

Urban Skyline Analysis from a Fractal Perspective: A Case Study of Zhonghua Avenue in Handan City

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Abstract:

The design of urban skylines has become a growing focal point for architects and urban managers, providing an important way to highlight the unique characteristics of a city. Focusing on Zhonghua Avenue in Handan City, this paper utilizes geographic information system (GIS) and urban height data, and employs the box-counting dimension from fractal theory to extract segments of the urban skyline, thereby calculating and evaluating the fractal dimension. By comparing with mature skylines in developed cities, urban skylines were subjected to quantitative evaluation, as well as morphological regulation and optimization from the perspective of fractal dimension. This research contributes theoretical approaches for the quantitative evaluation of urban skylines and provides reference and recommendations for the construction of urban height systems.

Keywords:

Urban Skyline, Quantitative Analysis, Fractal Dimension, Box-Counting Dimension, Zhonghua Avenue in Handan City

1. Introduction

The urban skyline is an important controlling element of three-dimensional morphology in urban cities. With the development of scientific urban planning and technological tools, quantitative evaluation criteria and precise control indicators have become essential to urban skyline research. Nevertheless, previous methods and standards for evaluating urban skylines were largely based on subjective and traditional aesthetics [2], lacking objective and precise quantitative metrics. In recent years, with the introduction of fractal theory, there has been a rising trend in the quantitative study of skylines using fractal theory. This paper leverages fractal theory to provide a precise description and quantitative analysis of the urban skyline along Zhonghua Avenue in Handan City, offering optimization strategies.

1.1. Western Urban Skyline literature review

The study of skylines originated in the West. In the late 19th century, the skyscraper boom in Chicago led Montgomery Schuyler to coin the term "skyline" for the new urban landscape formed by tall buildings, marking the beginning of skyline theory [1]. Kevin Lynch (1960) proposed the renowned five elements of city imageability in *The Image of the City*, which is widely considered the foundation of urban skyline theory [4]. Michael Trieb (1974), from a humanistic and psychology-oriented perspective, analyzed the forms of urban skylines and summarized practical methods for skyline design in *Urban Form—Theory and Practice* [5]. Wayne Attoe (1981) studied the development, aesthetics, and societal significance of urban skylines, proposing that the aesthetic experience of skylines depends on three factors: their own form, the surrounding environment, and the subjective interpretation of the observer [6].

1.2. Chinese Urban Skyline literature review

Research on urban skylines in China began in the 1980s and has rapidly evolved into two main directions in recent years. One focuses on subjective descriptions of urban skylines, while the other involves quantitative analysis, often closely integrated with GIS. Dongbin Su et al. explored principles and methods of building height control in domestic and foreign urban landscape planning, discussed how building height control can shape a favorable urban landscape, and provided methods for shaping a good urban skyline [5]. Junyan Yang proposed three influencing factors for urban skyline morphology, namely, outline recognition, outline fluctuation, and outline rhythm, and applied them to the skyline landscape evaluation in Wuxi and the overall image evaluation of Hong Kong's urban landscape [6]. With the innovation and development of research methods, quantitative analysis of urban skylines has gradually become a major focus. From a visual impact perspective, Xinyi Niu introduced two indicators for skyline evaluation—outline tortuosity and hierarchy—and applied GIS tools for quantitative evaluation of the urban skyline [7]. Yingchun Cao et al. incorporated fractal theory into the quantitative analysis of urban skylines, providing a precise quantitative description of the urban skyline [8]. Taking fractal dimension as a key indicator for evaluating waterfront skyline landscapes, Jun Yan conducted research from three aspects: building form, plant species configuration, and overall waterfront evaluation, and proposed a rational range for transformation and optimization [9,10].

1.3. A brief of Zhonghua Avenue for Urban Skyline

Handan City, with its profound history, witnessed rapid expansion of its urban built-up area after the reform and opening-up, leading to increased building density and the emergence of numerous high-rise buildings. Due to its advantageous geographical location, Zhonghua Avenue has become a hotspot for development and construction in Handan City. Located at the core of Handan City, Zhonghua Avenue spans approximately 10 km in a north-south direction, connecting Beihu Park and Nanhu Park. The continuously rising skyline along Zhonghua Avenue has resulted in practical issues such as a monotonous hierarchy and a lack of distinctive features. Without proper control and planning, the landscape of this vital road in Handan City could gradually blur and eventually be lost. The land use types on both sides of Zhonghua Avenue are diverse, including commercial, cultural, residential, administrative, and park green spaces. Iconic buildings such as Congtai (the architectural complex where King Wuling of the State of Zhao inspected the military

troops and enjoyed watching song and dance performances), New Century Center, Handan Museum, and Handan Library are concentrated along this avenue.

