Research Article

Fractal Design of Indoor and Outdoor Forms of Architectural Space Based on a Three-Dimensional Box Dimension Algorithm

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The three-dimensional organic growth features of buildings have been given more and more attention according to the unique view representation regulations of the indoor construction industry, in order to optimize the usage and allocation efficiency of building space. To explore the configuration structure of building function space, the three-dimensional box dimension algorithm is used to measure the fractal dimension of the indoor and outdoor form of building space, and the two-dimensional and three-dimensional fractal characteristics of building space are compared and analyzed; the method of the second derivative is utilized for the automatic recognition of fractal scale-free areas, aiming at the imprecise problem of the artificial judgment of scale-free areas in earlier fractal research of interior and outdoor forms of architectural space. The experimental results show that the second derivative method can effectively and automatically identify the scale-free region. The coefficients of linear fitting are above 0.990, and the indoor and outdoor forms of architectural space have clear fractal characteristics. After applying the method, the three-dimensional fractal dimension grows, indicating that the interior and outdoor form usage of architectural space in this area is generally effective and compact.

1. Introduction

Since Mandelbrot [1] put forward, the concept of fractal has quickly attracted the attention of various disciplines and become the main tool to describe complex and irregular geometric features. It is widely used in various fields such as architectural form, tunnel modeling, geological survey, and so on [2, 3]. At present, many types of research on an architectural form based on fractal theory have been carried out at home and abroad. However, traditional two-dimensional fractal research masks the slowdown of plane expansion caused by height growth, and the architectural form actually presents increasingly strong three-dimensional characteristics [4, 5]. However, due to the difficulty of information acquisition and analysis methods, the research on the indoor and outdoor forms of three-dimensional architectural space needs to be further optimized and analyzed.

Reference [6] summarizes the basic knowledge of fractal geometry, the relationship between fractal geometry and sustainable historical buildings in Vietnam, and the

applicability of fractal geometry in drawing biological simulation architectural forms harmonious with nature, which is helpful in creating sustainable buildings for the future. Reference [7] discusses the generative use of a genetic algorithm, which combines a computer-based fractal dimension tool called “dbvgen”. Fractals provide the quantitative and qualitative relationship between nature, the architectural environment, and computational mechanics. This paper discusses it as a bridge between these fields. The main goal is to develop and use complex analysis tools in a creative environment by using the fractal dimension and the Vollendorf method. Then the tool is tested in a complex case study project, and the results are discussed. Reference [8] studies the differential geometry of the Bertrand curve in three-dimensional space from the perspective of the surface curve. It defines a special surface, called a geodetic surface, which is generated by Geodesy in three-dimensional space. This kind of surface is the generalization of the ruling surface in three-dimensional Euclidean space. The results show that the Bertrand curve is related to the average curvature of the

main normal geodetic surface. Although the above methods use the fractal concept and theory to realize the corresponding application, the research on the internal significance of the indoor and outdoor form of three-dimensional architectural space compared with two-dimensional and its own fractal characteristics is still relatively weak [9]. Moreover, in the evolution of buildings, the physical space form is not only the expansion of the land area but also the continuous change of building height, showing a dynamic and random change process [10, 11]. In modern architectural construction, in order to improve the efficiency of architectural space utilization and space allocation, the architectural form presents more and more strong three-dimensional characteristics. The three-dimensional organic growth of architecture has become an important goal of architectural space development. A new quantitative measurement method based on the architectural three-dimensional spatial structure is needed to accurately and comprehensively explore the evolution law and temporal and spatial characteristics of architectural spatial structures [12, 13].

Based on this, this paper uses the three-dimensional box dimension algorithm to calculate the fractal dimensions of various types of indoor and outdoor forms of two-dimensional and three-dimensional building space and judge their fractal structure. Aiming at the problem that the artificial judgment method in the research of building fractals cannot accurately identify the scale-free area, this paper uses the second derivative method for reference to automatically identify the fractal scale-free area. This paper discusses the rationality of the indoor and outdoor layout of architectural space and the allocation system of functional space.

The research is organized as follows: The introduction is presented in Section 1. Section 2 analyzes the principle of the 3D box dimension algorithm. Section 3 discusses the box dimension result analysis in detail. Section 4 proposed the simulation experiment as well as experimental preparation, result, and analysis; Section 5, consists of a discussion portion. Finally, in Section 6, the research work is concluded.

