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Evaluating Street Character Using the 3D Fractal Analysis Method: Lefkoşa

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Abstract: The aim of this article is to reveal the mathematical dimension behind the complex structure of architectural fabric through a three-dimensional analysis. Given that the architectural character, which has evolved under the influence of various cultures over time, is crucial for urban integrity and sustainability, understanding the mathematical dimension underlying this character is of great importance for new designs and interventions in existing urban fabric. Therefore, streets in the Arabahmet neighbourhood of Lefkoşa Suriçi, which best represents the traditional fabric, were examined using a three-dimensional fractal analysis method. The analyses indicate that, in general, the fractal dimension values of the residential fabric-created streets are above 2.52, demonstrating a high level of character and complexity in these streets. Additionally, the fractal dimension values of these streets are close to each other, supporting the spatial and mass consistency of different streets within the same neighbourhood.

Keywords: Cube-counting method, 3D fractal analysis, Fractal dimension, Fractal geometry, Lefkoşa.

1. Introduction

In 1975, the term 'fractal,' derived from the Latin word 'fractus' by Benoît Mandelbrot, typically refers to a geometric object created through an iterative process. Often, the resulting shape can be divided into smaller parts, each resembling the original shape. Fractals possess infinite detail, and some exhibit a self-similar structure at different levels of magnification (Terzidis 2006; 2009). Considering that smooth lines and planes exist only in ideal mathematics, it can be argued that virtually everything in our natural surroundings exhibits a fractal structure. They can be found everywhere, from coastlines to boundaries, clouds to mountains, trees to plants, and even in architecture (Lorenz, 2003).

Urban texture results from numerous consecutive construction activities by individuals and communities over many years (Ben-Hamouche, 2009). Consequently, cities develop complex structures. The complexity of urban structures demonstrates that they are not composed solely of 0, 1, 2, and 3-dimensional objects, but also include objects that need to be expressed with rational numbers. Consequently, it has been observed that urban spaces exhibit fractal properties, especially in spontaneously developing cities, which tend to have high fractal values. Therefore, utilizing fractal dimension analysis to examine cities within the context of the complex structure we inhabit will lead to a better understanding of urban construction (Kaya and Bölen, 2006). This method allows for the mathematical dimension of an existing urban texture to be calculated, and assessments can be made based on the resulting numerical values.

When reviewing research conducted in the field of architecture in the literature, it is evident that fractal dimension analysis has been employed in various contexts, ranging from urban scale to street scale, building scale, and even for design exploration. Since the introduction of fractals by Mandelbrot, numerous researchers have used this method to understand the mathematical dimension of the built environment. Prominent studies from these research efforts are summarized below.

Fractal dimension analysis has recently been used in many studies to examine the complex structure of urban textures. In one study, İlhan and Ediz (2019). explored the temporal and spatial development of urban texture through fractal dimension values. This research interprets changes in the physical texture concretely through numerical data. In another study, Kaya and Bölen (2006) compared the complex structures of two spaces with different characters, traditional and modern, using fractal dimension analysis. Additionally, Atak Doğan and Çağdaş (2017) investigated fractal dimension calculations based on site plans, street silhouettes, building facades, and details to explore fractal consistency between different scales.

Apart from urban scale studies, fractal dimension analysis has also been used to evaluate different characteristics of street textures. Cooper (2003) analysed the physical characteristics that constitute street silhouettes by considering both the built environment and natural forms, conducting analyses based on horizon lines extracted from photographs. This study demonstrates how to calculate the fractal dimension of street silhouettes. Additionally, Cooper (2005) and Oppong et al. (2017) conducted a study on fractal dimension calculations for street edges, demonstrating how to calculate the fractal dimension for street edges and how to relate the obtained numerical values to the character of a place.

The analysis of architectural scale, initiated by Bovill's (1996) study of Amasya, has subsequently been tested in the plans and elevations of many famous modern architects' residences. Wen and Kao (2005) compared the works of Frank Lloyd Wright, Le Corbusier, and Mies Van Der Rohe from different periods. Ostwald and Vaughan (2008) evaluated Eileen Gray's designs, while Vaughan and Ostwald (2008) conducted an analysis of Kazuyo Sejima's residences. Later, Ostwald et al. (2009) measured and compared the fractal dimension of residential designs by various modern architects, including Le Corbusier, Eileen Gray, Peter Eisenman, and Kazuyo Sejma. These studies compared the complexity levels of both different architectural works and the works of the same architect from different periods.

Fractal analysis studies have also been conducted beyond residential architecture. Ediz and Ostwald (2012) used fractal dimension analysis to examine the complexity of visual layers on the facades of the Süleymaniye Mosque, one of Architect Sinan's works. This study focused on measuring and evaluating the relationship between form, ornamentation, and materials rather than interpreting Sinan's architectural work. A similar study was conducted by Ostwald and Ediz (2015) for the Kılıç Ali Paşa Mosque, following the methodological settings used in their previous study on the Süleymaniye Mosque. They used this approach to test the visual complexity of the structure and compare it to the previously analysed Süleymaniye Mosque. Additionally, Rian et al. (2007) evaluated the visual complexity of the Kandariya Mahadou Temple, Samper and Herrera (2014) analysed French Gothic Cathedrals, Shishin and Ismail (2016) assessed the visual complexity of Poi-Kalyan and Bibi-Khanym Mosques. Furthermore, fractal dimension analysis has been used in the studies of Ediz and Çağdaş (2005) for generating data for a three-dimensional generative system and in the research of Abdelsalam and Ibrahim (2019) for Al-Sultan Hassan Medrese.

Despite the increasing applications of fractal analysis at various scales, it is notable that most of these studies have been limited to two dimensions. While a few three-dimensional fractal analysis studies exist, they remain relatively scarce. Among these studies, Qin et al. (2015) used the three-dimensional box-counting method to examine the form of a city in two different periods. In a similar study, Liu and Chen (2022) analysed different urban areas in Shenyang, northeast China, using the three-dimensional box-counting method.

Fractal analysis, a frequently used method to emphasize the mathematical dimension behind an architectural structure or texture, is encountering applications at different scales. However, there is a shortage of three-dimensional fractal analysis studies in the fields of architecture and planning due to both modelling difficulties in the built environment and the lack of technical tools for analysis. In the reviewed studies, two-dimensional fractal analysis employed remotely sensed imagery or digital maps. In building scale studies, plans, elevations, and sections were used, while urban scale studies utilized the box-counting method based on site plans. In three-dimensional studies, remote sensing was used to extract building forms and heights for analysis. Additionally, the three-dimensional box-counting method was employed. This study differs from other three-dimensional studies in that it involves detailed modelling of individual architectural structures and street textures and utilizes the cube-counting method for three-dimensional fractal analysis. The developed model can be used as a tool for examining different residential textures in traditional contexts in Lefkoşa.