2. Materials and Methods

2.1. Introduction to Fractals

Fractals were proposed by mathematician B.B. Mandelbrot to describe irregular and fragmented shapes such as winding coastlines, undulating mountain ranges, and ever-changing cloud formations that exhibit "self-similarity" at different scales. Typically, these shapes are challenging to describe using traditional Euclidean geometry. Fractals have intricate structures at different scales (theoretically even infinite levels), and these structures demonstrate strict, approximate, or statistically significant self-similarity across different scales. The dimension of a fractal (also known as Hausdorff dimension) is strictly greater than its topological dimension and is often expressed as a fraction (typically retained to three decimal places) [3]. Fractals also possess scale invariance (also known as scale symmetry), where zooming in on any local part of a fractal will reveal the morphological characteristics of the original figure, representing quantitative properties of self-similar systems or structures—the fractal dimension remains unchanged. While mathematically or theoretically fractals feature strict self-similarity and infinite scale invariance, real-world fractals only demonstrate self-similarity and scale invariance within specific and often limited dimensional variation intervals [4]. Due to its excellence in describing and analyzing complex phenomena, fractal geometry has been widely applied in disciplines such as medicine, soil mechanics, seismology, and urban growth in recent years.

2.2. Calculation Methods

There are various methods for calculating fractal dimensions, with the box-counting dimension (also known as Minkowski dimension) being a commonly used and effective approach. The specific method is as follows: cover the fractal with a grid of equally sized squares (each side length δ), then progressively refine the grid size (e.g., halving the side length each time) and calculate the number of squares needed to cover the fractal. Subsequently, apply the formula below to calculate the box dimension. The box dimension is defined only when the top and bottom box dimensions are equal in the calculation of box-counting dimension [5]. Due to the enormous statistical quantity of boxes, fractal calculation software is typically employed to compute the box dimension. In this study, MATLAB is utilized to calculate the skyline dimension.

2.3. Urban Model Establishment

Traditionally, urban models are established using partial urban elevation points on a city CAD base map or calculating heights through urban projections. The former often results in incomplete model information and significant errors in urban height, while the latter typically involves excessive computational workload. In our urban design practice in Handan, Handan urban height data was downloaded from the urban height data for major cities in China provided in the Resource and Environment Science and Data Center of the Chinese Academy of Sciences. This data was then imported into a GIS platform, using ArcScene software to set up the stretch height and generate the model. For ease of operation, the GIS-generated model was exported as a CAD file and imported into SketchUp to establish a more accurate urban model. Subsequently,

the skyline on both the east and west sides of Zhonghua Avenue was obtained using the slicing tool.

2.4. Data Calculation

Due to the excessive length of Zhonghua Avenue and for ease of calculation, the skyline on both the east and west sides of Zhonghua Avenue was divided into four segments each (A, B, C, D) (See the Figure 1 and Figure 2 below), totaling eight segments using SketchUp. Mathematical modeling software MATLAB was then used to preprocess eight skyline images through image processing, distinguishing the studied area from the background to reduce interference, i.e., converting RGB to a binary two-dimensional matrix. The imported matrix data was transformed into binary data, and the FracLab toolbox was employed to calculate the box-counting fractal dimension of the images using the box-counting method.



Figure 1. West side of Zhonghua Avenue for Urban Skyline Analyses.



Figure 2. East side of Zhonghua Avenue for Urban Skyline Analyses.

3. Result and Discussion

The calculations with the fractal tool MATLAB revealed the dimensions of the skylines on both east and west sides of Zhonghua Avenue (See the Figures 3-10 and Table 1 below).

