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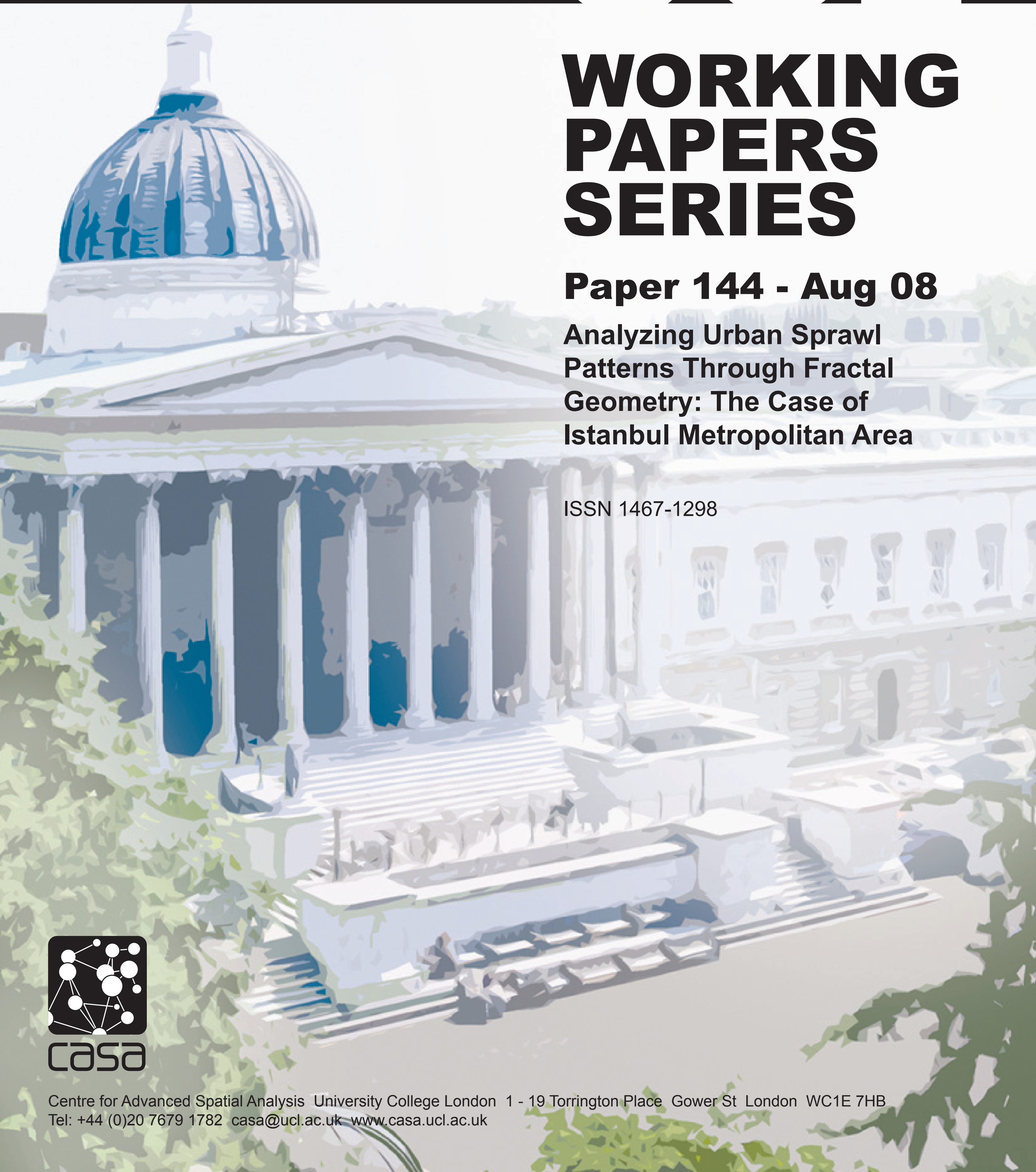

# WORKING PAPERS SERIES

## Paper 144 - Aug 08

## Analyzing Urban Sprawl Patterns Through Fractal Geometry: The Case of Istanbul Metropolitan Area

ISSN 1467-1298

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# ANALYZING URBAN SPRAWL PATTERNS THROUGH FRACTAL GEOMETRY: THE CASE OF ISTANBUL METROPOLITAN AREA

**Fatih Terzi [1,3] and H.Serdar Kaya [2,3]**

## Abstracts

Over the last decade, there has been a rapid increase in the amount of literature on the measurement of urban sprawl. Density gradients, sprawl indexes which are based on a series of measurable indicators and certain simulation techniques are some quantitative approaches used in previous studies. Recently, fractal analysis has been used in analyzing urban areas and a fractal theory of cities has been proposed. This study attempts to measure urban sprawl using a sprawl index and analyses urban form through fractal analysis for characterizing urban sprawl in Istanbul which has not been measured or characterized yet.

