Evaluating Geometric and Structured Fractal Analysis Methods to Determine the Optimal Approach for Urban Road Network Assessment

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Abstract. Urban networks are often classified as complex elements that influence the growth of cities beyond their boundaries. These networks are analysed using numerous approaches, tools, where fractal dimensions provide quantitative assessment of the spatial organisation. This study applies geometric and structured (network-based) fractal analysis techniques to the road network of Metropolitan City of Cagliari (MCC). It highlights the methodological differences and their implications across diverse fields. The geometric fractal analysis was conducted using Fractalyse, whereas the structured fractal analysis was performed using R programming. The findings derived from the structured approach (the latter) demonstrated a greater fractal dimension than those from the geometric approach (the former). This discrepancy suggests that the structured analysis approach provides a more accurate representation of the complexity in urban road network within the research area under study. Therefore, it captures the nuanced distinctions of connectivity and hierarchy which are sometimes omitted in geometric approaches. The analysis also reveals the importance of selecting appropriate methodologies to achieve higher accuracy in urban form assessments, especially when investigating spatial criteria such as accessibility and resilience. The findings highlight the potential of using structured fractal techniques in urban accessibility and planning applications. They can accurately assess complicated network behaviour and guide future research by integrating them with spatial analytic methods and tools. This study aids urban planners and researchers in evaluating urban infrastructure according to developing spatial demands using this robust framework.

Keywords: Fractal Dimension · Spatial Analysis · Urban Accessibility · Urban Networks · Cagliari (Italy)

1 Introduction

Urban growth and development are substantially enhanced by the urban road networks (URNs) which provide the backbone of city infrastructure, influencing mobility, accessibility, and urban sociability [1–5]. The adaptability of these networks to the escalating complexity of expanding cities may be explored, due to their complex spatial and

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functional roles resulting from their numerous interrelations. The assessment and quantification of these networks are essential for decision-making processes on accessibility, resilience, and sustainable development [6]. Nevertheless, understanding and assessing this complicated behaviour of the URNs pose a significant challenge, particularly with the proliferation of urban areas and evolving urban systems. In any case, it is still unclear which tools and techniques are most effective for untangling this complexity which arises from the randomisation of hierarchy and the unpredictability in connectivity [7].

A key question is whether urban networks are truly chaotic or whether hidden patterns can be revealed through fractal geometry—a mathematical framework that quantifies irregularity and self-similarity at various scales [8]. As a results, these attributes become disposable via fractal geometry, a mathematical framework that measures irregularity in shapes and self-similarity at different scales.

These methodologies using fractal analysis have evolved significantly, including geometric approaches that focus on spatial patterns and structured approaches that integrate network connectivity [9]. One such significant approach is fractal analysis for quantitatively evaluating the spatial organisation and scaling behaviours of URNs [10]. The existing research mostly focuses on either geometric or structural fractal approaches, without direct comparisons [11]. Can the selection of methodology substantially influence the understanding of network behaviour and its implications for urban planning and sustainability? Past research identifies fractal analysis as an effective tool to assess urban complexity, offering quantitative insights into spatial organisation and growth patterns [12-13]. While geometric fractal analysis (GFA) is widely used for its simplicity and ability to highlight spatial self-similarity; its effectiveness in addressing connectivity and hierarchy can be questioned. Can structural fractal analysis (SFA), which integrates network-based characteristics, provide a more comprehensive view of URN complexities?

Urban planners focus significantly on spatial analysis to guide decision-making processes, emphasising the importance of frameworks that accurately capture the complex nature of URNs [14]. Therefore, this study aims to evaluate the gap in methodological approach by evaluating and comparing the GFA and SFA, applied to the complex road network of Metropolitan City of Cagliari (MCC). The approach identifies Fractalyse as a suitable tool for applying GFA and statistical analysis tools (such as R, Python, MATLAB, etc.) for applying SFA. The aim is to emphasise on what unique insights do these methods provide and their potential influence on urban planning and sustainable development. The study seeks to identify the limitations of each approach with the goal of guiding urban researchers and practitioners. Does it demonstrate the potential of SFA over GFA specifically for network-based fractal analysis of URNs? Does SFA capture the connectivity and hierarchy of the URNs, which are often overlooked in the geometric approaches?