This study is organized into five sections. After the first section, the second section provides information on the relationship between fractal dimension and two-dimensional and three-dimensional fractal analysis. Section 3 introduces the methodology and study area. Section 4 presents findings and discussions, while Section 5 summarizes the study's conclusions.

2. Fractal Dimension

Although fractal structures are often defined by their characteristics such as self-similarity and complexity, most of the time, the only way to describe fractal structures is through fractal dimensions (Lorenz, 2009). Fractal dimension is the dimension of an object that has a non-integer value, unlike integer dimensions, due to the irregularity and level of detail of the object. This value takes on a range between one and two for two-dimensional objects ($1<D<2$) and a range between two and three for three-dimensional objects ($2<D<3$) (Rian et. all, 2007) (See Figure 1). In two-dimensional images, this value varies between 1 and 2,

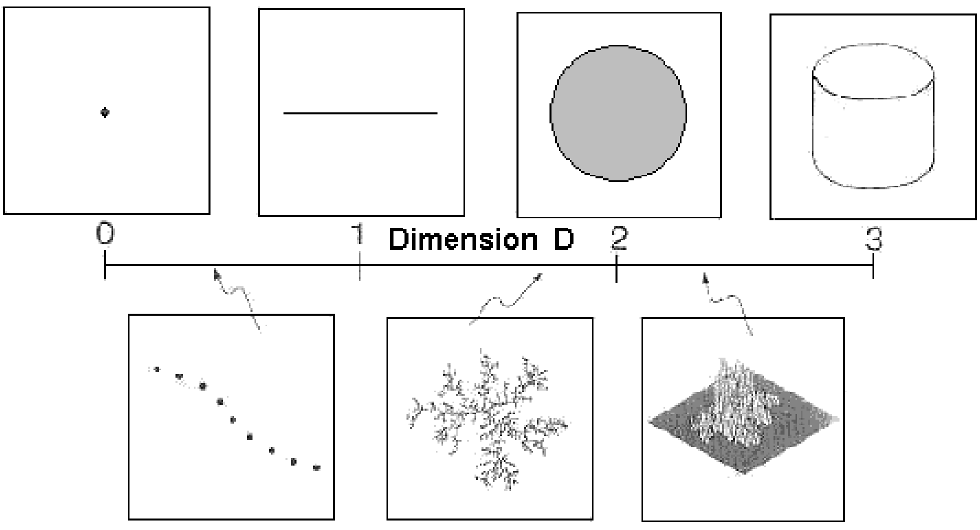
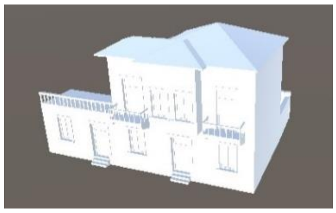
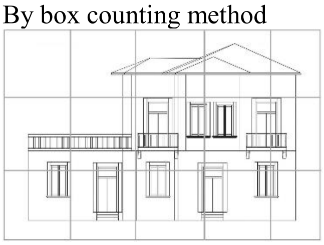
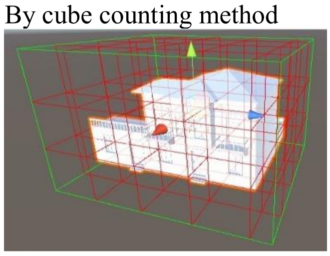


Figure 1: *Fractal Dimension Relationship (Batty and Longley, 1994)*

approaching 1 representing low complexity levels (Shishin and Ismail, 2016), and approaching 2 representing high complexity levels (Vaughan and Ostwald, 2009;2010). In the case of three-dimensional fractals, as the value approaches 2, it represents low complexity levels, and as it approaches 3, it represents high complexity levels

***Table 1:** A Comparison of Two-Dimensional and Three-Dimensional Fractal Analysis*

	Two-Dimensional Fractal Analysis	Three-Dimensional Fractal Analysis
Fractal value range	$1<FD<2$	$2<FD<3$
Data type	2-dimensional images and drawings 	3D model 
Calculation method	By box counting method 	By cube counting method 
Scale	From building scale to urban scale	Building and street scale (Under development for larger scales)
Requirements	Editing and Analysis tool ImageJ vb.	Modelling and Analysis tool blender unity
Assessment method	Information about the architectural structure or texture is produced through a single facade, silhouette, and site plan.	Information is produced through a three-dimensional scale representation of the architectural structure or texture.
Information obtained	Limited	Comprehensive

3. Material and Method

3.1.Method

This study presents a quantitative and qualitative approach based on three-dimensional fractal analysis, rooted in mathematics, along with a review of the literature in the pre-analysis phase. Furthermore, in the discussion section of the study, an approach transitioning between quantitative and qualitative aspects is employed by associating mathematical data with the physical characteristics of architectural products. Two different software programs were utilized for modelling and analysis. The "Blender" software was used for modelling, while the "Unity" game engine was used for analysis. Within the scope of the study, the houses comprising the street are considered as a whole. In this context, the entire street is modelled and analysed in three dimensions. The flowchart of the 3D fractal analysis process is provided in Figure 2.

The model that conducts three-dimensional fractal analysis of architectural texture within the scope of the study is based on the cube counting method. In the cube counting method, the fractal dimension of the model to be calculated is covered with an initial volume. This initial volume is determined by taking the outermost points of the model in the entire coordinate system as references. Once the initial volume is determined, it is obtained by adding 20% (1/5) of the short edge length to all edges of the model's outer boundaries. After the initial volume is created, the short edge (height) is divided into thirds (1/3) to determine the initial cube size. The division process continues until all volume cubes are covered. After this process is completed, the first cycle becomes ready for calculation. The number of cubes in the lower row of the initial volume (in the x direction) is defined as (1/S1). Then, cubes containing details (NS1) are identified. After this stage, a scaling factor is applied when