In this study, measures of sprawl were calculated at each neighborhood level and then integrated within sprawl index through "density" and "proximity" factors. This identifies the pattern of urban sprawl during six periods from 1975 to 2005, and then the urban form of Istanbul is quantified through fractal analysis in given periods in the context of sprawl dynamics. Our findings suggest that the fractal dimension of urban form is positively correlated with the urban sprawl index score when urban growth pattern is more likely "concentrated". However, a negative relationship has been observed between fractal dimension and sprawl index score when the urban growth pattern changes from the concentrated to the semi-linear form.

**Key words:** Urban Spatial Development, Urban Sprawl, Sprawl Index, Fractal Analysis

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## 1. INTRODUCTION

A number of definitions for urban sprawl have been put forward, but still there is considerable disagreement regarding a precise definition. In the absence of a clear way to identify urban sprawl, however, few definitions have gained widespread acceptance defining a series of characteristics or attributes. In these definitions, urban sprawl refers to a specific form of urban development characterized by low-density, leapfrog, commercial strip development and discontinuity (Ewing, 1997; Downs 1999; Galster et al., 2001; Malpezzi and Guo, 2001). Other important characteristics of sprawl include unlimited outward extension of development, dominance of transportation by private automobiles, fragmentation of land use, and large fiscal disparities among individual communities (Burchell 1998; Downs 1999; Brueckner 2000). Together, these features accelerate the spatial expansion of metropolitan areas by creating discontiguous land use patterns (Ewing 1997).

It is not immediately apparent how all the series of characteristics or attributes can be measured. Over the last decade, there has been a rapid increase in the amount of literature on the measurement of urban sprawl. This is because urban sprawl, which encompasses multiple aspects of urban spatial development, has been one of the debatable discussions in the field of urban and regional planning. Attempts have contributed to the current debate over its causes, consequences, and policy implications. Some researchers have identified measurable characteristics of sprawl, others have proposed specific indicators of sprawl to characterize patterns of urban sprawl. (Brueckner, 2000; Carruthers and Ulfarsson, 2002; Downs, 1999; Ewing, 1997; Galster et al, 2001; Gordon and Richardson, 1997; Peiser, 1989; Pendall, 1999).

Density is considered as one of the essential components of measuring sprawl. Since density is a very complex concept and its measures vary in several ways, it is important to clarify certain points. Torrens and Alberti (2000) pointed out that the density level at which a city might be regarded as sprawling, the scale at which density should be measured, and the extent of space over which density should be clarified in determining how the relationship between density and sprawl should be evaluated. Brueckner and Fansler (1983) and Peiser (1989) are among well-known papers by urban economists that use this measure.

The density gradient is an alternative approach to quantifying density instead of using the number of people or dwelling units per given area. The idea of a density gradient is the percentage change in density for a small change in distance from an urban center, or the density gradient of sprawl (Batty and Longley, 1994; Torrens and Alberti, 2000; Malpezzi and Guo, 2001). In fact, as Malpezzi and Guo (2001) emphasized, it can be argued that the density gradient model, which generalizes urban form as monocentric, is a good fit in explaining urban dynamism as cities grow and economies develop.

There have been other attempts to measure sprawl by developing quantifiable indicators. Using quantifiable indicators, researchers created a sprawl index based on factors that can be analyzed. Galster et al., (2000) identified eight dimensions of sprawl: density, continuity, concentration, compactness, centrality, nuclearity, diversity, and proximity. They created a series of Z scores for each dimension of 13 urbanized areas in USA and obtained a sprawl index to evaluate sprawlness for each urbanized area. Bertaud and Malpezzi (1999) developed a compactness index which is the ratio between the average distance per person to the CBD, and the average distance to the center of gravity of a cylindrical city whose circular base would be equal to the built-up area, and whose height would be the average population density. Ewing et al. (2002) also created a sprawl index based on four factors that can be measured and analyzed: (1) residential density, (2) neighborhood mix of homes, jobs, and services, (3) strength of activity centers and downtowns, and (4) accessibility of the street network. They applied these measures to 83 metropolitan areas in USA.

Some researchers also have identified measurable characteristics of sprawl and proposed specific indicators of sprawl to characterize patterns of urban growth and land use (Downs, 1999; Hasse and Lathrop, 2003). Using certain spatial simulation techniques, Tsai (2005) attempts to measure urban form both in theoretical simulations and while using empirical data from U.S. cities.

One other aspect of sprawl is the spatial configuration of built space in urban areas. The spatial configuration gives more information than the size or geometry of cities. Euclidean geometry is not powerful enough to explain the highly complex spatial organization, whereas fractal analysis offers a different perspective on the urban landscape which takes into account urban spatial complexity (Batty and Longley, 1994; Batty and Xie, 1996, Mehaffy and Salingaros, 2001, Bovill, 2000). In these studies, it is argued that the urban development process is chaotic, it can be defined as complex structure, and such complexity can be quantified through the spatial patterns which show the irregularity of their configuration.

Complex systems approaches treat the urban areas as dynamic, nonlinear, dissipative, open structures (Bertalanffy, 1968; Klir, 1972; Rapaport, 1972; Kirsbaum, 2002) which produces amorphous, convoluted geometry in space reflecting the sprawlness of the settlements. Attempts to measure the fractal dimension of the cities from all over the world have been found between 1.40 and 1.80 (Batty and Longley, 1994; Batty and Xie, 1996; Moon, 2002). McAdams (2008) reached similar results in the Istanbul case by using fractal and lacunarity values which measures the ratio of gappiness or spatial distribution of built up areas.