In addition, this study advances in the field of urban fractal analysis by contributing to the broader understanding of urban complexity. It highlights the significance of supporting development of equitable and sustainable urban environments through holistic and accurate methodologies in evaluating URNs. To achieve this, the Sect. 2 reviews the existing literature on the two fractal approaches, its application, and comprehensively establishes a theoretical foundation for each. The analysis starts with GFA, a

traditional method for analysing urban networks, highlighting its strengths and limitations in capturing spatial self-similarity (Sect. 2.1). Subsequently, Sect. 2.2 introduces SFA, a dynamic method which addresses the shortcomings of the geometric approaches. Section 2.3 elaborates the segregation concept and its measurement to develop a robust understanding of these concepts. Section 3 presents the data collecting methodology and the study area, followed by an explanation of the indices and dimensions considered for the research. The results are presented and analysed with specific focus on the statistical performance (R^2) of each segregation measure in Sect. 4. This part also does a comparative analysis. Section 5 presents the study's conclusion along with a discussion of the results. It highlights the advantages of SFA, providing recommendations for urban planners and researchers in their attempt for sustainable practices.

2 Literature Review

2.1 Geometrical Fractal Approach for Traditional Urban Analysis

The spatial organisation of the traditional urban forms is best assessed using geometrical fractal approaches, thus making them a powerful tool. With the evolution of cities and rapid urbanisation, geometrical patterns have acquired significant attention [15]. They determine spatial hierarchies, urban growth patterns, and self-similarities. In the late 20th century, Benoît Mandelbrot established fractal geometric approach to analyse the complexity of urban morphologies, integrating a novel mathematical framework [16-17]. It was characterised at multiple scales by repetitive and self-similar structures, exceeding the conventional Euclidean geometry.

Historic cities, or traditional urban fabrics may static or dynamic spatial structures depending on their nature of expansion. They can be characterised by non-linear growth or fractal-like form or even both. Researchers highlight that such urban patterns exhibit a scaling law, where spatial distribution of streets, blocks, and built forms maintain a degree of self-similarity. There are several examples from researchers like Batty and Longley (1994), where they highlighted fractal dimensions (Fig. 1) reflecting urban complexity and hierarchy [18]. Their research highlighted self-similarity growth pattern in cities and their recurring structures. Similarly, Batty and Longley (1994) illustrated the fractal characteristics of spatial pattern of London which demonstrate a road network and their scaling aspects resulting from urban expansion. On the other hand, Frankhauser (1998) utilised fractal analysis to examine the spatial organisation of cities such as Los Angeles and New York focussing on the disparities between compact and expansive urban forms [19]. In another study, De Keersmaecker Frankhauser and Thomas also emphasise that the fractal dimension of a city quantifies the complexity of its urban form while concurrently demonstrating its intrinsic hierarchical structure of that shape across various scales [20]. Tian et al. (2011) evaluated Chinese cities, such as Beijing and Shanghai, in a similar context. The rapid urbanisation in these cities expressed fractal development patterns in urban peripheries [21]. However, recent study on informal settlements of Latin American cities including Rio de Janeiro have also utilised fractal analysis to explore organic urban growth patterns [22].

Traditional geometric fractal studies utilise GFA to depict how cities transform over time, confirming the scaling principles that govern this transformation process [23, 24].

Consequently, they are essential for comprehending previous trends in urbanisation and forecasting future growth patterns.

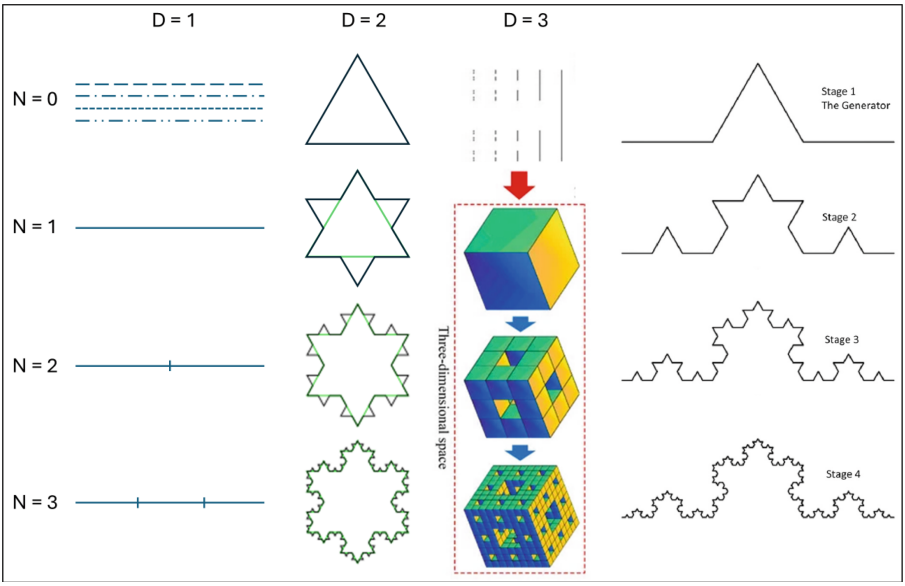

Fig. 1. General principal of Euclidean geometry (left) and geometric fractals (right) of a Koch curve [elaborated by the authors].