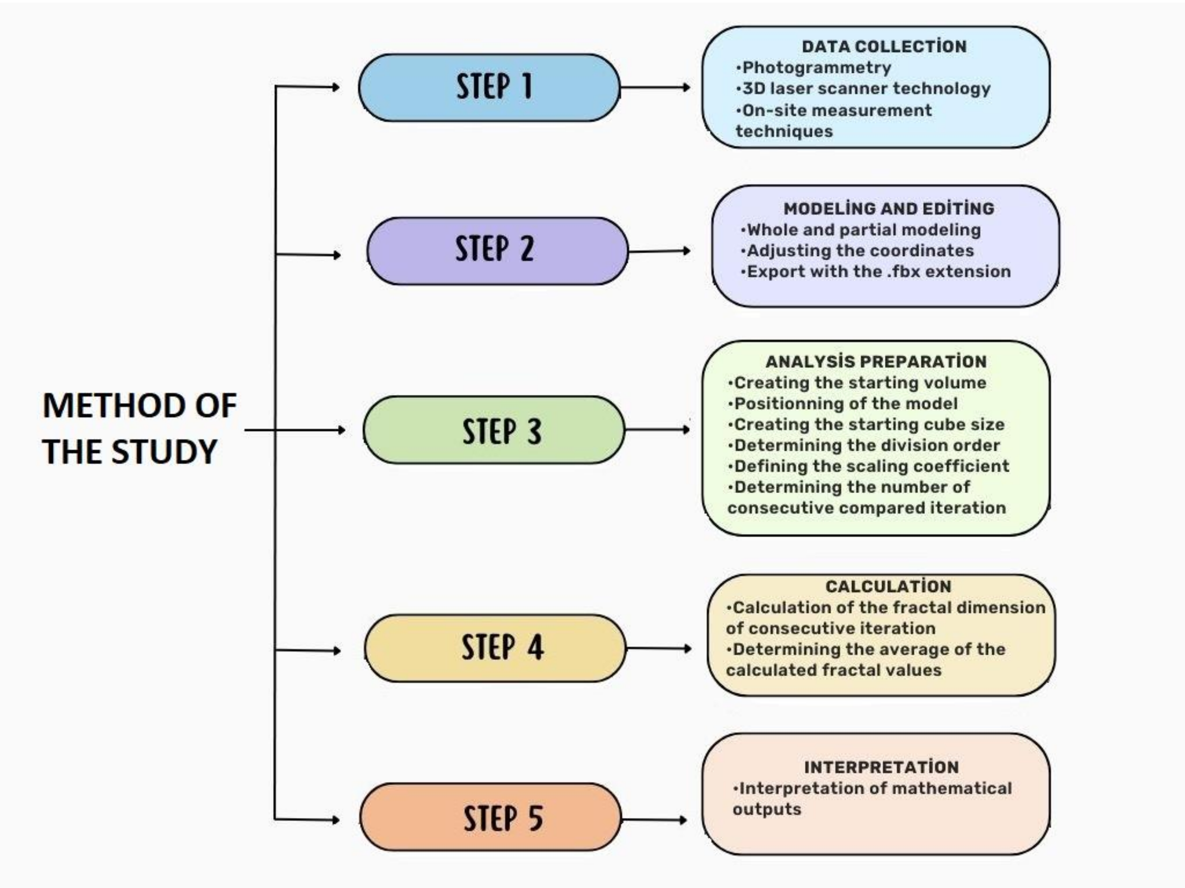


Figure 2: *Method of the study*

moving on to the next cycle (2:1). With this ratio, when the cube is divided by 2 in the x, y, and z axes, 8 cubes are formed within one unit cube. After the reduction process is completed, the number of cubes (1/S2) and the number of cubes containing details (NS2) are defined. Finally, the fractal dimension is calculated by comparing the formulas of two consecutive cycles. The average of these calculated fractal dimensions is taken to determine the average fractal dimension for the model (Figure 3). The formula for this calculation is as follows:

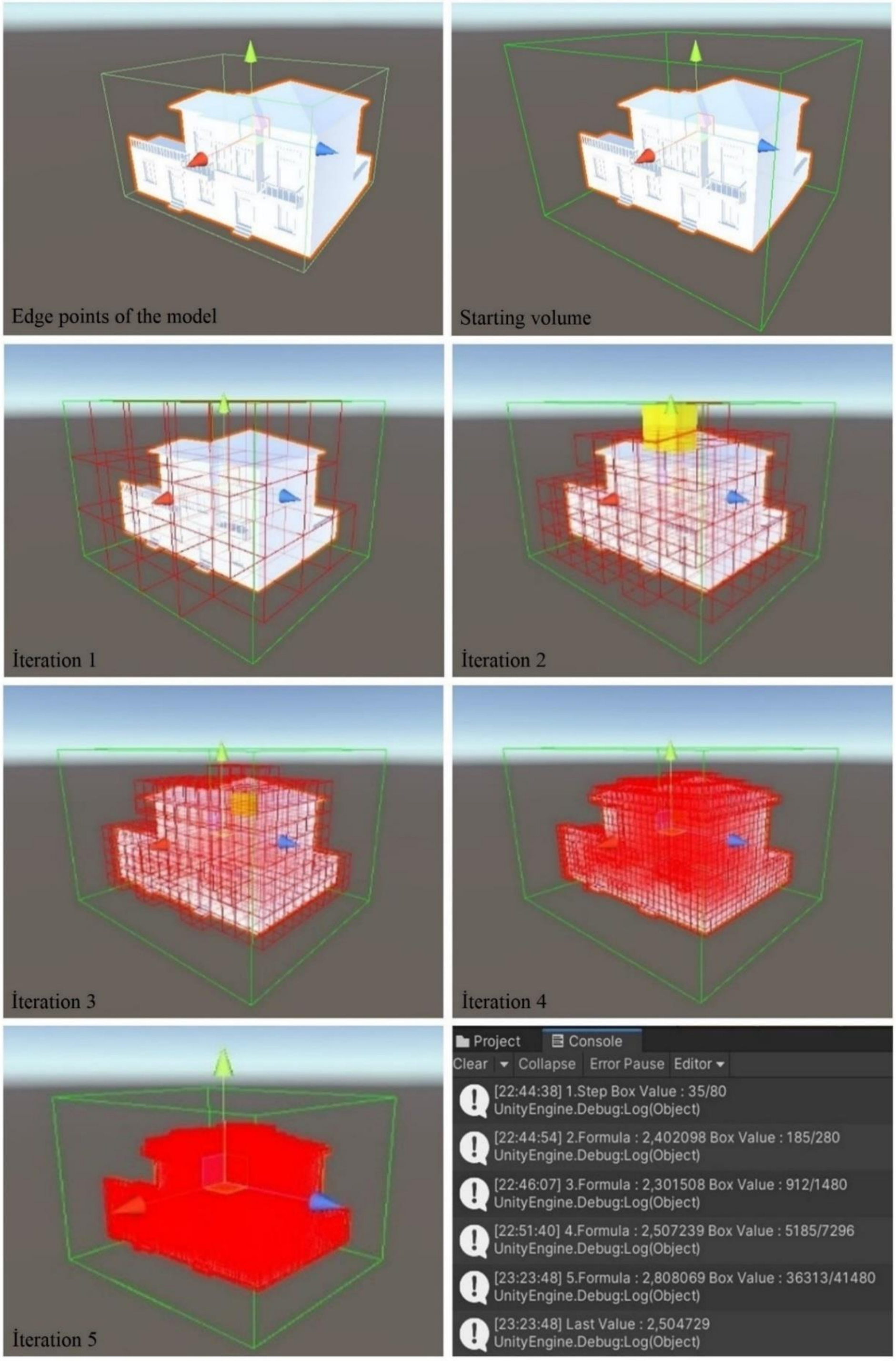


Figure 3: *Three-dimensional fractal analysis process (fractal analysis process in Unity program)*

$$D = (logN_{s2} - logN_{s1}) \,/\, (log1/S_{2} - log1/S_{1}) \qquad (1)$$

In this equation;
D: Fractal dimension according to cube counting method
NS1 = Number of cubes containing details in the first iteration
NS2 = Number of cubes containing details in the next iteration
1/S1 = Number of cubes at the base of the volume in the first iteration (in the x direction)
1/S2 = Number of cubes at the base of the volume in the next iteration (in the x direction)