2. Principle of 3D Box Dimension Algorithm

We cover the study area with boxes of different scales, that is, we measure the two-dimensional and three-dimensional airspace with boxes or cuboids of different scales, or rectangles or cuboids of different scales and sizes, and count the number of scales covering the whole space, that is, the corresponding measure, which is called the number of nonempty boxes [14]. In one calculation, the scale of different scales should be kept constant; that is, the length-width ratio should remain unchanged in the two-dimensional case and the length width height ratio should remain unchanged in the three-dimensional case. Therefore, the length and width (height) can be used as the measurement standard of scale. In order to facilitate the use of average width as a convenient statistical measure. Specific parameters are shown in Table 1.

Theoretically, in order to better reflect the nature of the indoor and outdoor form of the building space, the smaller

the scale of the smallest cuboid box, the better [15], but the actual data resolution is limited, the level of the indoor and outdoor form of the building space cannot reach infinity, and the measured data volume increases in geometric multiples as the scale becomes smaller, so the minimum grid-scale in this paper is taken as 0.10 m.

According to the above process, the box dimension value is calculated. The basic idea of the box-counting method is to use scales of different scales to measure space. For a specific scale r , it is assumed that the number of scales required for the measurement space is $n(r)$. Then, in a fractal dimension estimation process, the relationship between the linear scale of the measuring body and the number of measuring bodies follows a negative power law and it is expressed as

$$n(r) \propto r^{-q}, \quad (1)$$

where q is the fractal dimension. In one dimension, the ruler is a line segment. In the case of two dimensions, the ruler is either square or rectangular. In a three-dimensional case, the ruler is a cube or box. The “box” in the “box” method refers to the ruler such as line segments, rectangles, and cubes. The ruler quantity required in the whole space is the “number of nonempty boxes.” For two-dimensional scales, different rectangular scales should have the same aspect ratio to unify the standards determined by the scale. Theoretically, when the aspect ratio is constant, a class of results is obtained from the dimensions of the length scale and the width scale, respectively. Similarly, in the three-dimensional case, the length width height ratio of different cube scales must also be the same. If the length-width ratio is different, the length width height cannot be unified as the scale standard. Take logarithms on both sides of (1) to obtain

$$\lg n(r) = a \lg r^{-q}, \quad (2)$$

where a is a constant. It can be seen that, in the case of a fractal, the scale and the number of nonempty boxes have a linear relationship in the double logarithmic coordinate system. At this time, the least square method can be used for linear regression of the number of nonempty boxes, and the absolute value of the slope of the line is the fractal dimension.

Because the indoor and outdoor form of architectural space does not belong to the standard fractal in the mathematical sense, the existing measurement methods are difficult to find the optimal random fractal coverage. In the actual measurement, when the size of the measured object is too large or too small, the coincidence between the measured body and the fractal body is not ideal, and the scale relationship between the measurement scale and the corresponding measure cannot well reflect the fractal dimension value, which makes the indoor and outdoor form of the building space actually have fractal properties only on a certain scale, and this continuous scale corresponding range is called the scale-free area [16], also known as the scale area. In order to better determine the fractal structure of the measurement region, it is necessary to select the scale-free region of the measured box dimension.

TABLE 1: Summary of the number of two-dimensional boxes at different scales (unit: m).

Serial number	Box scale	Office nonempty box		Entertainment nonempty box		Leisure nonempty box	
		Box side length	Number of boxes	Box side length	Number of boxes	Box side length	Number of boxes
1	32768	3139.00		7571.00		12483.00	
2	16384	1569.50	1	3785.50	2	6241.50	2
3	8192	784.75	3	1892.75	3	3120.75	2
4	4096	392.38	19	946.38	17	1560.38	16
5	2048	196.19	69	473.19	63	780.19	62
6	1024	98.09	247	236.59	288	390.09	246
7	512	49.05	1007	118.30	1009	195.05	982
8	256	24.52	4014	59.15	4122	97.52	3762
9	128	12.26	16146	29.57	16253	48.76	15239
10	64	6.13	64329	14.79	65019	24.38	60585
11	32	3.07	257227	7.39	261142	12.19	242118
12	16	1.53	1034783	3.70	1043543	6.10	967922
13	8	0.77	4085054	1.85	4172771	3.05	3867418
14	4	0.38	16773440	0.92	16876096	1.52	15576526
15	2	0.19	67098216	0.46	67500975	0.76	62305797
16	1	0.10	242220375	0.23	270004917	0.38	249222764