However, GFA is visually accessible and computationally a simple method for analysing dynamic urbanisation patterns, with certain limitations [25]. A primary limitation is its failure to adequately consider connectivity and hierarchical structure intrinsic to URNs [26]. In contrast to the structured method, GFA perceives urban patterns as static and isolated entities, perhaps leading to an inadequate depiction of urban networks. This is crucial in the context of urban mobility and accessibility and necessitates the application of SFA, which incorporates network-based characteristics to offer a more refined comprehension of urban complexity.

2.2 Structural Fractal Approach for Dynamic Urban Analysis

The structural fractal analysis (SFA) embarks a transformative change in urban research. Exceeding the traditional GFA, this approach integrates dynamic and network-oriented attributes of the urban system. It investigates connectivity, hierarchy, and functional links and patterns within the URNs rather than only focussing on the spatial arrangement and physical structures. Thus, it makes SFA more useful for examining urban complexity, especially regarding mobility, accessibility, and resilience. Moreover, it considers temporal variations and dynamic interactions of different network, therefore, more accurate in depicting urban complexities [27].

SFA employs several advanced tools and techniques for analysing urban networks (Fig. 2) [28]. The box-counting method and spectral dimension are commonly used

for fractal dimensions to assess the scaling relationships and network typologies [29]. The literature underlines that the use of SFA is limited and unexplored from the context of urban road networks and complicated urban dynamics. However, it is observed that degree, betweenness, and closeness centralities are used as essential graph-theory metrics for understanding the structural characteristics of URNs. The degree centrality focusses on the road networks with highest number of direct connections, whereas the centrality identifies the critical transit locations that are vulnerable to the overall network performance [30]. The closeness centrality quantifies the average distance of a node to all others, focussing on geographical accessibility [31]. Thus, a multiscale analysis is a crucial part of SFA, analysing spatial data from local to regional scales.

It facilitates the identification of critical nodes in URNs to equitable accessibility to infrastructural services in urban areas. It can also aid in the development of plans to mitigate natural and manmade disasters and offering distinct advantages over the traditional GFA approach [32]. However, SFA has its limitations due to data availability. It is highly dependent on detailed data of network topology, traffic patterns, and land use in some studies, thus limiting the results. It is also complex as compared to GFA and thus result in interpretation difficulties and use of specialised tools and knowledge. But in either case, previous literature confirms that the use of SFA is relevant and effective in overcoming the limitations of GFA and thus improves in assessing URNs. While SFA offers a more comprehensive approach to understanding urban road networks by incorporating connectivity and hierarchical relationships, its applicability extends beyond spatial complexity to broader urban phenomena such as segregation. The subsequent part explores the integration of segregation metrics with fractal analysis to evaluate spatial inequalities in urban settings.

2.3 Measure of Segregation

In the urban contexts, the geographical and social division of various components within a city defines urban segregation. The concept of segregation influences the accessibility, equality, and overall functionality of the urban systems [33–36]. The segregation measures scientifically evaluate geographical and social differences to assess the influence of urban layouts on movement patterns and opportunities within urban areas [37]. However, the theoretical background of these measures is rooted in spatial organisation and urban morphology. They generate a sense of inclusion and exclusion by considering physical and social systems within a city. They utilise spatial proximity calculating the actual distance between different elements, along with network connectivity which examines the ease of accessibility [38]. The application of segregation measures is extensive and complex. They are crucial for identifying neighbourhoods with accessibility barriers to essential services, thus, impactful in equitable distribution of resources to mitigate these disparities [39]. They serve as valuable resources in managing the complexities of decision-making processes related to investments in connectivity and mobility. Consequently, they are crucial in evaluating the influence of urban design and planning on social cohesion and equality, fostering inclusion and reducing structural inequities.

3 Methodological Framework

3.1 Data and Study Area

This study focuses on URNs within the Metropolitan City of Cagliari (MCC), located in the southern Sardinia, Italy. The approach highlights analytical techniques to evaluate the fractal geometry of the road networks by two distinct methods – the traditional (GFA) and the empirical (SFA) fractal dimensions. The data for the study was obtained from local municipal records, OpenStreetMap (OSM), and regional geospatial databases maintained by Sardinia's public authorities (Fig. 2).