3.1. Material

Lefkoşa, which is a classic example of a city divided in many ways (Bakshi, 2012), has its origins dating back to the Byzantine period. During this period, the coastal cities of the island suffered significant damage due to Arab attacks, and as a result, the capital of that time, Salamis, was greatly affected. It was decided that the coastal cities were inadequately secure, leading to the relocation of the capital to Lefkoşa, located in the inland areas of the island. From that point onwards, Lefkoşa gained importance and became the capital of the island (Gürkan, 1989; Akçay, 2006). Previously a small town, Lefkoşa (Gürkan, 1989) transformed into a settlement resembling the medieval metropolises of the Western world during the Lusignan period, inhabited by nobles, merchants, and clergy (HadjiChristos, 2005). During the Venetian rule, Lefkoşa, which had expanded significantly (Demi, 1997), had its city walls reconstructed within a 3-mile radius, with St. Sophia Cathedral as the central point, reducing the city's circumference from 9 miles to 3 miles (Gürkan, 1989).

Upon taking control of the island from the Venetians, the Ottomans quickly began to develop and populate the capital, Lefkoşa. New housing was constructed on the vacant land within the city walls to accommodate the increasing population density. During this period, the city started to see the emergence of

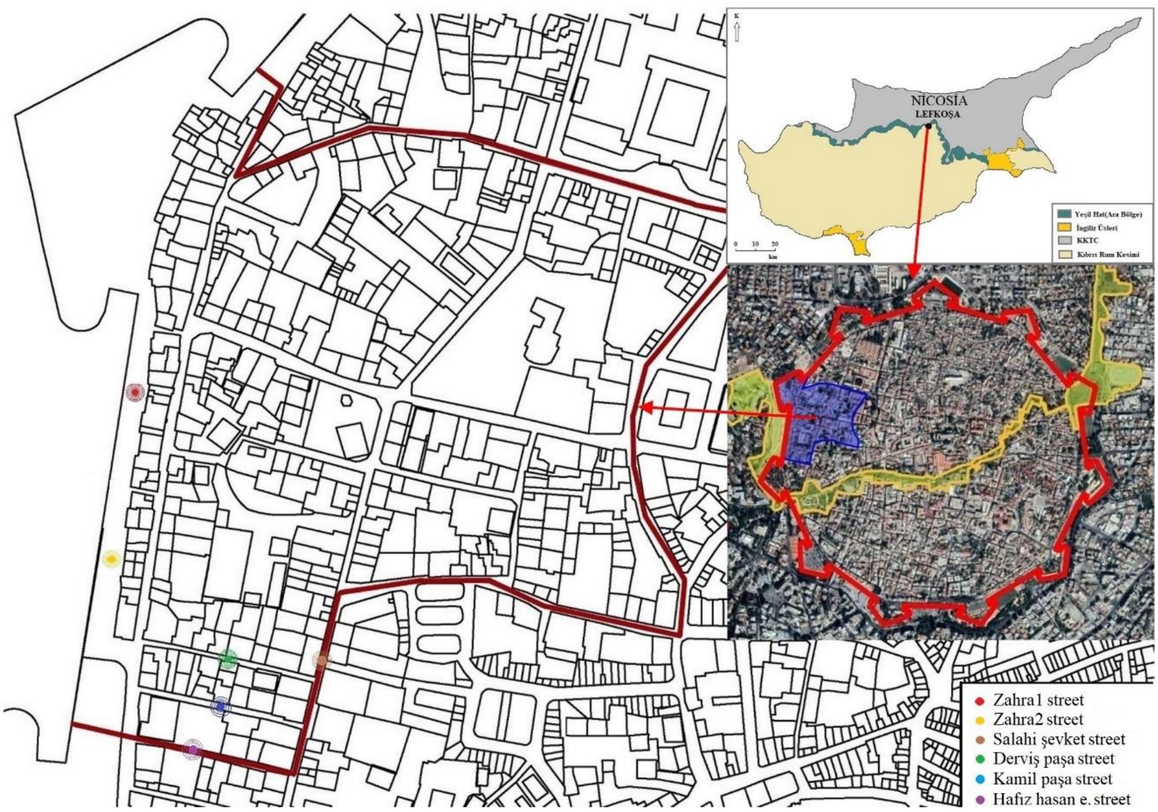


Figure 4: *Arabahmet neighbourhood texture and the location of selected streets.*

houses with bay windows and attached layouts, narrow winding streets surrounded by residential buildings, and in some places, dead-end alleys. With the onset of the British colonial era following the Ottoman rule, administrators encouraged the construction of houses outside the city walls, prompting the population to move beyond the walls. This led to the formation of new residential areas outside the city walls. As a result of these developments, the city began to expand beyond the walls it had been confined within since 1567 (Gürkan, 1989).

In 1960, with the establishment of the Republic of Cyprus, the British colonial era came to an end, and the island gained its independence. Ethnic conflicts between Turkish Cypriots and Greek Cypriots resulted in the division of Lefkoşa in 1963, marked by the Green Line. This Green Line separated the northern and southern parts of Lefkoşa, spatially restricting the two communities. Just like on the island as a whole, this spatial division that began to take shape in Lefkoşa became permanent in 1974, playing a significant role in the city's current spatial configuration (Gürdallı and Koldaş, 2017).

