Review

Assessing Urban Morphological Complexity Through Fractal Geometry: Evidence From Turkish Cities

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Received: 03.12.2025, Accepted: 21.05.2025
DOI: **10.17932/IAU.ARCH.2015.017/arch_v011i2005**

Abstract: *Complexity science examines the emergence of structure in self-organising open systems, where interactions among individual components give rise to dynamic and adaptive patterns. Within this paradigm, cities are conceptualised as complex systems characterised by adaptability, self-organisation and sensitivity to initial conditions, reshaping how urban environments are understood. Urban planning literature increasingly adopts this perspective, recognising that cities evolve through non-linear processes and often exhibit self-similar spatial configurations. Fractal geometry, introduced by Mandelbrot, provides a powerful analytical framework in this context, enabling the identification and measurement of structural complexity in urban systems by means of the fractal dimension [Fd]. This study synthesises the theoretical background of fractal structures in cities and outlines the main methods of fractal analysis, with a particular focus on their relevance for urban morphology and planning. It discusses key approaches such as multi-scale, self-affine and multi-fractal analyses, explaining how these methods capture density, continuity, fragmentation and boundary complexity in urban form. Drawing on empirical studies, especially those conducted in Turkish cities, the paper examines spatial patterns of Fd values from city centres to peripheral zones and explores the relationships between fractal dimension, urban sprawl, road network hierarchy and planning decisions. The findings demonstrate that fractal geometry offers a robust quantitative framework for assessing spatial heterogeneity, evaluating urban compactness and monitoring fragmentation processes. In doing so, fractal approaches strengthen the role of quantitative methods in contemporary urban planning by providing tools to guide sustainable and resilient urban growth.*

Keywords: *Fractal dimension, Road network analysis, Urban sprawl, Morphology, Fractal analysis of Turkish cities.*

Kentsel Morfolojik Karmaşıklığın Fraktal Geometri Yoluyla Değerlendirilmesi: Türkiye Kentlerinden Bulgular

Özet: *Karmaşıklık bilimi, bireysel bileşenler arasındaki etkileşimlerin dinamik ve uyarlanabilir örüntüler ürettiği, öz-düzenleyici açık sistemlerde yapının ortaya çıkışını inceleyen bir yaklaşımdır. Bu paradigma, kentleri uyarlanabilirlik, öz-düzenleme ve başlangıç koşullarına duyarlılık gibi özelliklerle tanımlanan karmaşık sistemler olarak ele alarak kentsel çevreyi anlama biçimimizi dönüştürmüştür. Kentsel planlama literatürü giderek artan biçimde bu bakış açısını benimsemekte ve kentlerin doğrusal olmayan süreçler aracılığıyla evrildiğini, çoğu zaman öz-benzerlik sergileyen mekânsal yapılara sahip olduğunu kabul etmektedir. Mandelbrot tarafından ortaya konan fraktal geometri, özellikle fraktal boyut [Fd] kavramı aracılığıyla kentsel sistemlerdeki yapısal karmaşıklığın tanımlanması ve ölçülmesine imkân tanımaktadır. Bu çalışma, kentlerde fraktal yapılara ilişkin kuramsal çerçeveyi derleyerek fraktal analiz yöntemlerinin temel ilkelerini ortaya koymakta ve fraktal analizlerin kent morfolojisi ile planlama pratiklerine yönelik sunduğu içgörüleri tartışmaktadır. Çok ölçekli, öz-afin [self-affine] ve çok-fraktal yaklaşımlar dâhil olmak üzere fraktal analiz türleri incelenmekte; bu yöntemlerin kentsel dokunun yoğunluk, süreklilik, parçalanma ve sınır karmaşıklığı gibi boyutlarını nasıl yakaladığı açıklanmaktadır. Özellikle Türkiye kentleri için gerçekleştirilen ampirik çalışmalar üzerinden Fd değerlerinin kent merkezlerinden çevreye doğru mekânsal farklılaşma örüntüleri ele alınmakta; fraktal boyut ile kentsel yayılma, yol ağı hiyerarşisi ve planlama kararları arasındaki ilişkiler tartışılmaktadır. Bulgular, fraktal geometrinin mekânsal heterojenliği nicelleştirme, kentsel sıkılığı [kompaktlığı] değerlendirme ve parçalanma süreçlerini izleme açısından güçlü bir analitik çerçeve sunduğunu göstermektedir.*

Böylece fraktal yaklaşımlar, sürdürülebilir ve dirençli kentsel büyümeyi yönlendirecek nicel yöntemler sağlayarak çağdaş kentsel planlamada güçlü bir araç olarak konumlanmaktadır.

Anahtar Kelimeler: *Fraktal boyut, Yol ağı analizi, Kentsel saçaklanma, Türkiye kentlerinin fraktal analizi.*

1.INTRODUCTION

Complexity science is defined as the study of emergence in self-organizing open systems. These systems, characterized by rules and structures, are inherently dynamic and evolve through numerous synergistic interactions rather than through predetermined plans or complete external control. Urban environments exemplify complexity through their non-linear interactions, emergent spatial patterns, and dynamic adaptability. Traditional deterministic urban planning methods often fall short in addressing this intrinsic complexity effectively. This limitation has led to a shift away from conventional, rigid classifications of cities and regions towards more adaptive and flexible frameworks influenced by evolving epistemological and ontological perspectives in both the physical and social sciences. Complexity science provides alternative frameworks— such as fractal geometry, dissipative structures, cellular automata, and agent-based models—to better understand and manage urban systems, with the cited studies serving as foundational and representative reviews of complexity-based urban approaches [1-6].

Among these, fractal geometry has emerged as particularly useful for interpreting urban morphology, spatial patterns, and development dynamics by identifying and measuring self-similarity across multiple scale self-similarity as reflected in a broad body of foundational studies [7-13].

Building on this perspective, the study offers an extensive overview of fractal analyses conducted on Turkish cities, emphasizing key findings, methodological diversity, and planning-relevant implications. The reviewed evidence is organized comparatively (Table 1) to clarify what fractal measures capture in urban contexts and to consolidate insights for urban planning practices and policies.

2. MATERIAL AND METHOD

This study adopts a synthetic approach to fractal analysis in urban morphology by examining how fractal geometry has been used to conceptualize cities as complex systems and to measure morphological complexity in Turkish cities. Rather than producing new empirical measurements, the paper systematically reviews and synthesizes existing studies, focusing on the analytical purpose of fractal metrics, their interpretation in planning-related discussions, and their application across different urban contexts in Türkiye. The reviewed literature is comparatively organized according to city, fractal analysis technique, and key findings, as summarized in Table 1, which provides a consolidated overview of methodological diversity and empirical insights reported in previous research.