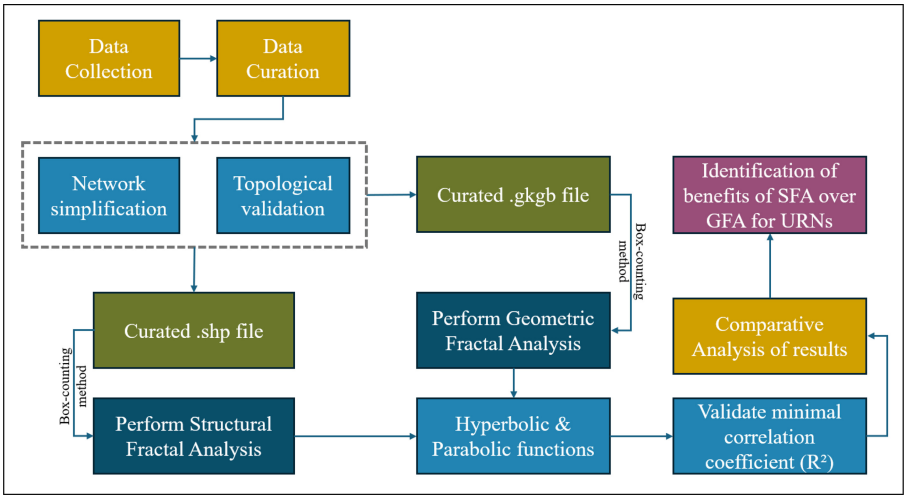

Fig. 2. Overall Methodological framework of the study.

Both the techniques utilise the road network data from spatial alignment of WGS 84/UTM Zone 32N coordinate system. This data was curated using network simplification to eliminate the redundant elements. These irrelevant elements included non-road features and broken geometries with a primary focus on urban thoroughfares. The subsequent step involved the topological validation of the geometries, meticulously addressing any discrepancies that arose. This was succeeded by an evaluation of the GFA in Fractalyse and SFA in R-programming, alongside various other statistical tools. Both the approaches utilised box-counting method (BCM) for calculating the fractal dimension. However, the major difference between the two techniques includes empirical and topological considerations in R while conducting the SFA. This is an approach not possible in GFA while calculating the fractal dimensions.

The MCC encompasses an extensive variety of environments, integrating urban, suburban, and rural landscapes within the region. This case study exemplifies an ideal focal point for examination within this research endeavour. It possesses diverse spatial characteristics, intricate topographical elements, and a strategically advantageous geographical position, rendering it ideal for comprehensive analysis. The MCC is comprised of 17

municipalities, listed in alphabetical order: Assemini, Cagliari, Capoterra, Elmas, Monserrato, Quartu Sant'Elena, Quartucciu, Selargius, Sestu, Decimomannu, Maracalagonis, Pula, Sarroch, Settimo San Pietro, Sinnai, Villa San Pietro, and Uta. Together, they constitute the metropolitan city of Cagliari and serve as a major economic hub within Sardinia (Fig. 3).

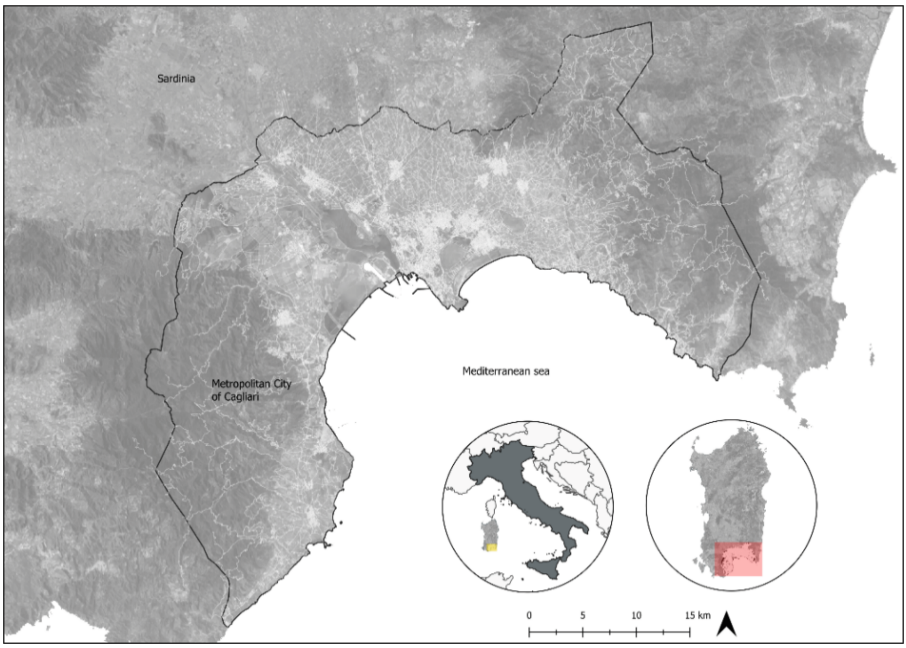

Fig. 3. Geographical location of the study area (authors' elaboration).

