) shows degree distributions $f(k)$ of economic nearest neighbors buildings in Manila and Quezon City. We observe that the degree distributions obey a scaling relation that is best represented by the exponential distribution. While having modes at $k = kNN$, the degree distribution shows to have tails that go to the higher values of k. Because of the random scattering of the facilities, some locations i will have $k > kNN$, with some facilities receiving more connections from farther away structures. We observe no significant differences across the two cities, suggesting that, ultimately, *when* to construct another structure is independent of *where* to construct it.

Fig. 3(a) shows the length distribution for Manila and Quezon City. The length distributions display a power-law trend in the tails, given by $p(L) \sim L^{\gamma}$, where $\gamma = -1.30$. We observe heterogeneity in the trends in both shorter and longer enclosed road lengths. The power-law decay is a manifestation of the underlying mechanisms behind street network formation, which may prove to be universal. Fig. 3(b) shows the relationship between the Voronoi area and the road length. As the Voronoi area increases, the enclosed road length also increases indicated by the positive slopes, $\alpha = 0.94$ and $\beta = 2.56$. The smaller Voronoi polygons enclose shorter roads while larger polygons enclose longer roads. Fig. 3(c) gives us insight about urbanization. Small Voronoi polygons corresponds to the places where economic hubs exist. Economic structures are clustered in economic hubs forming small polygons. Meanwhile, larger polygons correspond to the rural part of the city where economic structures are scattered.

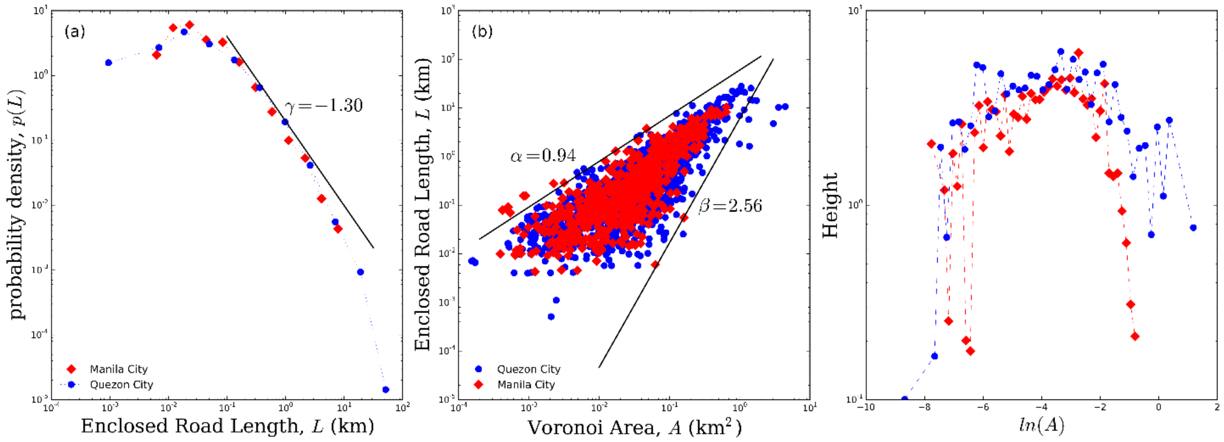

Figure 3. (a) Probability density distributions $p(L)$ of enclosed road lengths in Manila and Quezon City. The tail part of the distribution follows a power law distribution. (b) The enclosed road length increases as the Voronoi area increases. (c) Small Voronoi polygons are found at economic hubs while large polygons are found at rural part of both cities. [symbols and colors denote different cities].

IV. Summary and Conclusion

We have shown the regularity in the spatial organization of economic structures in self-organized cities. The distance and degree distributions follow a lognormal and exponential distributions. Meanwhile, the enclosed road length distributions display a power law trend. Upon looking at the actual distances between the connected locations in the kNN networks constructed, we have shown that the characteristic distances of the economic buildings are shorter, suggesting clustering. The distance distribution between economic structures show similarities between the two cities considered, suggesting that it is independent of the actual political conditions in the city but are more likely being governed by purely economic factors. The enclosed road length is positively correlated to the area of the Voronoi polygon. We have shown that smaller polygons are found at economic hubs while larger polygons are found at rural part of the cities. The work contributes to the literature on how urban growth can be quantified in space; more importantly, it shed light on local conditions, particularly in Metro Manila where each city enjoys a degree of autonomy, unlike other cities where growth is based on a global master plan. The insights from this work may thus aid in developing better strategies for governing growth in the local setting.

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