3.DEFINITION OF FRACTALS

In physics, the primary factors defining objects, spaces, or masses are typically space and time. Chaotic structures can be represented in space through non-linear dynamics, where complex spatial patterns emerge from simple interaction rules [14]. In such systems, chaos is not limited to spatial configurations but also manifests over time, as dynamic processes continuously modify system states. A defining characteristic of these dynamics is sensitivity to initial conditions, meaning that small variations at the outset may lead to substantially different trajectories over time. This inherent sensitivity renders chaotic systems resistant to traditional deterministic or reductionist analytical approaches. In this context, the emergence of fractal structures can be understood as the outcome of sustained interactions between temporal and spatial chaos within complex systems [15]. Complex systems differ from chaotic systems despite sharing certain characteristics. Specifically, complex systems are characterized by strong interdependencies among their components, such that the behavior of the whole cannot be reduced to the simple sum of its parts. These systems exhibit hierarchical structures that extend across multiple scales, with similar organizing principles observable at different levels of resolution. Moreover, emergent behavior in complex systems arises from global, self-organized interactions among components, producing scale-dependent patterns that are not imposed externally but generated through the dynamics of the system itself.

The term "fractal" was introduced by Benoît B. Mandelbrot in 1967 [16] to describe shapes characterized by intrinsic asymmetry, scale invariance, and self-similarity. Fractal geometry acts as a spatial representation of chaos theory, reflecting interactions between chaotic and orderly elements across multiple scales in complex systems. Jean-Pierre Baranger [15] emphasizes that fractals maintain their complexity at every scale, resisting simplification upon closer examination**.** Lewis Fry Richardson's work on measuring the length of coastlines and national boundaries [17] prompted Benoît B. Mandelbrot to further develop this idea through shoreline analysis in his paper *"How Long Is the Coast of Britain?"* [16]. Fractal objects are characterized by non-integer (Euclidean) dimensions between 1 and 2, being longer than a straight line yet shorter than a plane. Unlike the classical Euclidean framework that utilizes whole-number dimensions of 0 (point), 1 (line), 2 (plane), and 3 (cube), fractal analysis introduces fractional dimension (Fd). The top row in Figure 1 shows basic geometric forms while the bottom illustrates how complexity evolves with dimensionality: isolated points (0D), a branching fractal (~1.2D), and nested cubes (~2.3D). This progression demonstrates how increasing dimensions enable greater structural complexity, especially in fractal and spatial systems.

The key principles underlying fractal geometry include [7]:

- Self-similarity, wherein fractals exhibit consistent irregularity across different scales,
- Hierarchical order of self-similar elements such as trees, roads, and settlements,
- Non-differentiability, indicating fractals cannot be precisely defined by standard calculus methods.

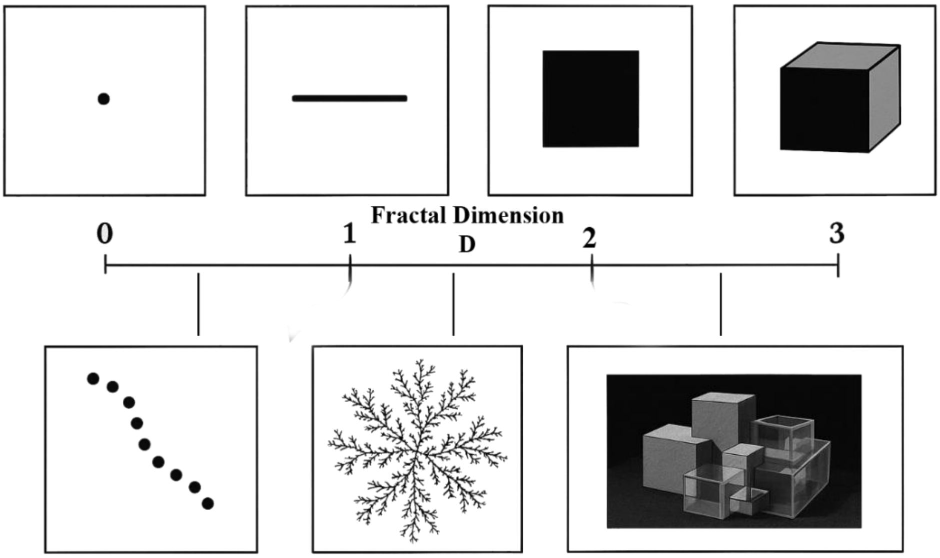

***Figure 1**. Dimensionality, Structural Complexity and Fractal Dimensions. Reproduced from [7].*

Fractals can also be generated artificially using iterative processes involving three main elements [18, 19]: (i) base material or concept, (ii) an initiator or initial shape, (iii) a generator, defining the repetitive transformation process.

To illustrate how fractal geometry translates abstract complexity principles into concrete geometric constructions, classical theoretical fractals are often used as explanatory models. The Koch Curve illustrates this concept effectively. It starts with a simple initiator [straight line] and repeatedly applies a generator (dividing the line into three segments and replacing the middle segment with two segments forming an equilateral triangle). Continuous iterations lead to increasingly complex yet self-similar patterns. Figure 2 illustrates the Koch curve generated by recursively applying a generator of 4 segments to an initial straight line (initiator). Each segment is scaled by a ratio r=1/3, resulting in a fractal with dimension D=log(4)/log(3)≈1.2618. At each iteration, every segment is replaced by the generator, increasing geometric complexity. The cascade tree on the right represents the recursive structure, where each node splits into 4 new branches per level. Other theoretical fractals include the Sierpinski Carpet, Dragon Curve, and the 'C' Curve, each having distinct fractal dimensions, such as "1.585" for the Sierpinski Carpet. These artificially created fractals find extensive applications, particularly in computer graphics and simulations, simplifying repetitive tasks and accurately modeling complex, self-similar structures.

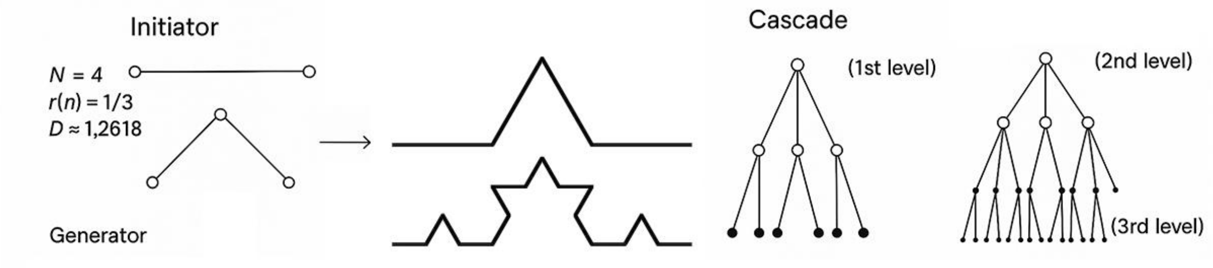

***Figure 2**. Koch Curve Construction and Recursive Tree. Reproduced from [7].*

4.SUBJECTS OF FRACTAL ANALYSIS

The literature on fractal analysis is extensive, offering diverse methodologies applicable across various disciplines. Multi-scale fractal structures, self-affine fractal structures, and multi-fractal structures are key fractal analysis techniques for modelling urban complexity.