The comparative research of traditional and modern settlement pattern by Kaya and Bolen (2006) shows a strong correlation between the changes in spatial pattern and fractal dimension in the Istanbul case.

Torrens (2000; 2006) evaluated urban sprawl as a kind of space filling process and fractal dimension is the measure of extent to which the city fills its two dimensional area. In his research, fractal dimension is defined as the ratio of the logarithmic functions of perimeter of space at a particular length scale and two dimensional area of the space.

Frenkel and Askhenazi (2008) classified the sprawl measurement methods in five main groups as growth rates, density, accessibility, aesthetic measures and spatial geometry. They used various sprawl measures and conclude with the idea that urban sprawl is a multidimensional phenomenon that should be described and quantified by a combination of several measures. They analyzed urban sprawl by spatial geometry and heterogeneity added to other methods in the Israeli case. An urban area is considered sprawling as long as its geometric configuration is irregular, scattered, and fragmented and one indicator to measure these configurations is fractal dimension. Increasing fractal dimension is evaluated as a reflection of sprawling process in twenty-nine urban settlements in Israel.

Chaos theory and fractal geometry provide a reliable base for understanding urban development in space. Principle characteristics of a chaotic system are existence of complexity and unpredictability, self-similarity, self-organization around points of attraction and the existence of fractal nature (Feder, 1988; Cramer, 1998). Chaos theory helps the understanding of open complex systems, while fractal geometry determines the complexity level of morphological differentiation and interrelation between spatial elements, evaluating its development process.

## 2. BACKGROUND TO DEVELOPMENT PROCESS OF ISTANBUL

As in many other metropolitan areas throughout the world, sprawling urban development and the associated conversion of rural land have become an important issue facing Istanbul which is the largest city in Turkey where its population increased from 3.904.588 to 12.573.836 between 1975 and 2007 primarily due to migration (TUIK, 2007). Starting from 1950's, Istanbul has faced huge growth and its structure is constantly evolving.

The rapid growth of the city since the 1950s, due to rural migration, has affected urban spatial development. Initially, the informal residential areas which were low density and were located at the periphery accelerated the expansion of Istanbul. As a consequence of sprawlness, illegal/informal residential areas have started to invade the water basins, forests and high quality agricultural land (Bolen, *et.al*, 2007). In addition, the construction of bridges on the Bosphorus and the Golden Horn have changed accessibility of various areas measurably (Dokmeci and Berkoz, 2000) and have thus caused a spatial transformation in the pattern of land-use.

This urban growth process continued by constructing bridges on the Bosphorus and peripheral highways which have had a significant impact on suburbanization and retail expansion patterns in the metropolitan area, accelerating urban sprawl to the boundaries. An increase in accessibility affected the location of the new residential settlements and also the location of the firms. The intersection of the highways appears to have attracted some retail and office space development (Ozus and Dokmeci, 2005; Dokmeci, et al, 2006). Besides, firms have established themselves at the periphery, in search of lower land and transportation costs, large plots for large modern office buildings and shopping malls. This commercial restructuring of the city has adjusted with different types and sizes of commercial facilities at suburban corners which contribute to the outward expansion of the city (Terzi et al, 2006; Terzi and Dokmeci, 2007). These mixed use complexes form the bases of new sub-centers of the city. Although, in the 1970s, the historical CBD of Istanbul started to decline as a result of the suburbanization movement, it began to recover after the 1980s with the help of revitalization projects (Ozus and Dokmeci, 2005; Dokmeci, et al, 2006).

As a result of this suburbanization movement, new subcenters have emerged and this multicenter development has been encouraged and supported by the Master Plans of 1980. Ongoing population growth with the result of a multi-centered peripherial development have dominated the development characteristics of the city. The districts of Bakirkoy and Kadikoy (see figure.1) with large commercial and retail areas have been proposed as primary subcenters in 1995's Master Plan of Istanbul (Istanbul City Planning Directorate, 1995). The trend of urban sprawl is likely to increase through the last master plan 2007 that proposed new housing development areas in the periphery (IMP, 2007). This plan also proposed new subcenters in the periphery, but one of the basic challenges of this plan was to control the growth of the city, protecting the ecologically sensitive natural resources like forests, water reservoirs, agricultural land and geologically risky land (Bolen, *et.al*, 2007).

## 3. DATA & METHODOLOGY

Quantification of urban sprawl patterns has traditionally been based on the notion of density (Pieser, 1989) which can be defined in various ways (persons or dwellings per hectare, or built up area over total area). Proximity to urban activity is another variable to be considered as another basic component of measuring sprawl (Gordon and Richardson, 1997; Bertaud and Malpezzi, 1999; Galster et al., 2000; Ewing et al. 2002). Thus, population density and the proximity to city centers are the variables used in the calculation of the sprawl index in this study. The contributions of population density and proximity to the center were equally weighted. Using the sprawl index, it is aimed to determine the urban sprawl pattern over the time. In the following steps, the urban spatial development pattern was examined by fractal analysis to characterize urban sprawl complexity within the time period. The data related to the built up areas were collected for each neighborhood level within the urbanized area of Istanbul for the years 1975, 1980, 1985, 1990, 1995 and 2005.