While new residential areas were emerging outside the walls of Lefkoşa, there was also an acceleration in the demolition of old houses to make way for reinforced concrete structures. As a result of these demolitions, the traditional street layout of Lefkoşa underwent a significant transformation. Many characteristic Lefkoşa houses did not survive the demolitions. However, some neighbourhoods, partly due to their proximity to the green line, escaped complete destruction. One of these neighbourhood was Arabahmet. Arabahmet, one of the neighbourhoods that best reflects the

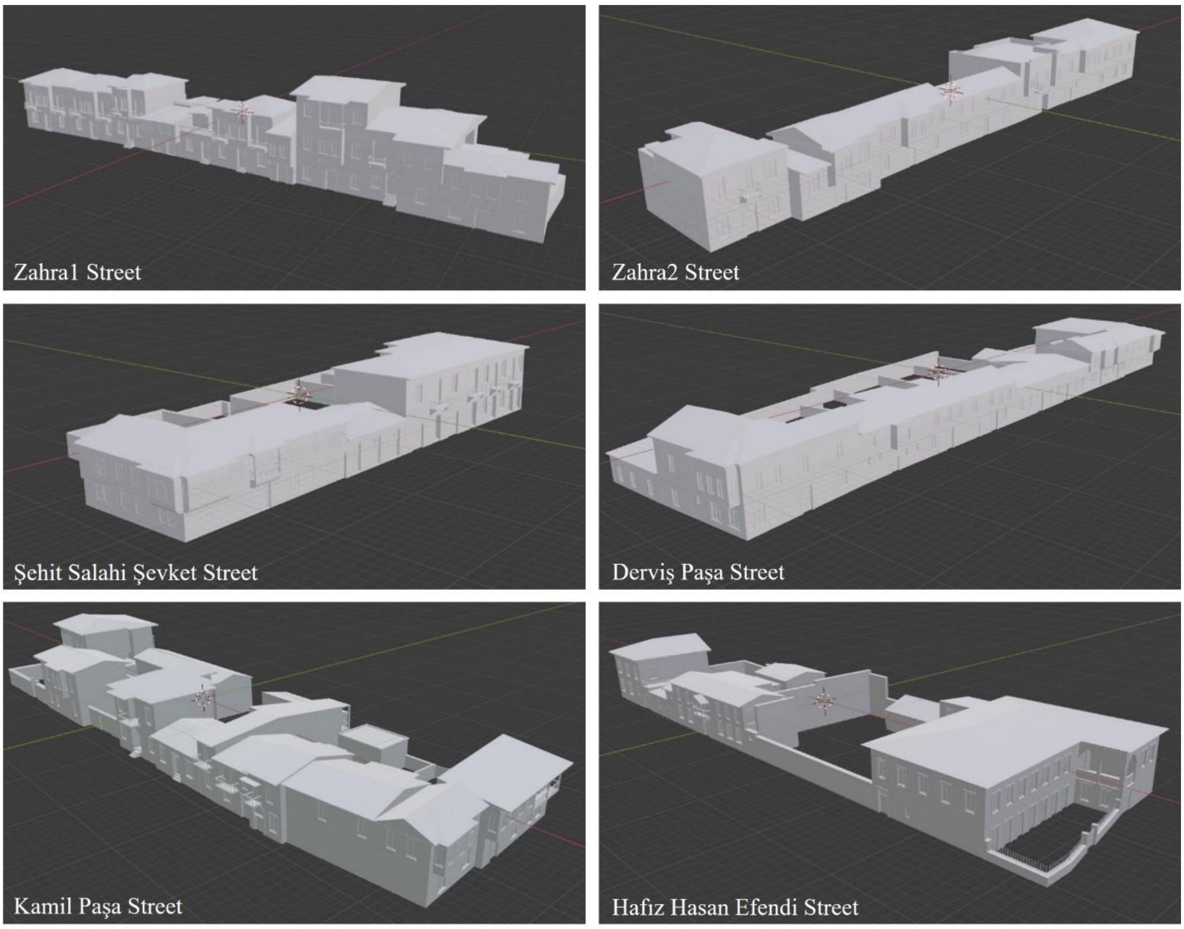


Figure 5: *Three-dimensional models of streets (visuals of streets modelled in 3D with the Blender program)*

traditional texture of the inner walls of Lefkoşa, was primarily used for residential purposes and featured a dense characteristic housing fabric bearing traces of various cultures. Even today, the neighbourhood, which is home to many historic houses, remains a place where Turkish, Armenian, Latin, and various other ethnic groups have lived together. It is possible to see the historic housing fabric on many streets of Arabahmet neighbourhood. Among these streets, Zahra1, Zahra2, Salahi Şevket, Derviş Paşa, Kâmil Paşa, and Hafız Hasan Efendi Street were selected for three-dimensional fractal analysis (see Figure 5).

4. FINDINGS AND DISCUSSIONS

The streets selected for analysis in the Arabahmet neighbourhood generally consist of two-story houses with courtyards and without courtyards. In addition to two-story houses, there are also a few single-story and three-story houses. Another characteristic of the houses on these streets is their bay windows. The mass movement created by the bay windows spilling onto the street can be observed in many street textures. Furthermore, the positioning of houses lined up side by side along a street, as well as the balconies and wide eaves that many houses have, contribute to a mass movement that spills onto the street. Thanks to these and many other features, these houses constitute the unique texture of the streets. The row houses on Zahra1 and Zahra2 streets create a visually more complex street texture compared to others. Hafız Hasan Efendi Street, with its larger courtyards, has a sparse texture formed by a small number of houses. In this regard, in the three-dimensional fractal analysis calculation, it is expected that Zahra1 and Zahra2 streets, which have a complex structure, will have a higher fractal dimension compared to other streets, while Hafız Hasan Efendi Street will have a lower dimension compared to others. Although some streets may exhibit certain differences compared to others, if the analysis results among the existing street textures show proximity, it will prove the spatial and mass consistency as well as continuity of the streets located within the same neighbourhood. The fractal dimension analysis results and graphical distribution of the six street textures created by courtyard and non-courtyard houses in the Arabahmet neighbourhood are provided below (See Figures 6, 7, 8, 9, 10, 11, 12, and Tables 2, 3).