Multi-Scale Fractal Structures

Multi-scale fractal structures demonstrate self-similarity across various scales of magnification. This means that the same spatial pattern repeats with increasing detail at finer levels, though the specific scaling behavior may vary. In practice, this is observed in urban development patterns where dense urban cores gradually transition into more fragmented suburban zones. In the seminal work of Frankhauser [9] more than 20 metropoles were analyzed, and the values of the scaling exponent remained at a constant level between 1.8 and 1.9 in central zones while in transient zones the scaling exponent dropped. For European agglomerations this decrease occurs within a rather restricted range of distances, whereas for the more homogeneous patterns of American cities the decrease of the scaling exponent extends to a wide range. These urban patterns are visualized using double-log plots, where breaks or changes in slope indicate varying fractal dimensions (Fd_s) across spatial regimes, each revealing different organizational principles.

Self-Affine Fractal Structures

Self-affine fractal structures exhibit self-similarity but with varying scale factors in different directions, leading to an anisotropic or directionally dependent pattern [18, 20]. Such fractals are commonly observed in natural phenomena like coastlines, mountains, and river networks, finding applications in geomorphology and image processing [21]. This is also particularly relevant in analyzing urban skylines or transportation corridors, where spatial features expand at varying rates horizontally and vertically.

Exploring self-affinity becomes pertinent when delving into three-dimensional fractals. While perfect self-similarity would yield a predictably monotonous complexity, real-world fractals often display statistical self-similarity, revealing layers of complexity. Natural occurrences exhibit multifaceted fractal behaviors that introduce additional intricacies. Figure 3 demonstrates the self-affine structure of the Barnsley Fern, generated using an iterated function system (IFS). The fern is composed of multiple copies of itself, each created by an affine transformation of the initial form.

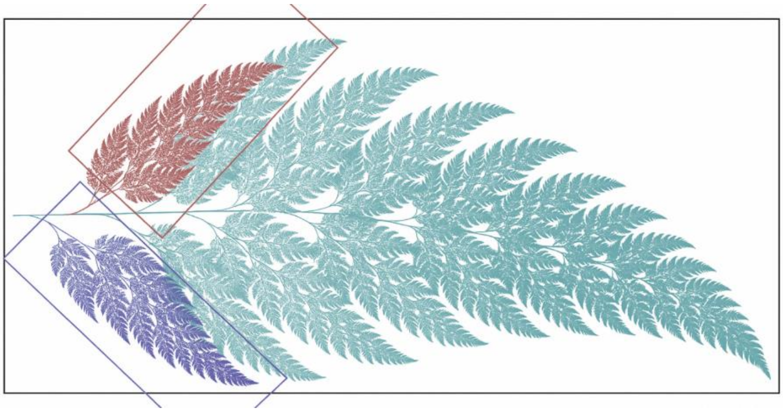

Figure 3. *Affine Self-Similarity in the Barnsley Fern.*

Multi-Fractal Structures

Unlike single-dimension fractals, multi-fractals consist of a range of Fractal Dimensions (Fd_s), capturing complex spatial variability and heterogeneity. This approach is ideal for analyzing uneven distributions of population density, land use intensity, or infrastructure. Cornelis J. G. Evertsz and Benoît B. Mandelbrot [22] define multi-fractality as the coexistence of multiple scaling behaviors within a single system. A practical urban application comes from Yanguang Chen and Jinfeng Wang [23], who used multi-fractal analysis to examine the distribution of urban built-up areas in Beijing. If various zones at the same level of an urban hierarchy have equal chances to develop, the city will have self-similarity; otherwise, it may have a multifractal structure. Their findings revealed that more developed districts showed higher Fractal Dimensions (Fd_s), while less developed peripheries displayed wider variation, pointing to unequal development patterns. This method enables planners to identify spatial imbalances, assess fragmentation, and guide equitable infrastructure investments.

5.FRACTAL GEOMETRY APPLICATIONS IN URBAN STUDIES

Fractal geometry, developed by Benoît Mandelbrot [24], provides quantitative tools to analyze complex spatial patterns that traditional Euclidean geometry cannot adequately describe. Fractals exhibit a different kind of regularity. However, at first glance, this may not be visible to the observer. Fractal geometry captures the intricacies of irregular, self-replicating forms across multiple scales, offering new insights into the spatial and functional organization of urban landscapes. Urban environments are complex mosaics integrating architectural designs, infrastructural networks, and human activities. Traditional analytical methods frequently overlook the nuanced and intricate processes that shape urban evolution. Benoît B. Mandelbrot's pioneering research on fractal patterns in coastlines laid the foundation for extensive urban applications, significantly advancing urban planning methodologies.

Fractal geometry offers an analytical framework for examining the spatial complexity of urban systems. It enables researchers and planners to uncover patterns of spatial organization, morphological change, and functional structure that are often obscured by traditional Euclidean models. Applications of fractal geometry in urban studies include:

Urban spatial analysis enablesplanners to examine the spatial arrangement of urban areas in order to detect patterns in the distribution of buildings, roadways, and other structural elements. Through such analyses, it becomes possible to map urban connectedness, distinguishing areas with high accessibility to services and facilities from more secluded or poorly connected locations. This perspective also supports the assessment of infrastructural resilience by identifying urban regions that may be more susceptible to disruptions, such as those caused by natural disasters. Furthermore, spatial analysis can be used to optimize transportation network structures—including bus and subway systems—by enhancing accessibility and reducing travel times, while also providing a basis for estimating broader impacts on urban performance and functionality. Fractal geometry supports the interpretation of hierarchical spatial structures, spatial thresholds, and multifractal properties in urban patterns [13]. Effective spatial planning recognizes urban forms as multi-scalar systems composed of nested hierarchies—such as central business districts, sub-centers, and peripheral zones—distributed across space [9, 25]. As cities expand, particularly under unregulated or uneven development, spatial fragmentation increases. Fractal analysis quantifies this complexity, allowing comparative evaluations of different urban morphologies.

The work of central place studies was not only involved with the scaling laws of complexity theory but also self-similarity, and self-organization are also properties, related to the complexity. A central place system can be seen as both a hierarchy with cascade structure and a network with self-similar properties. Hierarchical structure is a very significant notion for us to understand urban fractals [1, 7, 9]. Empirical studies have confirmed fractal properties in central place systems, such as the hierarchy of southern German cities [25], while theoretical work by Sandra L. Arlinghaus [26] and work with William C. Arlinghaus [27] articulated the fractal texture of central place networks. Expanding this approach, Guoqiang Shen [12] demonstrated that urbanized areas exhibit fractal properties with respect to scale-dependent changes in occupancy, land-use intensity, and density gradients. Similarly, Yang Chen [28] distinguished between the structural and textural fractality of central place systems, arguing that urban settlements display intermittent, fractal-like spatial arrangements governed by scaling laws.