The information was assembled for each of 787 neighborhoods which are the lowest administrative units in Turkey. Since this study focuses on urban spatial development, using GIS techniques 787 neighborhoods were clipped to the built up areas which have been taken as the statistical units for the calculation of the sprawl index.

### 3.1. Calculation of Sprawl Index and Sprawl Measurement

The first component of the sprawl index is “population density”. Population density provides an opportunity to measure the efficiency of residential land use over time. It is determined by the amount of residential area per person and measures the extent to which the type of development is sprawling or compact. Gross neighbourhood densities using population census results for the years1975, 1980, 1985, 1990, 1995 and 2005 (TUIK, 2007) were calculated using built up areas.

The second component of the sprawl index is “proximity”. Measuring the proximity of the neighborhood to the city center illustrates the extent of the population concentration in the urban core. As a result of Istanbul’s multi-centered development characteristics, new subcenters have emerged in 2005. There is a dominant center (Central Business District - CBD) in Istanbul and subcenters which have been defined in the Master Plan of Istanbul in 1980, 1995 and 2007. The measurement of proximity to centers is calculated as the geographic distance between two points. The first point represents the geometric mean of the built up area of each neighbourhood. The second point is the geometric means of the CBD and Subcenters. Proximity to the center has been calculated separately for six terms from 1975 to 2005. Since Istanbul has multi-center development characteristics, the distances to the CBD and subcenters have been calculated separately for the East and the West Side of Istanbul and weighted in accordance with the organized gross leasable retail area of each district (Table. 1).

Table 1. The Weight of CBD and Subcenters for East and West Side of Istanbul

| European Side (West) | Total Gross Leasable Areas | % | Weight |
|---|---|---|---|
| CBD | 335659 | 0.60 | 0.60 |
| Primary Center | 143114 | 0.26 | 0.26 |
| Secondary Center | 75724 | 0.14 | 0.14 |
| Total | 554497 | 1.00 | 1.00 |
| **Anatolian Side (East)** | **Total Gross Leasable Areas** | **%** | **Weight** |
| CBD | 335659 | 0.64 | 0.64 |
| Primary Center | 99026 | 0.19 | 0.19 |
| Secondary Center -1 | 41000 | 0.08 | 0.08 |
| Secondary Center -2 | 44500 | 0.09 | 0.09 |
| Total | 520185 | 1.00 | 1.00 |

Source: Trade Council of Shopping & Retailers (2008)

Before 2005, there was one primary subcenter on each side and no subcenters had yet emerged. Therefore the weight of the CBD has been taken as 0.75 in the calculation of proximity score, while the weight of primary subcenter is assumed as 0.25 for both sides. In 2005, new subcenters have emerged and the weight of CBD was taken as 0.60, primary subcenters as 0.26, and the secondary subcenter as 0.14 for calculation on the West Side. For the East Side, the CBD weight was taken as 0.64, primary subcenters as 0.19, the first secondary subcenter as 0.08 and the second secondary subcenter as 0.09 (Figure 1).

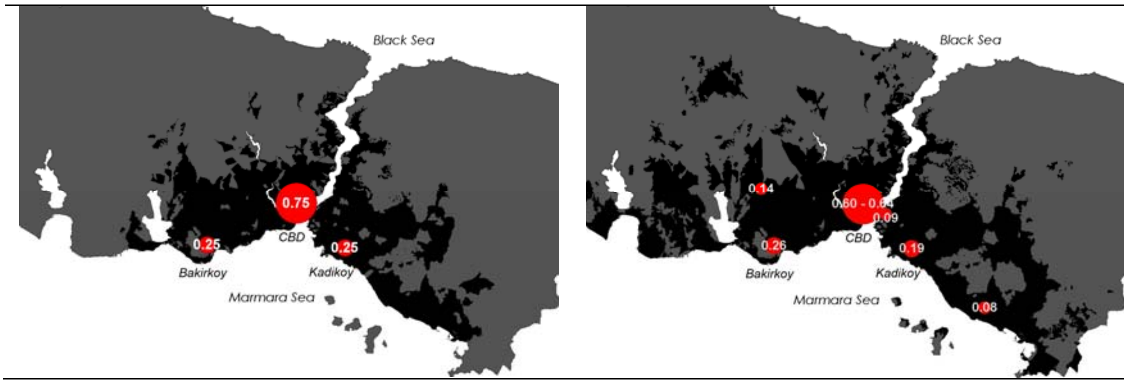

Figure 1. The weight of centers up to period of 1995 (on the left) and 2005 (on the right)

The sprawl index combines “density” and “proximity to centers”. Since density and proximity to centers have an inverse effect in the context of urban sprawl measurement, the proximity factor is considered as a negative component.