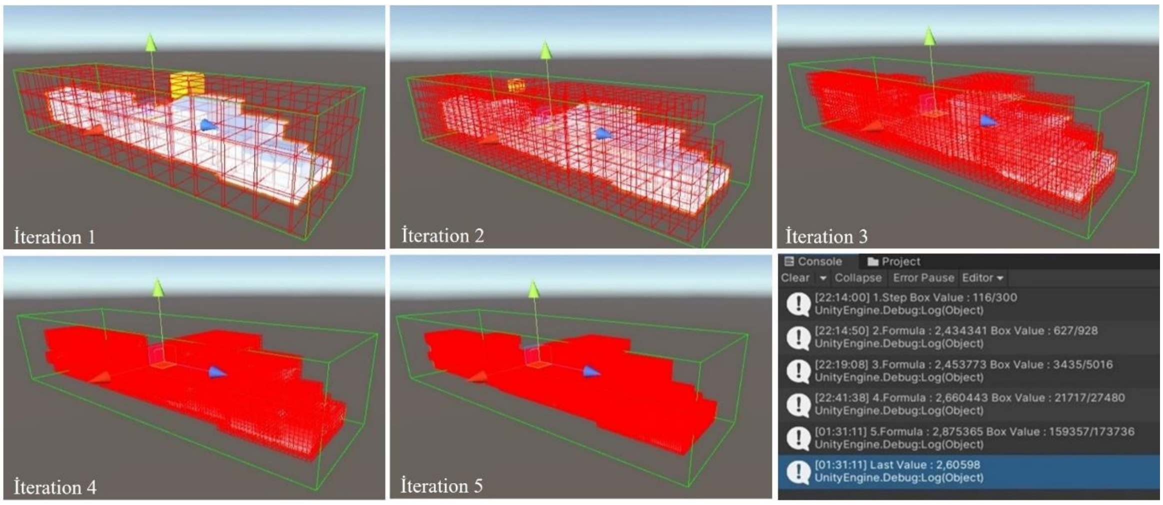


Figure 6: *Analysis process of the housing texture on Zahra1 street*

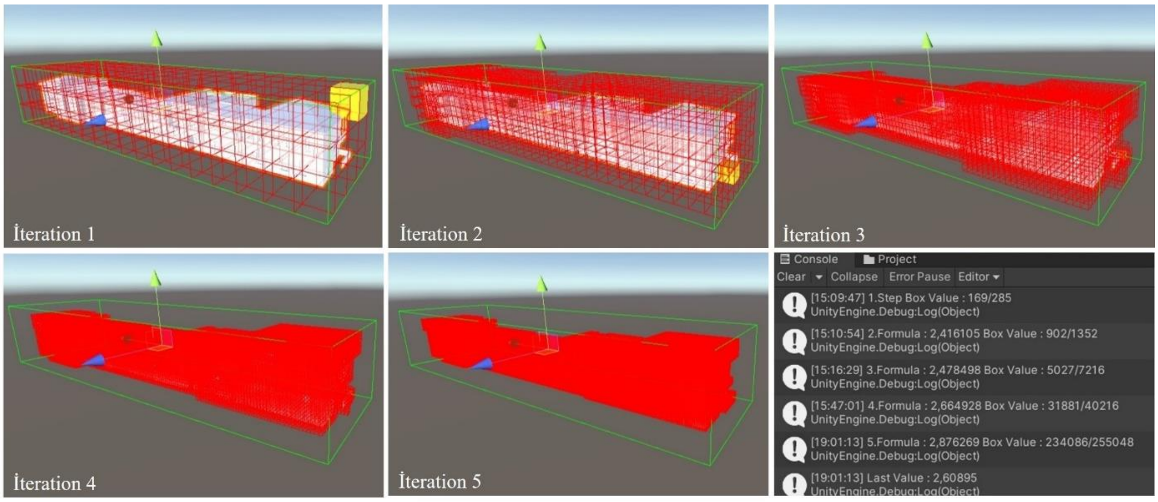


Figure 7: *Analysis process of the housing texture on Zahra2 street*

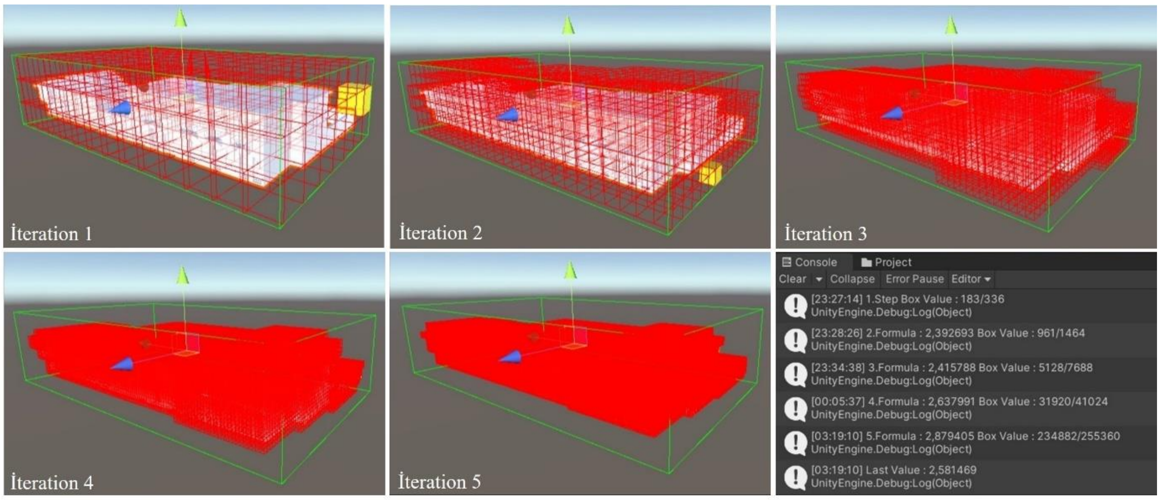


Figure 8: *Analysis process of the housing texture in Şehit Salahi Şevket street*