The core body of research on the spatial variation of fractal dimension values shows that these values are generally highest in central business districts and decrease toward the outer suburbs [7, 10, 29]. Moreover, the rise in central Fractal Dimensions (Fd_s) combined with a decline in peripheral values is associated with compact, well-structured development, whereas the opposite trend indicates urban sprawl. In addition to centrality, the relationship between urban form regularity and Fractal Dimensions (Fd_s) has also been discussed in urban morphology literature. Regular, grid-like urban layouts typically exhibit lower Fractal Dimensions (Fd_s), reflecting their geometric simplicity and lack of complexity across scales. In contrast, irregular, organically evolved urban forms display higher Fractal Dimensions (Fd_s), indicating greater spatial complexity and self-similarity [7, 30, 26, 31, 32].

Urban sprawl, characterized by outward expansion, low density, fragmented land use, and poor spatial continuity, has been extensively analyzed through fractal methods. Batty and Longley [7] were among the first to systematically demonstrate that urban sprawl exhibits lower Fractal Dimensions (Fd_s) compared to more compact urban forms, highlighting its fragmented and inefficient spatial structure. Frenkel and Ashkenazi [33] employed Fractal Dimensions (Fd_s) as indicators to quantify urban sprawl, effectively capturing the degree of fragmentation and further developed an integrated sprawl index combining various metrics of urban configuration and composition, demonstrating that lower Fractal Dimensions (Fd_s) are indicative of more sprawling and inefficient urban patterns. Similarly, De Keersmaecker et al. [30] explored the relationship between urban density and Fractal Dimensions (Fd_s) in the peripheral areas of Brussels, emphasizing the complex interplay between compactness and fragmentation. Generally, higher fractal values correlate with more compact and space-filling urban structures (yellow color boxes in Figure 4), whereas lower dimensions typically signal increasing sprawl and peripheral dispersion (blue color boxes in Figure 4).

Figure 4*. The color scale represents variations in fractal dimension (D) values. Lower fractal dimension values (blue tones) indicate more fragmented and less space-filling urban patterns, whereas higher values (yellow tones) correspond to denser, more space-filling and morphologically complex urban structures. Intermediate colors reflect transitional levels of urban complexity across the analyzed spatial grid. [34].*

Fractal Dimensions (Fd$_s$) have also informed urban morphology measurements. Thomas Frankhauser [25] employed Fractal Dimensions (Fd$_s$) analysis to examine the structure of European urban outskirts, aiming to classify urban agglomerations based on their spatial complexity. Similarly, Shen [12] compared the morphology of 20 urban areas in the United States, highlighting how variations in urban size and form are reflected in differences in Fds. In the context of longitudinal studies, Benguigui et al. [35] analyzed the built-up patterns of Tel Aviv, concluding that the Fractal Dimensions (Fd$_s$) of the metropolitan area tends to increase over time as urban growth progresses. This trend was later analyzed by Benguigui et al. [35], who further explored the leapfrog development of Tel Aviv’s periphery through fractal and scaling relationships such as area-perimeter analysis and rank-size distributions.

6.METHODS OF FRACTAL ANALYSIS IN CITIES

Two primary criteria commonly determine whether spatial forms exhibit fractal characteristics: power-law distributions and scale-free organization [7, 9]. A power-law distribution implies urban elements, such as building sizes or street lengths, exhibit disproportionate structures, where a few large elements coexist with numerous smaller ones, maintaining consistent scaling across multiple levels. Scale-free organization, by contrast, indicates the absence of characteristic lengths, meaning spatial patterns retain similar properties across different scales, Fractal Dimensions (Fd$_s$) quantify these spatial complexities using various techniques. The box-counting method is prevalent in urban morphology, overlaying grids onto urban forms and counting occupied cells at varying scales, thereby capturing the hierarchical arrangement of built environments [29, 9]. Alternatively, the mass-radius [area-radius] method calculates the number of urban elements within expanding radii from a central point, providing insights into urban density and scaling behaviors [11].

Fractal analysis techniques examine diverse urban structures, including macro-scale urban forms, road networks, and built environment patterns. There are three primary application methods, depending on urban analysis objectives:

Macro-form Analysis: Fractal analysis of urban macro-forms [12, 25] helps track city evolution, identify trends, and predict future growth. This approach also investigates urban compactness by assessing urban development levels and vacant spaces, linking directly to sustainable urban development. Understanding the compactness of cities is crucial for evaluating environmental sustainability and resource efficiency. By examining the fractal characteristics of urban macro form, researchers can identify factors contributing to compactness. Understanding urban macro-form characteristics provides a useful context for debates on compactness and sustainable urban development, particularly in relation to land-use, transportation, and zoning policies[36, 37]. Incorporating fractal principles into planning enables more coherent and adaptable spatial strategies, effectively managing urban heterogeneity, self-organization, and growth issues. Decision-makers can better address urbanization's complex challenges and opportunities

Road Network Analysis: Urban Road networks frequently exhibit fractal geometry, characterized by self-similarity across scales and non-integer dimensions ranging between 1 (linear) and 2 (planar). As cities expand and become more densely filled, the Fractal Dimensions (Fd_s) of their road networks typically increases. Practically, a higher Fd signifies enhanced connectivity and accessibility due to increased routing options and loops, particularly noticeable in central urban areas [10, 35]. An example of its application can be observed in Figure 5. It illustrates this approach, highlighting how road network fractal analysis enables observation of dynamic urban changes over time, revealing patterns of development direction, areas of urban growth, and spatial transformation. Increasing fractal dimension values indicate a transition toward more space-filling, continuous, and structurally complex urban patterns over time. [9, 10].

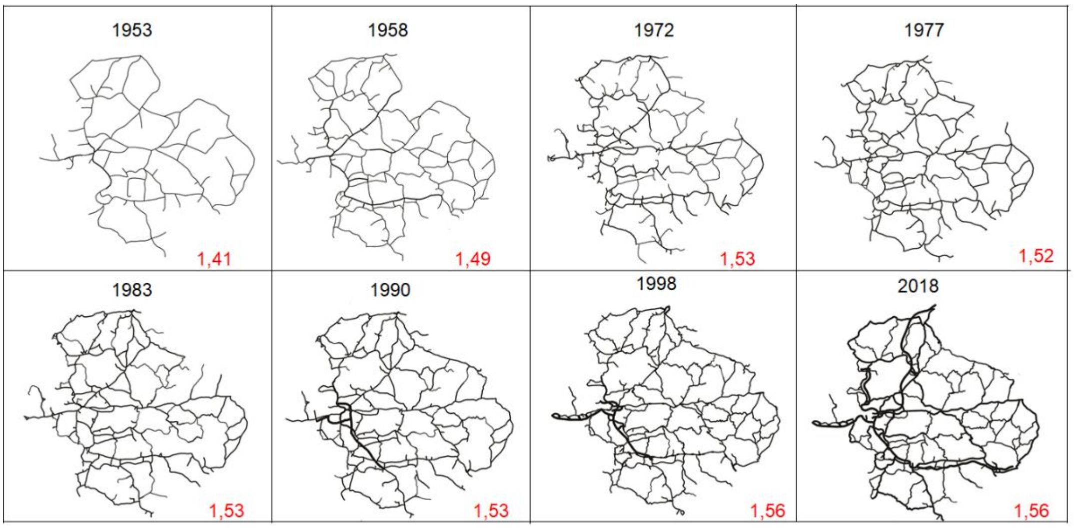

Figure 5. *emporal evolution of fractal dimension values in the İzmir regional hinterland (1953–2018), indicating changes in urban morphological complexity [46]*