In this paper, the second-order derivation method is used to judge the scale-free range most objectively. Because in the double logarithmic coordinate system, the points are generally distributed in a straight line, and the local slope of one derivative ($\lg r, \lg n(r)$) point fluctuates up and down within a certain range. In order to determine the amplitude of the wave, the slope is derived again to obtain the change rate of the first derivative, which fluctuates around 0. Using the calculation of the enclosed area between each point in the second derivative and the x -axis, we set a threshold point and select the area with the most continuous points as the scale-free area through comparative judgment, take the following measures:

The first derivative of the i point ($\lg r_i, \lg n(r_i)$), i.e., (3) can be used to compute the local slope.

$$\lg n'(r_i) = \frac{\lg n(r_{i+1}) + \lg n(r_{i-1}))}{\lg n(r_{i+1})\lg n(r_{i-1})}, \quad (3)$$

where $\lg n'(r_i)$ is the local slope of the i -th point; $i = 2, 3, \dots, k-1$. k is the number of points on the curve. The second derivative of the i -th point ($\lg r_i, \lg n(r_i)$), that is, the rate of change of the local slope can be calculated by

$$\lg n''(r_i) = \frac{\lg n'(r_{i+1}) + \lg n'(r_{i-1}))}{\lg n(r_{i+1})\lg n(r_{i-1})}. \quad (4)$$

The scale-free region S can be calculated by

$$S = \lg r \sum_{i=1} \lg n''(r_{i+1}), \quad (5)$$

where $i = 3 \leq j \leq k-5$ and j are points. When the number of points j is the same, the smaller the number of points S , the smaller the fluctuation range of the point column near 0. In this paper, when the threshold is 0.5, as long as $S \leq 0.5$, which is sufficient for the basic range of fractal dimension value ($q < 2$ in the two-dimensional case and $q < 3$ in the three-dimensional case), the continuous area with the largest number of points is the selected scale-free area.

3. Box Dimension Result Analysis

Based on Figure 1, after obtaining the three-dimensional fractal scale-free area of the indoor and outdoor space of the building according to equations (3)–(5), the points in the scale-free area of an area are linearly fitted by the least square method. The fractal dimension results are listed in Table 2. The fitting effect of the points in the fractal dimension scale-free area is shown in Figure 1, in which the absolute value of the linear slope is the fractal box dimension q .

By comparing the measurement coefficient R^2 of the fitting results in Table 2, it can be concluded that the linear fitting degree of all sequences is poor compared with that of the scale-free area. The R^2 of the fitting results of all sequences is much lower than that of the scale-free area, and the fractal dimension value calculated by all point column fitting is also quite different from that of the scale-free area. Therefore, the selection of the scale-free region is of great significance to obtain an accurate fractal dimension. A three-dimensional fractal analysis of the indoor and outdoor forms of office building space is shown in Figure 2.

It can be seen from Figure 2 that the fractal dimension of the three-dimensional spatial form of the indoor and outdoor space of the building is obtained by the second derivative method. The linear fitting result is good on the double logarithm diagram, and the dividing points of different scale areas can be accurately found (the data points in front of the scale-free area and the data points behind the scale-free area have a certain offset from the regression curve of the scale-free area). It shows that the method of determining the scale-free area through the second derivative given in this paper can well determine the fractal characteristics of the indoor and outdoor space form of buildings. From Table 3, it can be seen that the values of the determination coefficient R^2 of linear fitting of point series in the scale-free area for two years are more than 0.990.

FIGURE 1: Landscape analysis around the building.

TABLE 2: Total statistics of 2D box dimension value.

Range	Point column area	Parameter	Total	B	C	R	MW
To work in an office	All sequences	Box dimension value	1.999	1.9977	1.9773	1.9865	1.9499
		Corresponding R2	0.9998	0.9999	0.999	0.9996	0.9931
	Scale-free region	Box dimension value	1.9948	1.9936	1.9938	1.9877	1.9916
		Corresponding R2	0.1	1	0.9999	0.9996	1
Entertainment	All sequences	Box dimension value	1.9812	1.9374	1.9936	1.9967	1.97
		Corresponding R2	0.999	0.9981	1	0.9999	0.9989
	Scale-free region	Box dimension value	1.9922	1.9862	1.9886	1.9828	1.9883
		Corresponding R2	0.9999	0.9995	0.9999	0.9999	0.9998
Leisure time	All sequences	Box dimension value	1.9875	1.9835	1.9763	1.947	1.9471
		Corresponding R2	0.9982	0.9975	0.9998	0.9986	0.9961
	Scale-free region	Box dimension value	1.9926	1.9915	1.9843	1.9898	1.983
		Corresponding R2	1	0.9999	0.9999	1	1

This is based on a 95% confidence level.