The diverse topographical features include a combination of coastal areas, plains and hilly landscapes, which significantly impact the road network hierarchies. Therefore, providing a suitable context for examining flexibility and diversity of urban structures. Over the period, the metropolitan area has witnessed a contrasting urban growth pattern. The historical centres showcase compact and irregular layouts, whereas contemporary layouts follow a structured and grid-based patterns. The contrast between the unplanned, dense urban morphology and intentionally controlled development also makes Cagliari exceptionally conducive to fractal analysis.

Thus, the contrast in urban layouts offer an excellent scope to analyse the fractal properties of URNs across different spatial and temporal contexts of MCC. Therefore, it is considered as the administrative and economic centre of Sardinia, supporting the mobility demands of the city. It is therefore critical to evaluate the resilience, accessibility and adaptability of this study area.

Additionally, the strategic location of Cagliari as a major coastal city contributes to its urban diversity and amplifies its significance for conducting this study. Coastal communities often have distinct geographical limitations due to adjacent water bodies,

resulting in irregular expansion patterns influencing connectivity and hierarchy of road networks. The natural barriers of MCC lead to unique urban configurations and as a result, the road networks are adjusted to limited expansion possibilities. The climate related concerns such as sea-level rise, coastal erosion, and extreme weather events have a deep impact on infrastructure development. Thus, compelling resilience and versatility as essential factors while planning these areas. Therefore, assessing the road networks of MCC using fractal analysis can help improve long-term sustainability in similar contexts. The subsequent section presents segregation indices that include both geometric and structural fractal methodologies to measure segregation within various urban frameworks.

3.2 Segregation Index

This study quantitatively evaluates the urban segregation by using segregation indices based on the concept of fractal dimension integrating both GFA and SFA. The GFA (D_f) is calculated using box-counting method, expressed as:

$$D_f = \lim_{\epsilon \to 0} \frac{\log N(\varepsilon)}{\log(1/\varepsilon)} \tag{1}$$

where $N(\varepsilon)$ is the number of boxes of size ϵ needed to cover the structure. Therefore, capturing the self-similarity and spatial distribution of the URNs. However, there is lack of sensitivity to network connectivity and hierarchical patterns in this method but remain effective for basic understanding.

On the other hand, the SFA considers graph-based indices to incorporate network connectivity. It is expressed as:

$$D_s = (\log C(k))/(\log k) \tag{2}$$

where $C(k)$ represents the clustering coefficient as a function of the degree k. However, it will also be interesting to consider the other complimentary metrics, including degree centrality (DC_i), betweenness centrality (BC_i), and closeness centrality (CC_i), which can provide further refined evaluations.

$$DC_i = (deg(i))/(N-1) \tag{3}$$

$$BC_i = \sum_{j \neq i \neq k} \sigma_{jk}(i)/\sigma_{jk} \tag{4}$$

$$CC_i = \frac{N-1}{\sum_{j=1}^{N-1} d(i,j)} \tag{5}$$

where $deg(i)$ is the number of connection nodes present in node i, σ_{jk} is the total number of shortest paths between nodes j and k, $\sigma_{jk}(i)$ is the number of those paths that pass through i, $d(i,j)$ is the shortest path distance between nodes i and j. Thus, the comparison of segregation indices explains the relationship between spatial patterns and

network connectedness, offering an enhanced perspective of urban segregation. However, the most significant and essential among these are fractal dimensions for both the approaches (D_f and D_s). This dual approach identifies critical zones of segregation, evaluates accessibility disparities, and highlight the connectivity between spatial and structural elements. The subsequent subsection builds upon these ideas by exploring the methodological complexities of fractal dimensions, including their calculation, interpretation, and implications for urban network assessment. The subsequent part delineates the approach for determining fractal dimensions, which support the comparative analysis, thus ensuring the validity of these evaluations. Larger fractal dimension values (approaching 2) in both GFA and SFA signify that the networks exhibit more complexity, spatial occupation, and connectivity. These traits signify enhanced network efficiency and accessibility. Alternatively, lower values—approaching 1—suggest linear, less interconnected patterns often associated with diminished movement potential. Similarly, higher centrality metrics in SFA—such as degree and closeness—denote nodes with stronger connections and strategic significance within the network.