Analysis of Built Environment Structure: Fractal analysis is also applicable to specific components within the built environment (Figure 6). Beyond merely computing Fractal Dimensions (Fd_s), the concept of lacunarity is employed to evaluate the texture and spatial organization of urban forms, particularly regarding void distribution within built-up areas. This approach builds upon foundational research in statistical fractal geometry, notably Benoît B. Mandelbrot's [38] conceptualization of gaps or lacunae within fractal structures, later adapted to ecological and urban studies to characterize clustering patterns and spatial voids. Lagarias [34] utilized lacunarity to examine urban compactness, demonstrating that fragmented urban development patterns typically exhibit lower Fractal Dimensions (Fd_s) and higher lacunarity, indicative of spatial inefficiencies.

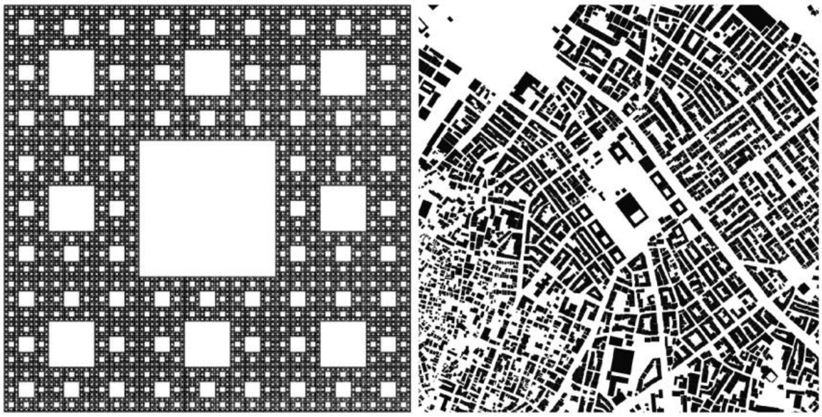

***Figure 6**. Theoretical Fractal of Sierpinski Carpet and İstanbul's Fractal Urban Pattern, [39].*

In analyzing road systems, fractal methods typically involve box-counting and mass-radius (sandbox) techniques. The box-counting method involves overlaying grids at various scales and counting occupied cells, plotting results on a log-log graph to derive the Fractal Dimensions (Fd_s). In contrast, mass-radius approaches measure how the cumulative length or density of roads increases outward from a central point, highlighting scale-invariant growth patterns. Frankhauser [10] and Shen [12] have effectively employed these techniques to assess densification and spatial expansion. Additional methodologies, including network-based box-covering and ruler (divider) techniques, provide alternative perimeter-focused and topological perspectives. Urban roadway networks, land-use patterns, and the distribution of city elements have been consistently shown to be hierarchical, self-similar, and diverse [40]. Their fractal characteristics enable simplified quantification through Fractal Dimensions (Fd_s), reflecting their spatial occupation capacity and distributional efficiency within urban spaces.

7.FRACTAL STUDIES CONDUCTED FOR CITIES IN TÜRKİYE

In Türkiye, a growing body of research has emerged, adapting fractal methods to local urban systems. These studies have aimed to measure, visualize, and model urban development patterns by calculating Fractal Dimensions (Fd_s), employing methods such as box-counting, lacunarity, and space syntax. As cities increasingly confront challenges related to sprawl, densification, and infrastructural reconfiguration, fractal analysis has proven to be a valuable tool for assessing spatial efficiency, urban form, and the impact of planning interventions across different scales. Mehmet Ali Yüzer's PhD thesis [41] constitutes one of the earliest systematic studies on fractal analysis in Turkish urban research. The primary objective of the study was to forecast urban development patterns based on the fractal structure of the metropolitan area, utilizing a cellular automata model. Emphasizing fractal analysis as a complementary tool for predicting macroform development and land-use changes, Mehmet Ali Yüzer calculated the Fractal Dimension (Fd) of Bursa's built-up area, comparing the urban form corresponding to a population of 1.066.559 in 1997 with projections for a population of 2.813.394 by the year 2020.

Using the box-counting method applied over a 1-hectare grid, observed in Figure 7, the Fractal Dimension (Fd) of Bursa's metropolitan area in 1995 was determined to be approximately 1.60, whereas the projected urban form for 2020 exhibited a Fractal Dimensions (Fd_S) of 1.89. The simulation framework, built on cellular automata principles, grounded the urban growth rate between 1995 and 2020 on the differences in Fractal Dimension Fds. Notably, this research was conducted without the use of specialized fractal analysis software, making it one of the pioneering studies in Türkiye to systematically link urban growth modeling with fractal geometry. Another significant contribution to the fractal literature in Türkiye is H. Serdar Kaya's Msc thesis [42], which approaches urban space through the theoretical frameworks of complexity and chaos, incorporating fractal measurement methods across various scales, from the city level down to building facades. Employing the box-counting method applied to road networks via HarFA software, the study calculated the Fractal Dimensions (Fd_S) of traditional urban fabrics in several cities, as listed in Table 1, finding values between 1.49 and 1.89.

***Figure 7**. The Fractal Structure of Bursa's Built-up Area in 1995 [65]*

In addition, H. Serdar Kaya [42] undertook a detailed analysis of two neighborhoods in İstanbul, examining their road networks, boundaries, blocks, silhouettes, and building facades. The results demonstrated that the neighborhood located within the historical peninsula exhibited a higher Fractal Dimensions (Fd_S) highlighting the multi-fractal structure of İstanbul. Specifically, the Fd of the road network in Cerrahpaşa was calculated as 1.72, compared to 1.40 for Marmara Evleri, a modern residential area characterized by grid-planned apartment blocks. Building on these findings, H. Serdar Kaya and Fulin Bölen [43] articulated two critical observations: (i) the modernist planning approach, with its emphasis on ordered geometries, has resulted in open spaces becoming undefined and underutilized, disrupting the continuity of intricate urban systems by producing enclosed and isolated areas; and (ii) the absence of a hierarchical structure within the transportation network, combined with a high degree of geometric regularity, has diminished the potential for interaction and connectivity among urban elements.

Following Mehmet Ali Yüzer's [41] pioneering work, Gizem Erdoğan and K. Mert Çubukçu [44] investigated changes in Bursa's fractal dimension values to evaluate the efficiency of space utilization. Utilizing remote sensing data and applying the box-counting method through Fractalyse software, they determined that Bursa's fractal dimension values increased from 1.68 in 2002 to 1.71 in 2012. This finding aligns with theoretical predictions by Micheal Batty and Paul Longley [7], and Micheal Batty and Yichun

Xie [45], who argued that Fractal Dimensions (Fd_s) typically rise over time due to population growth and the spatial densification associated with planned urban development. Moreover, they attribute part of this positive trend to the enactment of the 2004 Metropolitan Municipality Law (Law No. 5216), which centralized planning authority, promoted a more structured and measurable growth trajectory for Bursa's metropolitan area. In contrast, Fatih Terzi and H. Serdar Kaya [46] reveal a different dynamic in İstanbul's urban evolution. Their fractal analysis identifies a 'concentrated urban form' between 1975 and 1995, followed by the emergence of a more 'dispersed and semi-linear form' between 1995 and 2005.