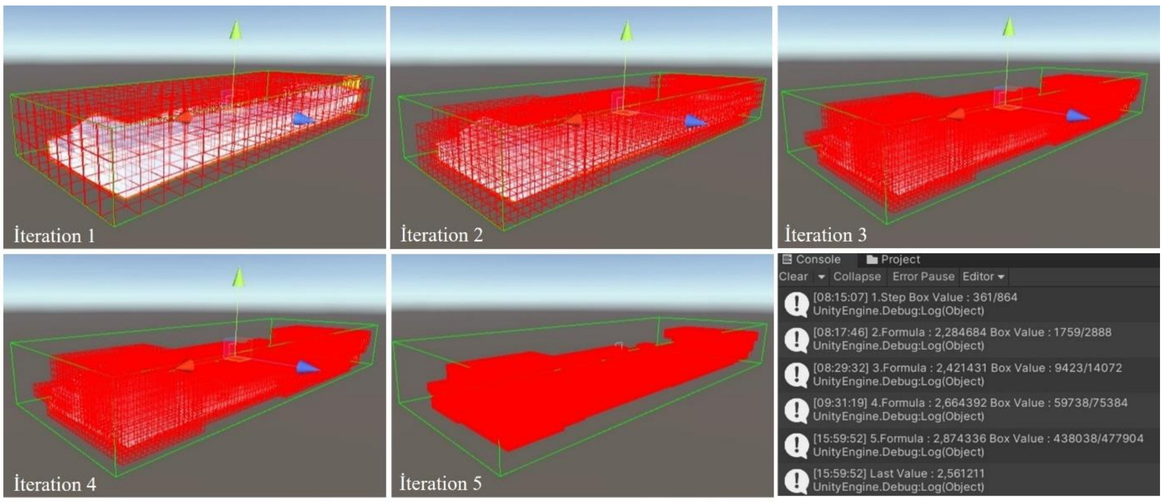


Figure 9: *Analysis process of the housing texture on Derviş Paşa Street*

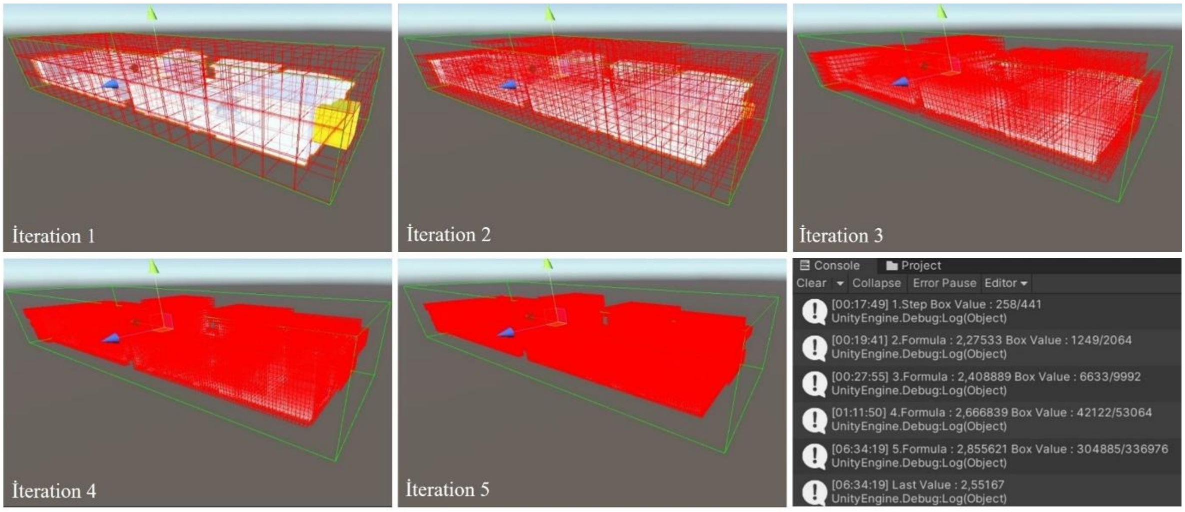


Figure 10: *Analysis process of the housing texture on Kamil Pasha Street*

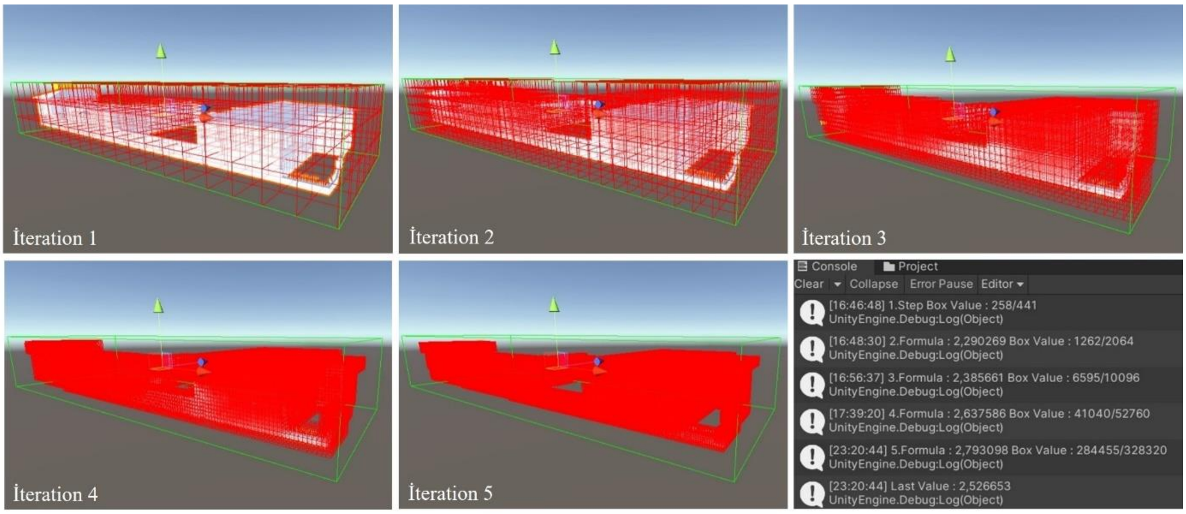


Figure 11: *Analysis process of the housing texture on Hafiz Hasan Efendi Street*

Table 2: *Three-dimensional fractal analysis results of streets.*

Street		First Iteration	Second Iteration	Third Iteration	Fourt Iteration	Average of four Iteration
Zahra1 Street	Courtyard	2,434341	2,453773	2,660443	2,875365	**2,605980**
	Without Courtyard	2,408807	2,454739	2,671998	2,878294	**2,603459**
Zahra2 Street	Courtyard	2,416105	2,478498	2,664928	2,876269	**2,608950**
	Without Courtyard	2,269402	2,498857	2,691815	2,870593	**2,582667**
Salahi Şevket Street	Courtyard	2,392693	2,415788	2,637991	2,879405	**2,581469**
	Without Courtyard	2,448377	2,627051	2,738452	2,905627	**2,679877**
Derviş Paşa Street	Courtyard	2,284684	2,421431	2,664392	2,874336	**2,561211**
	Without Courtyard	2,481443	2,506240	2,698071	2,882273	**2,642007**
Kâmil Paşa Street	Courtyard	2,275330	2,408889	2,666839	2,855621	**2,551670**
	Without Courtyard	2,263792	2,460923	2,681286	2,870149	**2,569037**

Hafız Hasan Efendi Street	Courtyard	2,290269	2,385661	2,637586	2,793098	**2,526653**
	Without Courtyard	2,332382	2,427597	2,683604	2,816236	**2,564955**

Table 3: *Fractal dimension relationship between streets.*

	Zahra1	Zahra2	Salahi Şevket	Derviş Paşa	Kamil Paşa	Hafız Hasan Efendi	**Range/ Gap**	**%**
Street (Courtyard)	2,606	2,609	2,581	2,561	2,552	2,527	**0,082**	**8,2**
Street (Without Courtyard)	2,603	2,583	2,680	2,642	2,569	2,565	**0,115**	**11,5**
Range/Gap	**0,003**	**0,026**	**0.099**	**0,081**	**0,017**	**0,038**		
%	0,3	2,6	9,9	8,1	1,7	3,8		