The sprawl index was calculated as follows:

(1) $S_n = ZsD - ZsP$

(2) $ZsD = \frac{x_D - \mu_D}{\sigma_D}$

(3) $ZsP = [(\frac{x_{P;CBD} - \mu_P}{\sigma_P}) * W_{CBD} + (\frac{x_{P;C1} - \mu_P}{\sigma_P}) * W_{C1} + (\frac{x_{P;C2} - \mu_P}{\sigma_P}) * W_{C2} + ...]$

where

$S_n$: *Sprawl index for year "n"*

*ZsD: Standardized values of gross population density of a neighbourhood*

*ZsP: Sum of standardized values of geographic distance for a neighbourhood to the CBD, Primary Center and Secondary Center(s)*

$W_{CBD};W_{C1};W_{C2}$: *Weights of the City Centers of the CBD, Primary (C1) and Secondary Centers (C2).*

The standardized values of "population density" and "proximity to center" were combined to calculate the overall Sprawl Index, ranking the most and least sprawling neighborhood. Evaluation of the sprawl index is based on:

- if a neighborhood has a sprawl score value defined by 1 standard deviation below the mean of the sprawl index, it is represented as a sprawled neighborhood;
- if it has a value defined by 1 standard deviation above the mean of the sprawl index, it is represented as a compact neighborhood;
- if the value is within an interval of 1 standard deviation of the mean of sprawl index, it is represented as a neighbourhood in transition which means that the neighborhood is neither sprawling nor compact (Figure 2).

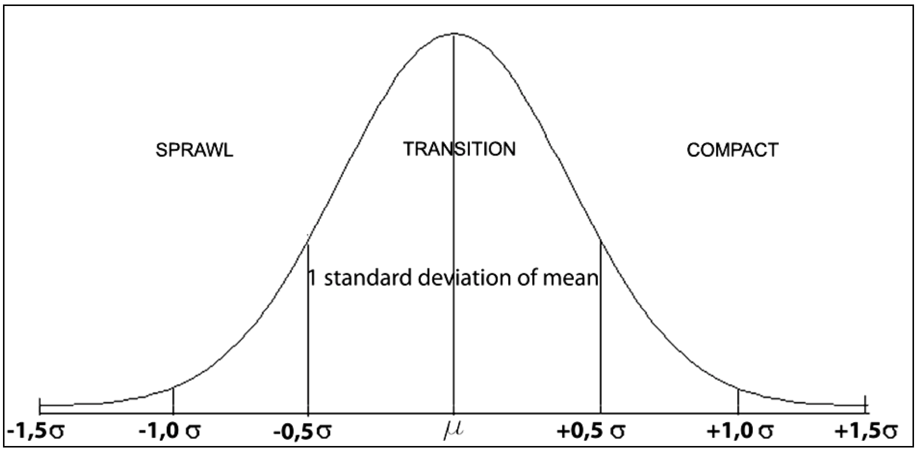

Figure 2. Evaluation of Overall Sprawl Scores

From the database created by the sprawl index of six five year periods, urban spatial development is mapped as in Figure 3.