As the population of the mega city continued to increase and its boundaries approached environmental thresholds, multi-centered development strategies through master plans encouraged further outward expansion. This expansion led to a decline in İstanbul's Fractal Dimensions (Fd_s) values, indicating increasing spatial fragmentation. These findings of Fatih Terzi and H. Serdar Kaya [46] underscore a negative correlation between Fractal Dimensions (Fd_s) and urban sprawl. Another significant study examining the long-term evolution of space-filling efficiency in urban form was conducted by Gizem Erdoğan and K. Mert Çubukçu [47]. Using aerial photographs and satellite imagery of the metropolitan area of İzmir, they calculated the Fractal Dimensions (Fd_s) of the urban macroform boundaries for the years 1951, 1963, 1987, 1996, and 2000. Their findings, as seen in Figure 8, the progressive increase in fractal dimension (D) values over time, indicating a transition from more fragmented and less space-filling urban patterns toward increasingly compact, continuous, and morphologically complex urban form. Higher D values reflect intensified spatial occupation and structural integration of the metropolitan area. Notably, the decrease in Fractal Dimensions (Fd_s) observed in the second period is attributed to the first major wave of urban spillover triggered by rural-to-urban migration during the 1950s.

A comparable pattern was identified in Bursa by Ceyda İlhan and Özgür M. Ediz [48], where the Fractal Dimensions (Fd_s) sharply declined from 1.82 to 1.57 between 1939 and 1958, coinciding with the onset of industrial development, the establishment of the Bursa Organized Industrial Zone, and the expansion of surrounding villages. Lacunarity analysis further corroborates this shift, with an increase in porosity value during the same period, reflecting a more fragmented and perforated urban structure. In subsequent decades, an increase in the Fractal Dimensions (Fd_s) and a concurrent decrease in lacunarity indicated that the urban fabric gradually became more continuous and homogeneous. This evolution toward greater compactness can be attributed to infill development along main transport corridors and the closure of spatial gaps between previously isolated settlements. Neşe Aydın [49] identified a similar trajectory in the city of Isparta, where satellite image analysis at two-year intervals between 2003 and 2015 revealed a steady trend toward urban compactness, characterized by a reduction in void spaces relative to built-up areas.

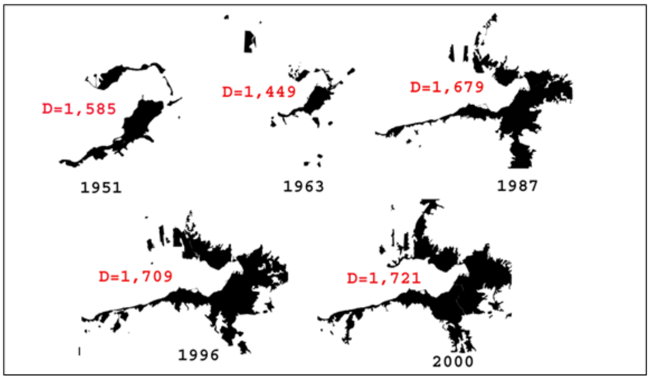

***Figure 8**. Temporal change in fractal dimension values of the İzmir Metropolitan Area between 1951 and 2000 [47].*

Another historical analysis of urban Fd change is provided by Beyza Köprülü and Mehmet Topçu [50], who calculated fractal dimension values across six different periods between 1946 and 2020 in the evolution of Konya's urban texture. Their findings demonstrate a rapid increase in the fractal values beginning in 1999, particularly in the last three periods, reflecting the intensification of urbanization and corresponding rise in the complexity. Moreover, by analyzing several neighborhoods characterized by different urban textures the study revealed that the transition from traditional, organically evolved forms to modernist urban construction was associated with a noticeable decrease in Fractal Dimensions (Fd_s). On the other hand, Atabeyoğlu and Bulut [51] conducted a fractal analysis for the city of Ordu using Harfa 5.3 software, aiming to explore the relationship between Fd and various spatial parameters. A quantitative evaluation was carried out by analyzing fifteen neighborhood-level spatial factors, including aesthetic, historical, and touristic values, as well as green area density.

One of the major findings of Ömer Atabeyoğlu and Yahya Bulut [51] was that Ordu's overall Fd, calculated at 1.49, was significantly lower than the values typically observed for other Turkish cities, such as İstanbul, where Fractal Dimensions (Fd_s) in 2006 ranged from approximately 1.70 to 1.80, comparable to those observed in major European metropolitan areas [19]. However, while the average Fd for the city of Ordu was relatively low, individual neighborhoods exhibited Fractal Dimensions (Fd_s) closer to 1.7. This suggests that although individual districts possessed sufficient spatial complexity, the city as a whole appeared simpler, more uniform, and aesthetically less rich when considered as a unified system. Furthermore, the study highlighted that the distribution of green areas across Ordu was highly uneven. Although certain parts of the city exhibited dense "green tissues," other zones suffered from a marked deficiency of green spaces, as reflected in the lower average fractal values for green areas.

H. Serdar Kaya and Fulin Bölen [52] conducted a comprehensive analysis of İstanbul's urban structure by jointly examining geometrical, topological, use- and perception-related, and complexity parameters as complementary dimensions. Their study focused on the multi-Fd of İstanbul by considering scaling relationships, developing an integrated model to provide a deeper understanding of the city's urban character. This model synthesizes multiple morphological parameters—fractal analysis, lacunarity, and space syntax—to map urban patterns from the building scale to the citywide level. The model conceptualizes the "DNA" of urban form, highlighting that İstanbul does not follow a consistent pattern of densification from the center toward the periphery. Instead, the level of spatial complexity tends to increase in relation to the age of the urban pattern, with historic areas. A broader national study was conducted by Ceyda İlhan and Necmi Gürsakal [53], who employed the open-source software ImageJ and its FracLac plugin to perform fractal analysis across all 81 provincial centers in Türkiye. Their findings, subsequently subjected to hierarchical cluster analysis, revealed that smaller-sized cities tend to exhibit more morphological similarities.