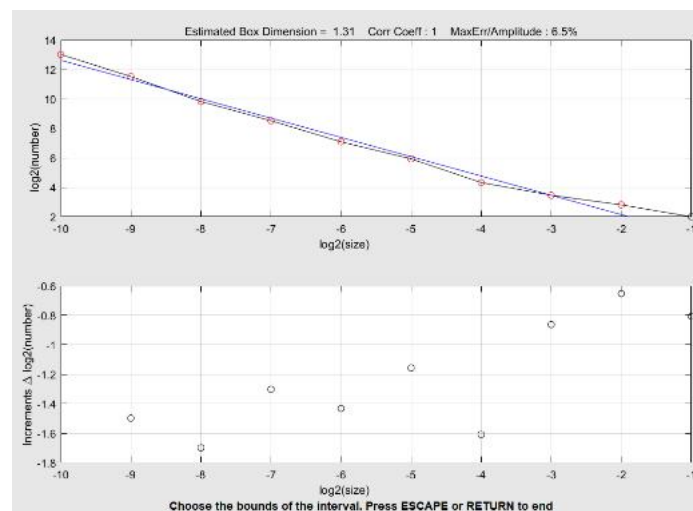


Figure 3. East side A of Fractal calculation results.

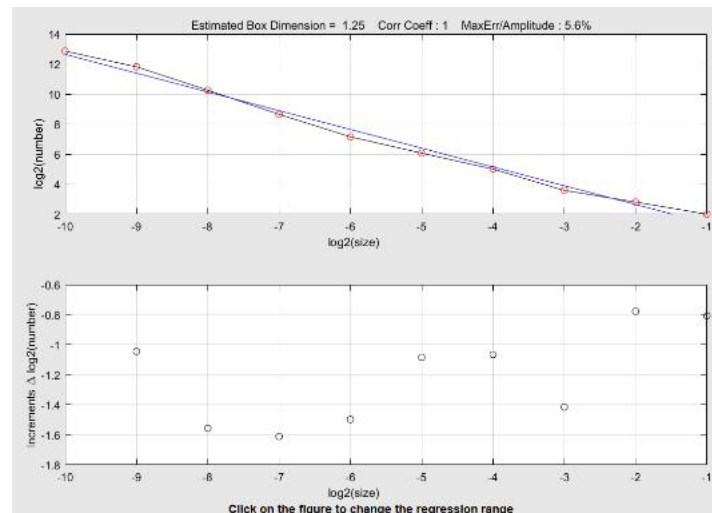


Figure 4. East side B of Fractal calculation results.

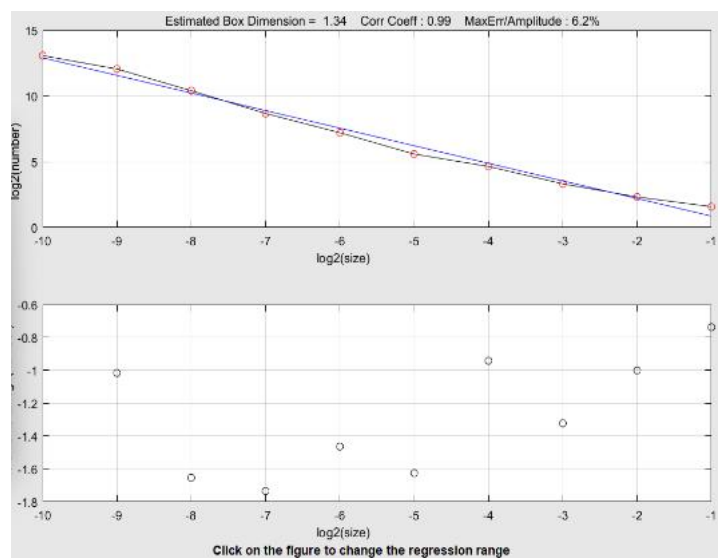


Figure 5. East side C of Fractal calculation results.