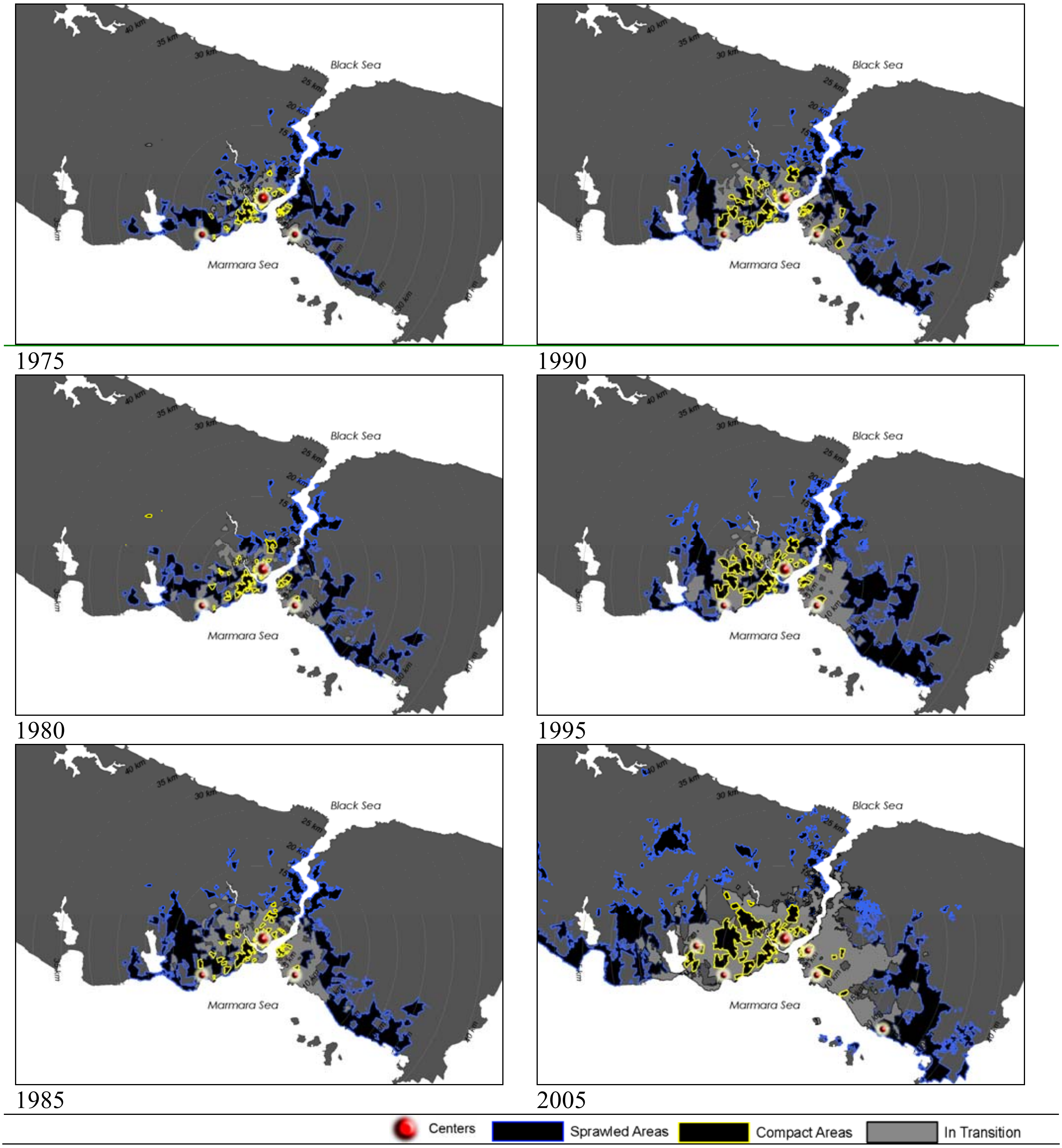


Figure 3. Urban Spatial Development of Istanbul.

From a visual representation of urban spatial development in Figure 4, some obvious patterns emerged from 1975 to 2005. Firstly, rapid urban expansion with low density development towards the peripheries has been observed. Secondly, multicentered development characteristics have led to increase densities of neighborhoods which are close to the primary and secondary subcenters during the time, and have increased population concentration in the urban core. Thirdly, it appears that leapfrog sprawl characteristics dominated urban spatial development near to 1995, but its difference from that in the west is that there can be a density increase of neighborhoods and it turns into a compact pattern. In the example of Istanbul, sprawling neighborhoods have turned into compact patterns due to increasing density and\or emerging new subcenters. Lastly, in 2005, the characteristics of urban spatial structure have been changed and the city has been extended to the west in a linear form along E-5 Highway due to extension of Urban Service Areas of Istanbul Municipality by the 5216 act in 2004. These initial findings were tested through fractal analysis whose aim is to quantify the degree of urban sprawl within the six five year periods.

## 3.2. Sprawl Measurement through Fractal Analysis

The word "fractal" comes from "frangere" which means "to break", to create irregular fragments (Mandelbrot, 1983). Fractal geometry is different from Euclidean geometry which proposes only the integer dimensions of 0, 1, 2, 3 etc., however it is possible to measure fractional dimensions with fractal geometry. Besides, these values could vary according to perceived distance to objects. Elemental forms of the physical environment could have a fractal dimension as a part of real life (Gleick, 1997).

The fractal dimension can be explained as the resulting dimension of a space filling process, the values of which can take on the values between 1 and 2. There are several methods to measure fractal dimension of an object, but the box counting method is the most suitable for measuring fractal dimension of complex structures. Moreover it can be easily shown by visual presentation methods such as city maps, and aerial or satellite images. Fractal dimensions to analyze changes in spatial configuration have been calculated as follows (Peitgen *et. al*,1993):

$$D= [\log N (2^{-(k+1)})- \log N(2^{-k})] / [\log 2^{k+1}- \log 2^{k}] = \log_2 [N(2^{-(k+1)}) / N(2^{-k})]$$

where

*D: Fractal dimension*

*k: natural number; 0,1,2,…*

$2^{-k}$ *=s:grid size (e.g.:* $2^0$ *=1 coarsest grid)*

*N: count of each "s" grid sizes*

Urban space does not always represent an ideal fractal structures on all scales as in deterministic fractals generated by computer such as the Sierpinsky carpet and Cantor set, so it has no unique fractal dimension. Especially at minimum and maximum scales, fractal values tend to fluctuate. Because of this, urban patterns need to be analyzed several times with different grid sizes to obtain a spectrum of fractal dimensions, instead of measuring the dimension with only two mesh sizes to find the fractal dimension of an urban space and define the value which has maximum frequency as a dimension of that sample.

In this research, fractal dimensions are used to analyze the changes in spatial configuration in Istanbul between 1975 and 2005 and have been calculated using the "HarFa" program developed by Martin Nezadal and Oldrich Zmeskal (Brno University of Technology, Institute of Physical and Applied Chemistry). This program allows for the calculation of the box counting dimension with several grid sizes. The smallest grid size is defined as a 300m x

300m square after analysing the existing fragmentation of the built up area of Istanbul. This size corresponds the minimum grid size of 6 pixels. The maximum grid size is defined as the 3km x 3km square which is 60 pixels in the whole image. At larger grid sizes, small changes would be omitted and measurement results can be misleading (Figure 4).