3.3 Fractal Dimension

Both the concepts explained in the previous sections, highlight the significance of fractal dimension. The calculation method followed is BCM, which is commonly used, for both the cases (Fig. 4).

However, it is interesting to note that the difference in results is highlighted by the factors considered in both the approaches. The BCM superimposes a grid of boxes of varied dimensions (ε) over the spatial structure and enumerates the number of boxes ($N(\varepsilon)$) that include a part of the structure. It provides a scale-dependent method to include the complex road patterns, building layouts, and blocks in urban areas. Therefore, the fractal dimension derives from the log – log relationship between $N(\varepsilon)$ and ε, , represented on a straight-line plot. Here, the straight line indicates self-similarity, and the slope indicates fractal dimension. Thus, it is essential to also consider the scaling behaviour (b) and the overall R^2 value to ensure validity of the fitness of the model. The scaling factor can be expressed as follows:

$$N(\varepsilon) = b.\varepsilon^{-D_f} \tag{6}$$

where $N(r)$ is the measured quantity (boxes, in this case) at a scale of ε, b is the scaling factor, and D_f is the fractal dimension.

In the context of URNs, the BCM estimates the extent to which the network fills the space across multiple scales. Thus, a smaller ε value highlights local feature and complicated road details, while a larger ε provide a broader and generalised view of the spatial organisation and hierarchy.



Fig. 4. BCM sample analysis of a case study from (a – f represents different iterations of box sizes) Budge Budge West Bengal, India [40].

Table 1 represents the degree of complexity in urban structures, based on the inclination of the fractal dimension values.

Table 1. Degree of complexity in urban structures based on fractal dimension values.

Fractal dimension range	Interpretation	Examples
Close to 1	Linear or low-complexity patterns	Simple grid-like layouts
Between 1 and 2	Intricate patterns with self-similarity	Organic or historical urban forms
Close to 2	Dense, highly interconnected systems	Modern, mixed-use developments

4 Results and Analysis

4.1 Coefficient of Determination for Each Segregation

Geometric Fractal Analysis

The GFA for MCC explores the geometric behaviour of spatial organisation and scaling factor of the URNs within it. The fractal dimension value of (D_f) 1.191 highlights a low level of complex and space-filling urban network compared to denser urban layouts (Fig. 5).

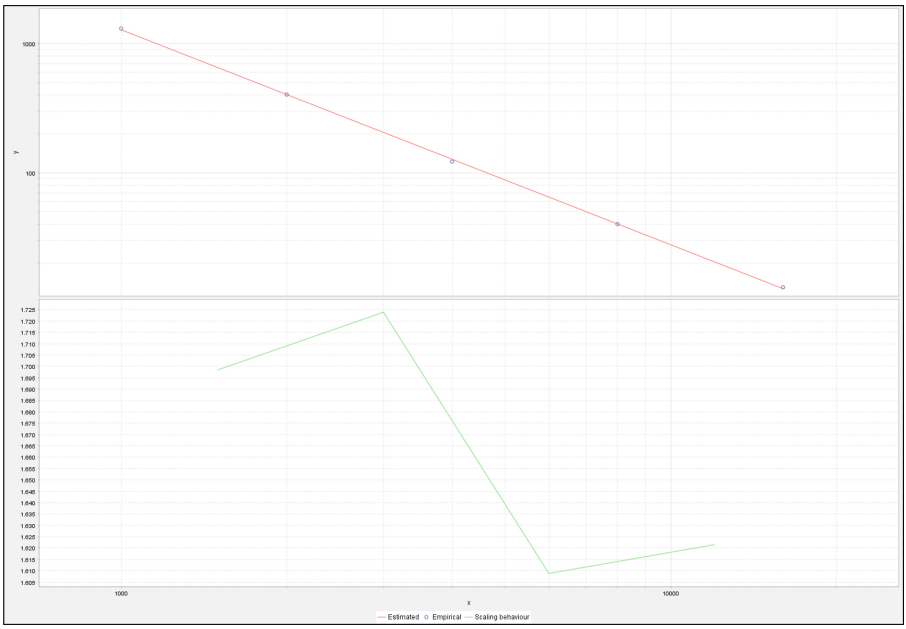

Fig. 5. Analysis results of Fractalyse for GFA using BCM, showcasing log-log plot (top) and scaling behaviour (bottom). Source: authors' elaboration.