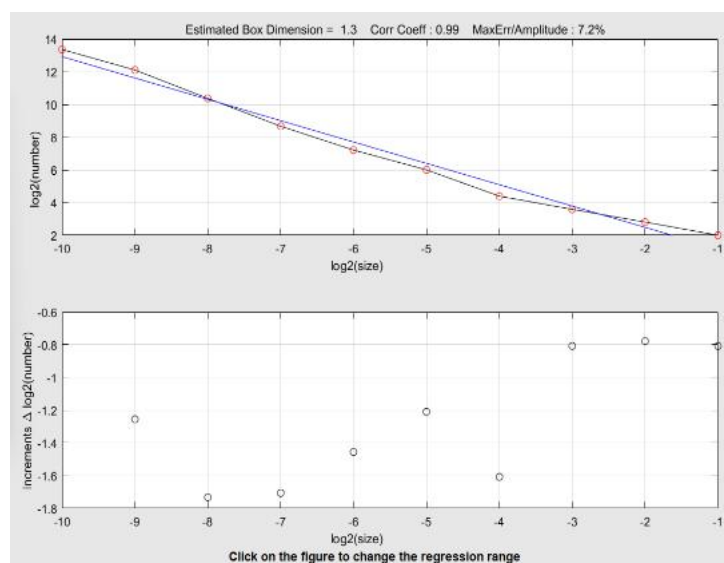


Figure 6. East side D of Fractal calculation results.

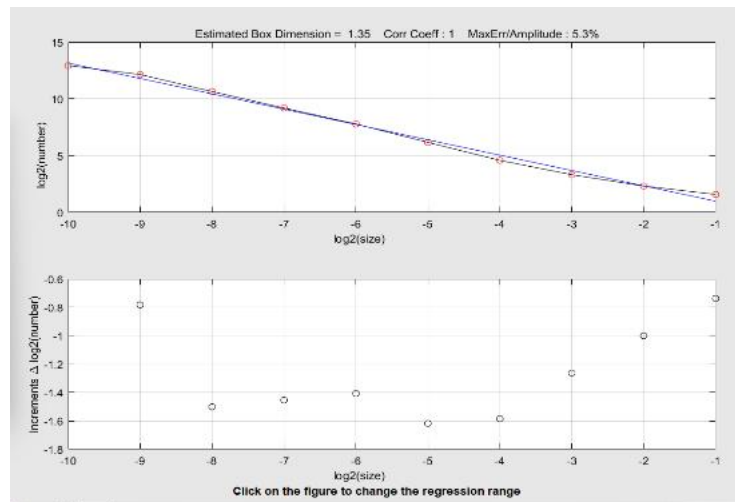


Figure 7. West side A of Fractal calculation results.

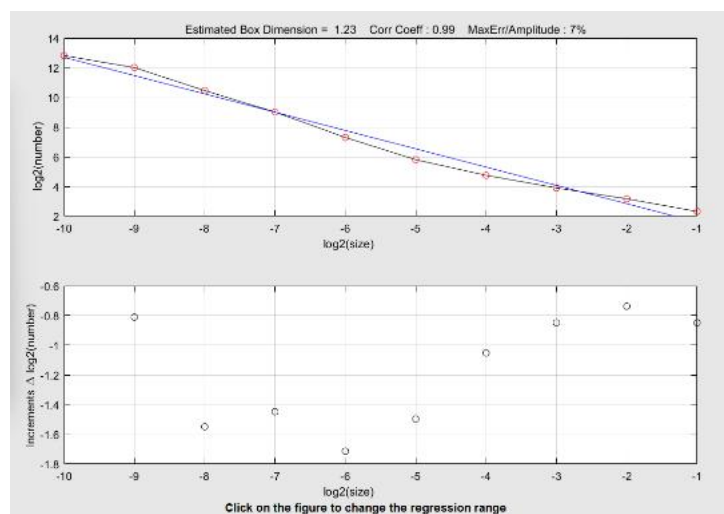


Figure 8. West side B of Fractal calculation results.

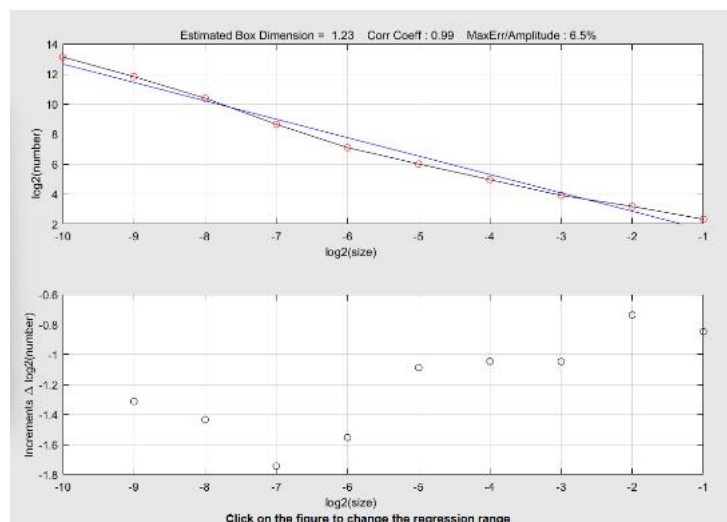


Figure 9. West side C of Fractal calculation results.