Image size: 150 km - Min grid size: 300m - Max. Grid size: 3km

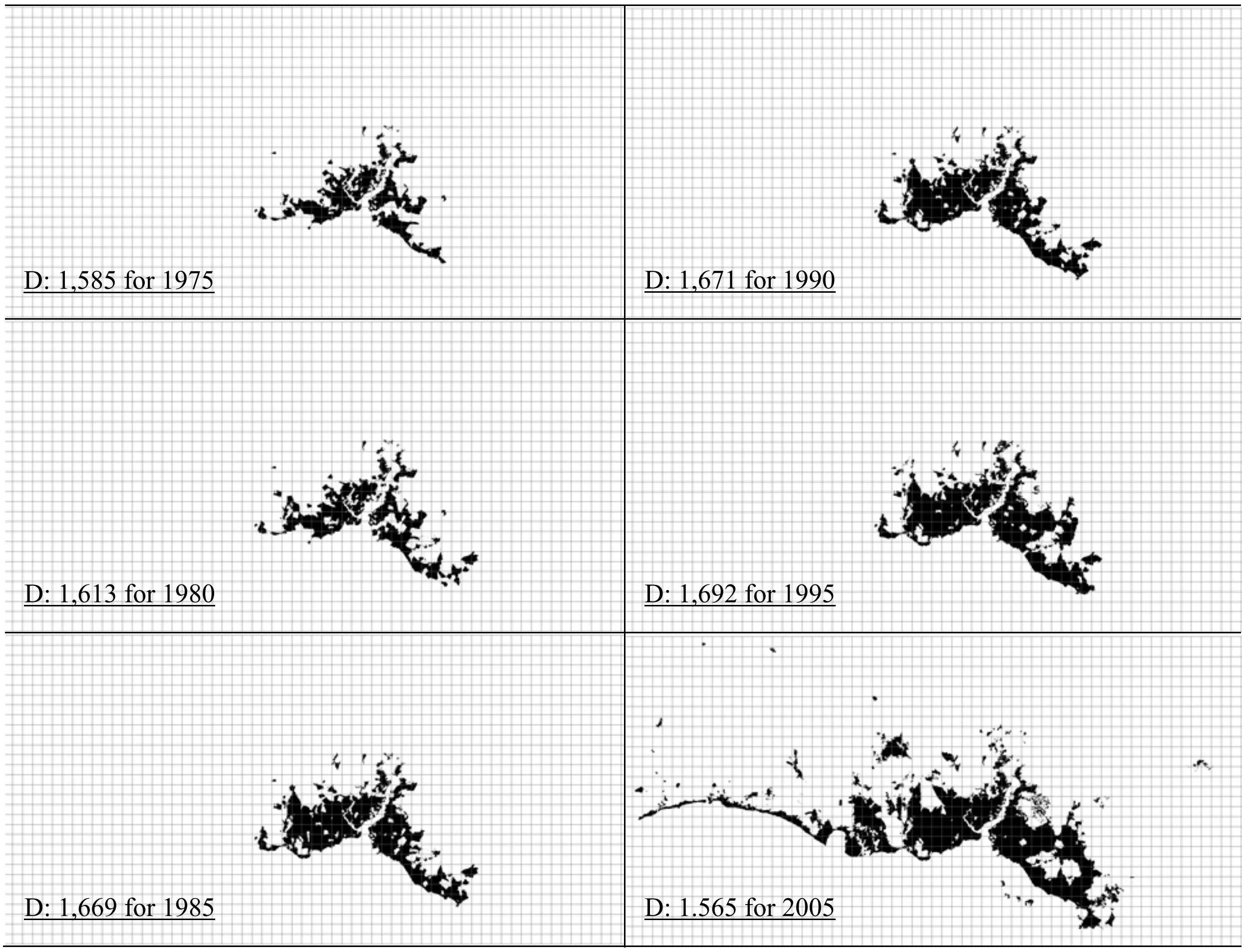


Figure 4. Changing spatial configuration of Istanbul from 1975 to 2005

According to these results, we can draw some important conclusions for the fractal analyses of Istanbul. Istanbul which is surrounded by the Marmara Sea from the south, shows rapid urban expansion in the east-west and northern directions. This urban growth pattern is a “concentrated urban form” from 1975 to 1995 and becomes semi-linear from 1995 to 2005 primarily due to natural environment characteristics and multicentered development proposed by the various Master Plans.

The natural environment characteristics such as the Bosphorus, hilly topography, forest areas and water basins give a more fragmented geometry to the city which leads to higher fractal dimension.

Rapid increases in fractal dimension between 1975 and 1990 can be interpreted as evidence of a sprawling process due to informal settlements at the periphery around the single central core as the result of a rapid development process. In 1984, informal settlements were legally given permission to intensify into high density areas (Bolen, 2004; Terzi and Bolen, 2005). This process is reflected in our calculations of relatively small change in fractal dimensions between 1980 and 1990. After 1990s, new emerging neighborhoods especially on the Anatolian Side (also known as the East Side) caused an expansion through the north and east of the city. This emerged as new finger-like settlements near the existing settlements which also causes an increase in fractal dimension (Figure 5).