One notable contribution is the identification of a statistically significant positive correlation [$p<0.01$] between Fractal Dimensions (Fd_s) and socio-economic indicators such as population size and GDP per capita at the provincial level. Complementing these findings, Rana İbrahim Abid and Ahmet Tortum [54] performed a nationwide analysis of Türkiye's provincial centers, focusing specifically on transportation networks. Using BENOIT software, they analyzed merged railway and road network systems based on OpenStreetMap data, cropped according to visualized urban boundaries. Their study examined the correlations between Fractal Dimensions (Fd_s) and variables such as the number and total length of network lines, urbanized area, and population. The results indicate positive correlations across all variables, with the number of transportation lines showing the strongest relationship to Fractal Dimensions (Fd_s). This suggests that a more mature city is likely to possess a denser, more intricate transport network system than a less mature one. In contrast, a moderate correlation was observed with population, leading to the conclusion that further population growth does not necessarily translate into increased spatial complexity. The spatio-temporal evolution of the urban fabric across 17 districts of Samsun province was analyzed by Derya Öztürk Engin and Uğur Gündüz [55] through the integration of GIS and fractal analysis, using CORINE Level-2 land use/cover data for the years 1990 and 2012. Areal transformations were identified via superimposition and cross-tabulation techniques, while fractal analysis was employed to assess patterns of urban sprawl and spatial heterogeneity. In a related study, Sıla Özdemir [56] investigated regional complexity in the İzmir by analyzing an extended territorial scale encompassing major connecting corridors of adjacent provinces, including Manisa and Aydın (Figure 9). The study focused primarily on temporal changes in the structure of 1:25,000-scale road networks from the 1950s to the present, segmented into four distinct time periods. By correlating population data with road network-derived Fractal Dimensions (Fd_s), the research identified a statistically significant positive relationship [$p<0.01$]; however, continuous population growth did not always correspond with increased spatial complexity. Instead, the extended region displayed alternating periods of stability and transformation, a dynamic consistent with chaos theory [56].

As Micheal Batty [1] and Peter M. Allen [57] note, cities often exhibit chaotic behavior over the long term, wherein steady states or slow processes are punctuated by rapid changes and turbulence in the short run. In addition to the extended regional analysis, Sıla Özdemir [56] calculated the Fractal Dimensions (Fd_s) of 30 districts within İzmir province, analyzing both individual components and the provincial system as a whole. Interestingly, non-urban peripheral settlements exhibited relatively high Fractal Dimensions (Fd_s) during the earlier periods, which the study attributes to the complex spatial patterns of rural and agricultural land use. These findings suggest that spatial isolation can itself embody a degree of intrinsic complexity. Moreover, the study identified spatial clustering tendencies among İzmir’s districts, allowing for the delineation of sub-regions based on similarities and differences in their Fractal Dimensions (Fd_s). The findings emphasized that network complexity is not solely determined by centrality; traditional rural settlements such as Ödemiş consistently exhibited high Fractal Dimensions (Fd_s) values, suggesting that spatial complexity can also emerge in peripheral and historically evolved areas.

Sıla Özdemir [56] further advanced its analytical framework by integrating space syntax metrics to examine the internal dynamics of spatial complexity. Sub-regions were defined endogenously, based on functional and morphological relationships, rather than constrained by official administrative boundaries. This approach revealed the changing spatial linkages between the central city and sub-centers, as well as between the broader metropolitan region and its hinterland. Building on this foundation, Şahin [58] employed the same road network dataset for İzmir, covering the period from the 1950s to the present. In this study, road patterns were segmented according to master plan boundaries corresponding to each historical planning phase, enabling the assessment of metropolitan-scale spatial complexity. Şahin investigated the relationship between metropolitan-level land use planning decisions and temporal changes in Fractal Dimensions (Fd_s) values, placing particular emphasis on the interplay between unplanned urban development and the self-adaptive capacities of the metropolitan system. The findings conclude that spatial planning interventions—including master plans—actively shape and trigger morphological transformations, both within the designated planning areas and in their surrounding contexts through spatial interaction and diffusion effects.

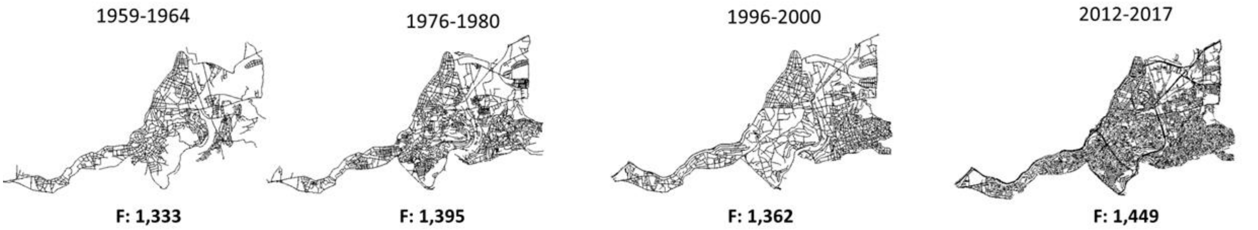

Figure 9. *Fractal Dimension Changes of Konak District [46]*

This section provides a comprehensive review of empirical studies conducted in Türkiye that apply fractal geometry to urban form, macrostructure, transportation networks, and land use patterns. From early foundational work by Mehmet Ali Yüzer [41] and H. Serdar Kaya [42] to more recent integrative approaches by Sıla Özdemir [56] and Mustafa Raşit Şahin [58], this literature reflects the methodological evolution and thematic diversification of fractal analysis within the Turkish urban context. In addition, the list of studies is given in Table 1. Almost all uses box-counting methods. These contributions not only validate the relevance of fractal methods for measuring space-filling efficiency and spatial heterogeneity but also demonstrate their capacity to uncover long-term urban dynamics, regional complexity, and the differentiated impacts of planning practices in metropolitan and peripheral settings. The reviewed body of research illustrates the increasing methodological sophistication and empirical richness of fractal studies conducted in Türkiye's urban environments. From Bursa and İstanbul to İzmir, Konya, and Ordu, Fractal Dimensions (Fd$_s$) have been used to assess urban compactness, sprawl, and morphological transitions across both historical and contemporary time frames. These analyses reveal that fractal geometry is not merely a descriptive tool, but a diagnostic and predictive framework capable of capturing the non-linear, multi-scalar, and often chaotic behavior of urban systems.

Table 1. A Literature Review of Fractal Dimension Analysis of Turkish Cities

Reference	Case City/ Region	Analysis Method	Main Findings
[65]	Bursa	Grid based box-counting; Urban macroform	Fd of the metropolitan area is calculated as 1.60 for 1995 and forecasted as 1.89 for the projection year of 2020.
[34]	Çorum, Erzurum, Giresun, İzmit, K.Maraş, Mardin, Siirt, Sivas, Trabzon & two neighborhoods of İstanbul	Box-counting; Urban macroform, road network, blocks, street silhouette & facades	Fds of road networks across different cities are ranging from 1.49 to 1.89. Fd in Cerrahpaşa is calculated as 1.718, compared to 1.402 for Marmara Evleri.
[35]	İstanbul	Not mentioned; Blocks	Fds of İstanbul, generally between 1.7 and 1.8 in 2006 are comparable to those of other cities in Europe and the developing world. Fractal values around 1.7 and lower reflect modern layout.
[45]	İstanbul	Box-counting; Urban macroform	Fds between 1975-1995 are gradually increased from 1.58 to 1.70. Fractal value decreases to 1.57 in 2005.
[58]	İzmir	Box-counting; Urban macroform	Fds are increasing from 1.59 in 1951 to 1.72 in 2000. Decrease in 1963 can be explained by rural immigration during the 1950s.
[21]	Bursa	Box-counting;	Fd increased from 1.68 in 2002 to 1.71 in 2012.