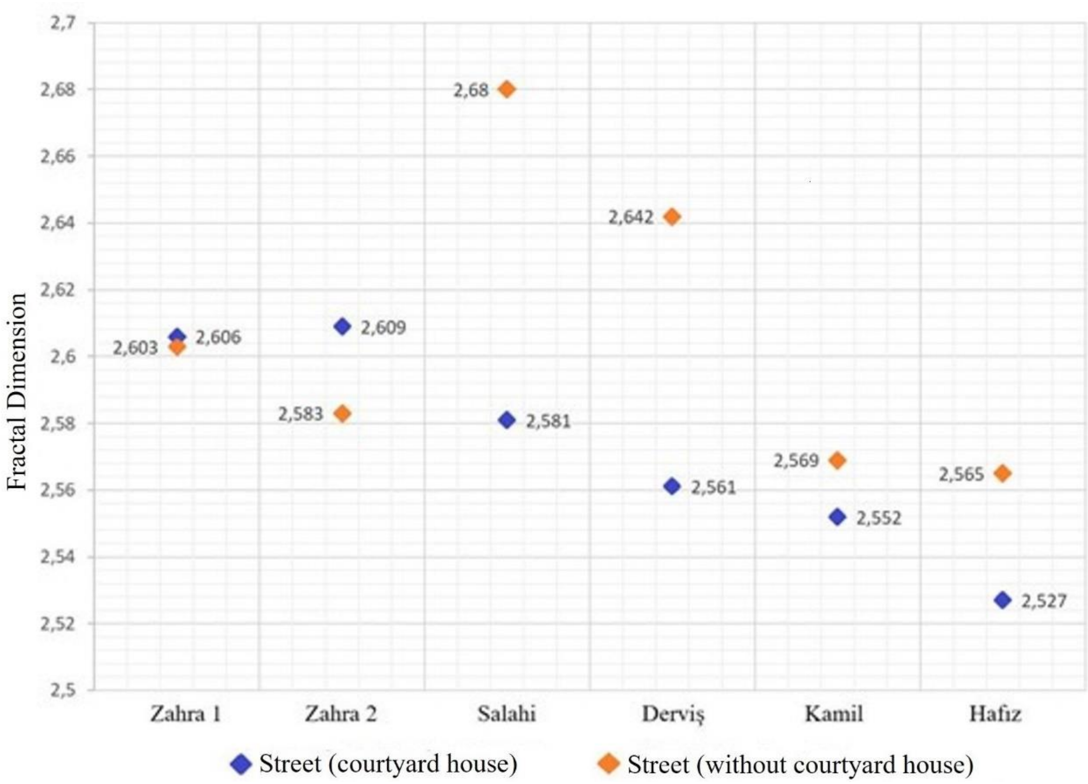


Figure 12: *Graph showing the fractal dimension of streets.*

The fractal values of streets formed by houses with courtyards vary between 2.527 and 2.609 in the analysis of these streets after five cycles. In these street analyses, where the average is calculated after five cycles, Hafız Hasan Efendi Street has the lowest value, while Zahra2 Street has the highest value. In the analysis of streets formed by houses without courtyards, the lowest value is measured at 2.565 in Hafız Street, while the highest value is measured at 2.680 in Salahi Şevket Street. In the three-dimensional fractal analysis calculations, streets formed by houses with courtyards are ranked from low to high in terms of fractal dimension as follows: Hafız Hasan Efendi, Kâmil Paşa, Derviş Paşa, Salahi Şevket, Zahra1, and Zahra2. Streets formed by houses without courtyards are ranked as follows: Hafız Hasan Efendi, Kâmil Paşa, Zahra2, Zahra1, Derviş Paşa, and Salahi Şevket.

The street texture created by row houses on Zahra Street visually appears more complex compared to others. The high fractal value calculated on this street actually confirms the expectation that the fractal dimension of the street is higher than other streets. As a result of these analyses, the fractal dimensions of Zahra1 and Zahra2 streets are very close to each other, indicating a strong spatial and mass coherence relationship between the two sections on a single street. In addition, while the fractal dimension increases in other streets in calculations made without courtyards, it decreases in these two streets. In street analyses where houses are evaluated with their courtyards, the 8.2% difference between the highest and lowest fractal values among these six streets indicates the fractal dimension consistency among these streets. In fact, from the results obtained from fractal dimension calculations, it can be inferred that Zahra2 street has a high level of complexity, while Hafız Hasan Street has a lower level of complexity in streets formed by houses with courtyards.

In the analyses of streets formed by houses with and without courtyards, the smallest difference was obtained in Zahra1 Street. The reason for this is related to the fact that the courtyards of the houses on Zahra1 Street are within the outer boundaries of the corner houses located at both ends of the street, and most of the houses do not have courtyards, and those that do have small courtyards. Despite the increase in the ratio of houses with courtyards in Kâmil, Zahra2, and Hafız streets, they exhibit a similar fractal value range to Zahra1 street. The streets with the highest range of fractal values are Salahi Şevket and Derviş Paşa Streets. This difference can be related to the extension of courtyard walls from the rear facade of the houses to the outside in these streets. The similarity of analyses in different street textures indicates the similarity in the spatial and mass structure of streets located in the same neighbourhood.

5. Conclusion

The different streets located in the Arabahmet neighbourhood of Nicosia, which has preserved its traditional character within the city walls, were analysed using a three-dimensional fractal analysis method, and interpreted based on mathematical data while maintaining their traditional fabric. The fractal dimension of streets formed by courtyard houses varies between 2.527 and 2.609, while the streets formed by houses without courtyards range from 2.565 to 2.680. It is observed that the fractal dimensions of these streets are very close to each other, indicating a strong degree of consistency in the streets. The degree of closeness between the obtained fractal dimension results demonstrates the continuity of streets located in the same neighbourhood. The fractal dimensions obtained from street-scale analyses actually represent a numerical outcome of the complex fabric formed by housing units coming together over time. In this study, analyses that were previously reduced to two dimensions, such as site plans, floor plans, elevations, and silhouettes, were conducted through a scaled model of architectural fabric.

The developed model in this study was used solely to mathematically evaluate the physical properties of the fabric. The biggest advantage of the model is its ability to analyse the architectural product in a more comprehensive manner as a whole. In two-dimensional analysis studies, the facade facing the street or all facades are separately analysed, and an average value is attempted to be calculated for a single dwelling. However, in three-dimensional analysis, more features of the building are considered, such as heights, widths, roofs and eaves, if any, bay windows, balconies and consoles, windows and doors, stairs, garden walls, as well as all indentations and projections. Examining the structure with its third-dimensional features as a whole not only allows for a better understanding of its character but also provides more comprehensive information about the building compared to two-dimensional studies. Another advantage of the model is its effectiveness in revealing the mathematical data of the fabric created by each building or building group that makes up the architectural fabric. Therefore, this model provides an opportunity to concretely visualize hidden dimensions and mathematically define architectural products.

With the further development and use of this method on a larger scale, the relationship between different scales can be explored. Furthermore, it can be used to study third-dimensional changes in urban fabric. In addition to these, in urban research, in the initial stages of designing new structures, and in interventions to the existing fabric to ensure the continuity of the urban fabric, this method can be used as a tool to obtain objective data by relevant institutions. In conclusion, it is believed that this developed method will increasingly become widespread and contribute to the literature through three-dimensional analysis.

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