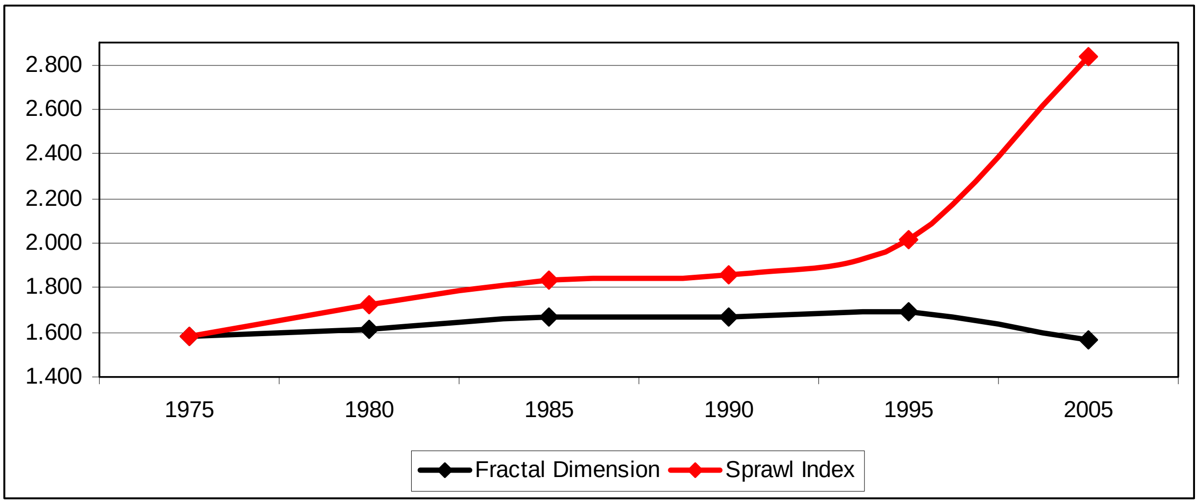

Figure 5. Change of Fractal Dimensions of Urban Form and Standardized Values of Sprawl Index for Istanbul from 1975 to 2005

The multicentered development characteristics which were proposed by the Master Plan of 1995 (Istanbul Metropolitan Municipality- City Planning Directorate, 1995) led an increase in density in secondary subcenters thus converting some of the fragmented areas into one single area.

After the year 2000, the city has been extended to the west in a linear form along the E-5 Highway due to an extension of Urban Service Areas. This has affected the fractal dimension with the addition of another characteristic of the sprawling process which is more independent as a linear expansion through the east-west direction. Expanding the service areas through contiguous areas has given a more linear shape to the city after 2004 rather than the areal shape seen up to 2004. These two different urban sprawl patterns have been reflected in the calculation of the sprawl index and fractal dimension (figure 5). From the figure 5, there has been an increase both in the sprawl index values which measure 'sprawlness' and fractal dimension which measures urban form until 1995. An increase in sprawl index values which indicate the continuance of urban sprawl process after 1995 is observed, whilst a dramatic decrease of fractal dimension identifying urban form changes from concentrated to semi-linear forms of which the fractal dimensions are lower then the previous terms.  Therefore, this process is the reason for the dramatic decrease in fractal dimension after 2004.

## 4. CONCLUSION

The issue of urban sprawl is of crucial importance in urban growth management all over the world. The patterns of urban spatial development are highly complex and require the theoretical and methodological framework which we have emphasized. In this study, we have tried to provide a sprawl measurement methodology that contributes to our understanding of sprawl dynamics through urban sprawl index and fractal analysis. Through the estimation of fractal dimension, urban form can be examined and important conclusions related to urban sprawlness can be drawn.

In the case study of Istanbul, we have attempted to measure urban sprawl using a sprawl index and we have analyzed urban form through fractal analysis which also characterizes urban sprawl. According to the sprawl measurement through the sprawl index, urban expansion with low density development towards to the periphery has dominated urban spatial development until 1995, but its difference from sprawl in the west is that there can be density increase in various neighborhoods. Importantly, neighborhoods are already sprawling have turned into compact patterns due to increasing density and\or emerging new subcenters. This urban development pattern is subject to an increase in fractal dimension. In contrast, with the extension of Urban Service Areas which causes semi-linear development in the Istanbul Case, a decrease in fractal dimension is observed.

This research shows that the process of urban sprawl is multidimensional and different methods need to be used together. Fractal dimension is one of these methods that can contribute to our understanding of spatial development of the city. In the Istanbul case, the research shows that changes in spatial configuration and fractal dimension provide a meaningful way of providing an efficient method of measuring sprawl in comparison with other methods.

**ACKNOWLEDGEMENT**

This study was supported by the Turkish Scientific and Technological Research Council of Turkey (TUBITAK) under the 2214 - Fellowship Program.

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