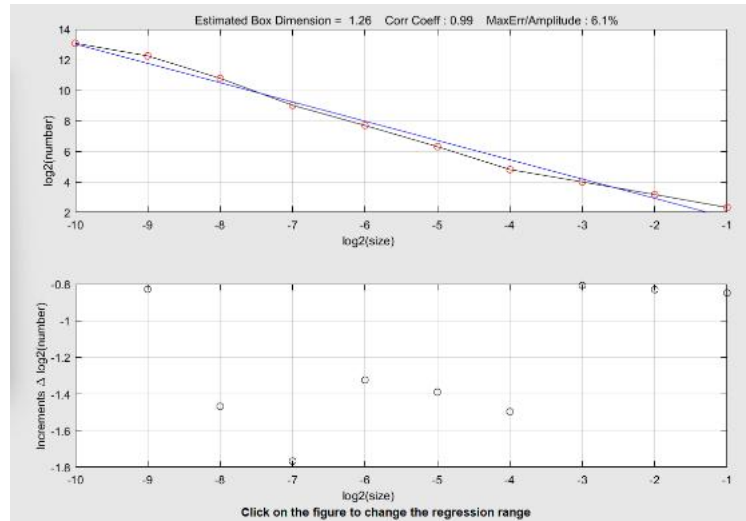


Figure 10. West side D of Fractal calculation results.

It can be observed that the fractal dimensions of the skylines on both sides of Zhonghua Avenue were concentrated between 1.20 and 1.35 from Table 1. Further analysis reveals that the fractal dimensions of segments B and C on the west side and segment B on the east side were slightly low, while those of the other segments were relatively high. The reason for this lies in the fact that segments B and C on the west side and segment B on the east side of Zhonghua Avenue are precisely situated in the central area of both the avenue and Handan City. This region has the most diverse land use types, including commercial, public, business, park green spaces, and urban squares. In contrast, the other segments primarily consist of residential land use and some office buildings.

Table 1. Fractal calculation results.

East side		West side	
A	1.31	A	1.35
B	1.25	B	1.23
C	1.34	C	1.23
D	1.3	D	1.26

Referencing the fractal dimension calculations of mature skylines in developed cities, such as New York, Miami, Toronto, and Hong Kong, the skyline dimensions generally range from 1.180 to 1.200. The rapidly developing city of Dubai can even reach 1.230. The skylines of central areas in developed cities in China, such as Lujiazui in Shanghai, central business district (CBD) in Beijing, downtown Wuhan, and the core areas of Guangzhou, typically fall between 1.160 and 1.180. Skylines in ordinary cities have dimensions roughly between 1.140 and 1.150. The fractal dimensions of well-preserved historical cities and historic districts are relatively low, all below 1.140.

However, the fractal dimensions of the skylines on both sides of Zhonghua Avenue in Handan are significantly high. One reason is that using SketchUp to slice the images may lead to a slightly high fractal dimension due to a low viewpoint. Another reason is that the quantity of high-rise buildings on Zhonghua Avenue is slightly low and relatively dispersed, causing significant elevation differences with adjacent areas. The third reason is that the skylines on both sides of Zhonghua Avenue exhibit overall small variations and are relatively flat, with flat areas concentrated in segments A and D on both sides, representing urban villages, and some low-level industrial land.

Therefore, the optimization strategy for the skylines on both sides of Zhonghua Avenue in Handan includes 1. strengthening the building types in segments A and D on both sides of Zhonghua Avenue and 2. overall enhancing the building elevation differences along Zhonghua Avenue.

4. Conclusions

Fractal theory and its calculation methods can measure skylines precisely, providing a powerful tool for the quantitative study and planning practice of urban skylines. Currently, rapid urbanization is driving drastic changes in urban morphology, making dynamic monitoring and precise control of skylines even more crucial. Based on fractal theory, a preliminary evaluation of the Zhonghua Avenue skyline in Handan was proposed, along with recommended optimization strategies.

Conflicts of Interest

The author declares that there is no conflict of interest regarding the publication of this article.

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