The scaling coefficient (b), found to be 0.287 reflects a constant magnitude of spatial pattern. It indicates a less prominent spatial feature at the smallest scales considered, meaning, a lesser number of boxes to cover the urban structure at the smallest box size of ε. . The significantly high coefficient of determination ($R^2 = 0.985$) confirms the model fitness to the theoretical fractal framework. The analysis is statistically robust, as assured by the extremely low p-value (0.000) supports the low scaling behaviour. Confidence interval (95%) and bootstrapping values (1.104–1.265) further validate the precision of the fractal dimension estimation. The log-log plot (Fig. 6) showcases a sparse connection, with linearity and branching patterns. Nevertheless, the actual road layout showcases a more fractal behaviour than expressed from the GFA. Therefore, the level of actual road density is not expressed completely in this analysis. The results from GFA indicate a relatively low fractal dimension, suggesting a limited representation of road network complexity. However, given its inability to account for connectivity and hierarchical structures, a complementary approach—SFA—is necessary to gain a more comprehensive understanding of urban road network dynamics.

Structural Fractal Analysis

The SFA was conducted using R-programming and BCM approach. The estimated fractal dimension value (D_s) is 1.40, indicating a moderately complex and branching structure, which is deviated from the previous GFA. This value suggests that the partially filled road network, more complex than simple grid systems. However, they are not as irregular

as the chaotic systems. Therefore, this spatial system balances between linearity and interconnectedness.

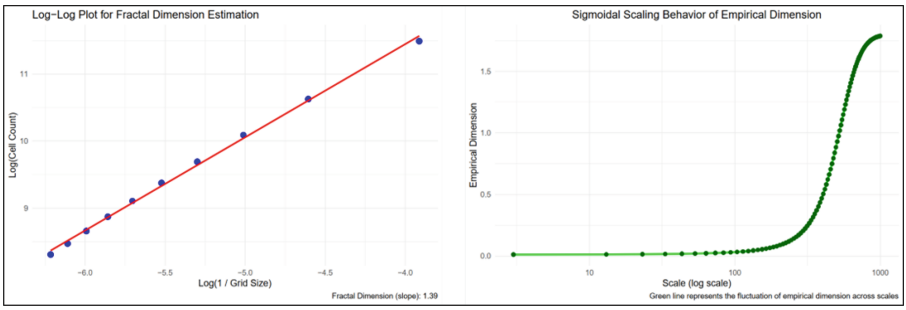

Fig. 6. Analysis results of R-programming for SFA using BCM, showcasing log-log plot (left) and scaling behaviour (right). Source: authors' elaboration.

The scaling factor ($b = 1.387$) in SFA represents a baseline spatial intensity of the URNs at the smallest analysed scale. It explains network density and spatial organisation at finer spatial levels. The high value of coefficient of determination ($R^2 = 0.998$) confirm the model fitness and validity of results. The *p*-value ($5.441e^{-12}$) was found to be extremely low which further validates the statistical significance of the scaling behaviour, thus ruling out the chances of sample randomisation. The precision of fractal dimension is highlighted by both the confidence interval (95%) and bootstrap confidence interval (1.343–1.503). Both demonstrate a high degree of consistency. The log-log plot (Fig. 6) reveals a clear linear trend which denote a stable scaling relationship between size of road segment and number of roads. The sigmoidal scaling behaviour plot (Fig. 6) suggests that the fractal network of the road network becomes more prominent at larger scales.

The overall visual representation of the MCC align with the estimated fractal dimension values. Thus, offering a tangible representations of URNs spatial organisation. Therefore, these findings highlight the complex and hierarchical structure of the road network in the study area. This suggests that the network is highly accessible and efficient through its fractal properties. Unlike GFA, the SFA results reveal a more intricate and interconnected urban structure, with higher fractal dimensions reflecting enhanced network efficiency. This comparative perspective prepares for the subsequent section, which evaluates the strengths and limitations of both approaches through a detailed comparative analysis.

4.2 Comparative Analysis

Both GFA and SFA approaches are commonly used techniques for conducting fractal analysis in urban areas. However, based on the application, the efficiency of both the approaches are varied. Both the approaches provide estimation of spatial scaling behaviour of the URNs. But from the results, we can declare that the SFA using R-programming emerges as a more robust and content-sensitive approach for analysing the structural characteristics of road networks.