		Urban macroform	
[22]	Ordu	Box-counting; Aerial photographs and street scenes	Fd of the city as a whole is 1.49. However, individual neighborhoods exhibit Fds closer to 1.70.
[5]	Isparta	Box-counting; Urban macroform	Fds are increasing from 1.36 in 2003 to 1.43 in 2015.
[6]	İstanbul	Box-counting; Urban blocks	Highest Fds, 1.80 in the European and 1.77 in the Anatolian side, are seen in the historical core. It reduces to 1.40 in the newly developed periphery.
[27]	Bursa	Box-counting; Urban macroform	Fractality and lacunarity values in 1939 are 1.82 and 0.14. The city has compacted from 1.57 and 0.62 in 1958 to 1.80 and 0.21 in 2019.
[28]	81 provincial centers of Türkiye	Box-counting; Road network	Highest Fds are 1.77 of Ankara, 1.74 of Kocaeli and 1.73 of Antalya while lowest Fds are 1.34 of Bitlis, 1.39 of Çankırı and 1.42 of Bilecik. Lowest lacunarity values are 0.45 of Kocaeli, 0.46 of Zonguldak and 0.55 of Düzce while highest values are 1.09 of Kırşehir, 1.05 of Hakkari and 1.04 of Çanakkale.
[50]	Samsun	Box-counting; Corine data	Fds increase in 9 of 17 districts of Samsun between 1990-2012, and lacunarity index also increase in 6 of them.
[1]	81 provincial centers of Türkiye	Box-counting; Road and railway network	Fds are between 1.438 and 1.795. Strongest positive correlation is with the log of number of transport lines. Moderate positive correlations are found with the logs of both urbanized area and population.
[46]	Extended region of İzmir, province & 30 districts of İzmir	Box-counting; Road network	Fd of extended region of İzmir is steadily increasing from 1.41 in 1953 to 1.56 in 2018. Fds of province are 1.50 in 1958-1964, 1.58 in 1976-1980, 1.82 in 1996-2000, and 1.72 in 2012-2018. Fds of Konak among districts are 1.33, 1.40, 1.36 and 1.45 from mid 1950s to late 2010s.
[39]	Konya	Box-counting; Urban macroform	Fd in 1941 increases from 1.62 to 1.67 in 1964, then decreases to 1.61 in 1982. Fds are increasing from 1.60 in 1999 to 1.68 in 2020.
[56]	Metropolitan area of İzmir	Box-counting; Road network	Fds in 1950s are increasing from 1.49 to 1.58 in 2020s within the boundary of Aru Master Plan. Fds are increasing from 1.37 to 1.48 within the boundary of IMM Plan for 1973-78. Fds are increasing from 1.41 to 1.59 within the boundary of IMM Plan for 1989. Fds are increasing from 1.28 to 1.41 within the boundary of IMM Plan for 2012.

8.CONCLUSION AND RECOMMENDATIONS

The integration of fractal geometry into urban planning has not only enriched our theoretical understanding of spatial complexity but also expanded the practical tools available for analyzing and guiding urban development. Cities should be viewed as self-organizing systems whose forms emerge from bottom-up processes rather than top-down designs [1, 2, 3, 5]. This perspective challenges conventional planning paradigms by recognizing the dynamic, adaptive, and often non-linear nature of urban growth. Fractal geometry offers a quantitative framework to represent these complex dynamics, capturing the irregularity, scale dependence, and self-similarity observed in urban structures. This study has examined the multifaceted applications of fractal analysis in urban contexts, revealing underlying order within the apparent chaos of cities.

Fractal geometry introduces a dynamic dimension to urban studies, allowing for the anticipation of development trends and the formulation of responsive planning strategies. Multi-scale fractal structures have enriched our understanding of urban form by revealing hidden systems across various levels of magnification, helping planners detect patterns often overlooked by traditional methods. This layered complexity supports urban designs that align aesthetic, functional, and environmental dimensions. Likewise, self-affine fractal structures underscore the inherent adaptability of cities, reflecting their capacity to adjust to evolving demands and environments —a foundational principle in promoting urban resilience. The investigation of multi-fractal structures further captures the hierarchical and heterogeneous nature of urban complexity, providing a holistic understanding that supports optimized spatial organization and resource distribution.

By applying fractal geometry to urban morphology, insights into the distribution of built forms, public spaces, and architectural features have been harnessed to foster designs that resonate with aesthetic appeal and functional efficiency. Numerous studies have demonstrated that urban formation and spatial distribution adhere to fractal principles. Essential findings from these studies indicate that Fractal Dimensions (Fd_s) typically increase as cities expand and infill, shifting to denser, more space-filling urban forms. Benguigui et al. [8], for instance, illustrated how Tel Aviv’s street network evolved from a fractal configuration concentrated in its core towards a comprehensive, city-wide fractal structure following substantial peripheral development. Similarly, Guangjiyan Shen [12] documented Baltimore’s fractal growth over two centuries, or for Antwrep [59] by using road system as a fractal structure, noting a consistent rise in spatial complexity. These empirical examples show that fractal metrics can reflect shifting urban patterns, offering planners a quantitative basis for assessing spatial efficiency and fragmentation.

In Türkiye, extensive empirical research has validated the utility of fractal geometry in assessing urban morphological changes and guiding sustainable urban development policies. City-specific and nationwide studies conducted in Turkish cities reveal significant findings regarding the current complexity dynamics of cities and the impact of urban development and sprawl on urban complexity and efficiency. The consistent use of fractal methodologies across diverse urban settings underscores their versatility and robustness. Future urban planning approaches, leveraging fractal analysis, can more precisely address the nuanced dynamics of urban growth, promoting resilient, adaptive, and coherent urban spatial strategies. Despite its promise, the challenge remains in translating fractal-based insights into actionable planning policies. Translating fractal insights into regulatory frameworks, zoning policies, or design guidelines requires further methodological refinement and institutional adaptation.

As De Roo et al. [60] and Emine Yetişkul [6, 61] discuss, planners must navigate between order and complexity, embedding flexibility within planning systems while maintaining regulatory coherence. This requires a shift in planning practice—away from rigid, deterministic approaches toward adaptive frameworks that acknowledge and work with the inherent complexity of urban systems. Fractal geometry offers a powerful paradigm for interpreting and shaping urban systems. It bridges analytical rigor with creative vision, equipping planners and researchers with the tools to understand urban complexity in ways that traditional models cannot. In conclusion, fractal geometry emerges not simply as a descriptive technique but as a foundational component of a new urban science—one that understands cities as evolving, complex systems and equips us to design them more effectively in a rapidly changing world.

ACKNOWLEDGEMENTS

The author declares no conflict of interest and no specific funding for this study.

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