The first approach with lower value of fractal dimension suggesting linear spatial organisation. The second approach with a higher value of fractal dimension and scaling behaviour highlights complex and tree-like branching of road networks. While both the methods yield higher statistical reliability ($R^2 = 0.984$ and 0.998) and the *p*-values (0.00 and $5.441e^{-12}$), the SFA approach provides a higher estimation in both cases and more detailed and granular representation of spatial scaling characteristics. This also includes narrower confidence intervals and distinction of road network linearity. A superior method was SFA which examined the hierarchical and structural organisation of spatial systems, including road network at various scales. The methodological framework considers spatial dependencies and scaling interactions within the URNs. Thus, making it effective for identifying fine-grained differences in road density and connectivity patterns. However, context-specific variations, such as consistency in network and urban connectivity remain neglected in SFA using R-programming. It often provides flexibility and computational efficiency which depends on generalised algorithms. It requires high-quality, detailed network data, and its computational complexity may present challenges in data-scarce or resource-constrained environments. Additionally, interpreting multi-scalar network metrics can demand specialised knowledge, potentially limiting its practical use among non-expert planners.

Moreover, SFA also provides a clear and interpretability process by incorporating niche-focussed observations into scaling analysis in alignment with real-world spatial dynamics. The results obtained through this analysis demonstrate a greater correlation with empirical data regarding the URN morphology. Thus, suggesting a more organised spatial structure, making it advantageous for applications required for precise urban modelling in transportation planning, accessibility, resilient assessment, and resource allocation. The comparative analysis highlights the superiority of SFA in capturing network hierarchy and connectivity, offering a more detailed perspective on urban road networks. Building upon these findings, the final section synthesises key insights and discusses their implications for urban planning, accessibility, and future research directions.

5 Discussion and Conclusions

This study is a comparative evaluation of geometric fractal analysis (GFA) and structural fractal analysis (SFA) corresponding to the assessment of complex urban road networks (URNs). After applying both the techniques to the Metropolitan City of Cagliari (MCC), it was observed that the SFA provides a more precise and efficient representation of hierarchy and connectivity of the network. The increased fractal dimensions derived from SFA illustrates the complex connection and spatial organisation that GFA fails to capture due to its limitations. Although GFA is beneficial for estimating self-similarity, it fails to incorporate network typology limitations. Thus, ineffective in precise assessment of urban accessibility and resilience. The coefficient of determination (R^2) proves the statistical robustness and validates its superiority in delineating structural attributes of URNs. Thus, the findings of this study highlight the necessity and suitability of choosing the appropriate fractal analysis method for road networks.

The study findings also guide planners to improve urban accessibility strategies and enhance the sustainability of transport corridors at different scales. The Cagliari case

study shows that more connected and accessible urban areas are associated with locations having larger fractal dimensions (as determined by SFA), especially in ancient city cores. However, newer peripheral areas with diminished fractal values exhibit less connectivity, so highlighting the regions where planners need to prioritise on improving accessibility. These findings enable planners to manage interventions utilising fractal thresholds as indicators, so ensuring equitable infrastructure development and more resilient urban networks. The hierarchical structure of road networks in MCC indicates historic urban centres with distinct fractal values as compared to contemporary grid-like development. Thus, it is considered crucial to choose the appropriate analytical approach. The findings also emphasise on incorporating these techniques in climate adaptation measures and transportation corridor enhancement. It further highlights the significance of fractal methods in assessing multiscale urban typologies. Thus, future studies could investigate the integration of fractal analysis with agent-based models. This would aid in analysing the impact of urban form on pedestrian accessibility and movement patterns. Comparative studies across diverse urban scales would also help in evaluating the efficiency of SFA. Integrating demographic, economic, and land-use datasets could provide a more comprehensive analysis. This would enable the correlation of fractal complexity with actual urban functions, improving the relevance of planning interventions based on social and spatial equity considerations. Additionally, the integration of fractal analysis with machine learning techniques may help improve automated urban morphology segregation, facilitating data-driven design decisions. The methodological framework presented here is replicable and adaptable to other urban contexts, particularly where spatial network data is available. Its application across cities of varying sizes and morphologies could validate its broader utility and reveal context-specific dynamics of urban complexity. As urban areas fall prey to rapid urbanisation, fractal analysis proves to be a critical tool for measuring urban complexity, bridging the gap between mathematical modelling and practical urban planning applications. Therefore, it assists professionals and researchers in creating more resilient and robust urban settings that lead to sustainable and adaptive urban expansion.

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Author Contribution

T. Alam and C.Garau---This paper is the result of the joint work of the authors. 'Abstract', the 'Methodological Framework' (with sub-paragraphs) and 'Results and Analysis' (with sub-paragraphs) were written jointly by the authors. TA wrote 'Introduction', 'Geometrical Fractal Approach for Traditional Urban Analysis' and 'Measure of Segregation'. CG wrote 'Structural Fractal Approach for Dynamic Urban Analysis' and 'Discussion and Conclusions'. CG coordinated and supervised the paper.

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