4. Simulation Experiment

Returning to terminology, a simulation study is a simulation. An experiment in which the system's components (e.g., probability distribution parameters) are given specific values or explored in a specific order and the results are recorded. For process analysis and optimization, simulation is employed. A simulation, which is based on process models and organizational structures, allows for the comparison of real and desired processes in terms of feasibility and efficiency.

4.1. Experimental Preparation. Before the experiment, the computer architecture shown in Figure 3 is designed to complete the fractal numerical acquisition and simulation of indoor and outdoor forms of architectural space.

Under the test framework structure shown in Figure 3, Java is used as the programming language, the 6G memory Intel (R)

Core (TM) i7 is used as the model carrying hardware, and the development tool eclipse is used to develop the model data. The data files are set for the location and movement of logistics vehicles. Each file corresponds to the number of indoor and outdoor fractal forms of different building spaces. The data of the set fractal object is shown in Table 3.

Taking the fractal dataset in Table 3 as the experimental object, after transmitting the data in the table to the server in the test frame structure, experiments are carried out using the methods of reference [6], reference [7], and the indoor and outdoor morphological fractal design of building space based on the three-dimensional box dimension algorithm designed in this paper, and the performance of the three fractal designs is compared.

4.2. Results and Analysis. Based on the above experimental preparation, it is assumed that the number of forms in indoor and outdoor building space is n , and the fractal data

FIGURE 2: Three-dimensional fractal analysis of the indoor and outdoor forms of office building space: (a) 3D fractal analysis diagram of the office building; (b) 3D fractal analysis diagram of entertainment building; and (c) 3D fractal analysis diagram of the leisure building.

TABLE 3: The set fractal object data.

Serial number	Data size (M)
1	2.4
2	3.3
3	3.1
4	2.3
5	3.5
6	3.3
7	2.2
8	2.2
9	3.8
10	2.2
11	3.5
12	3.5
13	2.5
14	3.4
15	2.7

objects of different methods are b . The fractal point update parameter relationship of the construction method can be expressed as

$$p = \frac{b}{n} \times 100\%, \quad (6)$$

where p represents the fractal point update parameter. When the fractal point update parameter is larger, the fractal information of the method is more obvious. Taking the fractal data prepared in the experiment as the target processing object, the fractal point update parameter results of the three methods are shown in Table 4.

According to the fractal point update parameter results shown in Table 4, for the same data file, the fractal point update parameters of the three methods are different. According to the values in Table 4, the average fractal point update parameters of the method in reference [6] are about 45.4%, and the update parameters are the smallest, indicating that there is less fractal point information updated by the method in reference [6] in the fractal design of indoor and outdoor forms of building space. The effect of update optimization is poor. The average fractal point update parameters of the method in reference [7] are about 68.7%, and the update parameters are large, which shows that the model actually updates more fractal information about indoor and outdoor forms of building space, and the update optimization effect is strong. The average fractal point update parameter of the fractal design of the indoor and outdoor forms of building space based on the three-dimensional box dimension algorithm designed in this paper is about 82.4%. Compared with the methods in the two references, the update parameter value is the largest, indicating that this method actually updates the most fractal information about the indoor and outdoor forms of building space, and the update optimization effect is the most obvious.

The above experimental environment is kept unchanged. We call the indoor and outdoor map of building space in an area as the experimental environment and use the matching accuracy value between fractal points and design objectives as the performance index. The matching accuracy can be calculated as

$$C = \frac{C_p}{C_n} \times 100\%, \quad (7)$$

where C_p represents the building space location points correctly matched, and C_n represents the number of fractal points to be matched. The indoor and outdoor information of the building space controlled by the actual matching is the same, and the correct matching results of the final three methods are shown in Figure 4.

According to the correct matching results shown in Figure 4, taking the fractal point position points in the experimental preparation file as the experimental object, according to the calculation results, with the continuous increase of the number of fractal points, the matching rate value of the method in reference [7] continues to increase. When the number of data points is 100000, the correct matching rate value is about 85%. Under 100000 location points, the correct matching rate of the method in reference [6] is about 88%, while the correct matching rate of the design method in this paper is about 95% under the same number of location points. Compared with the two references, this model can correctly match the most fractal points.

The three approaches are regulated to process the same location file at the same time in the above experimental environment. After defining the same fractal points, when the return value of the definition method is 0, the fractal point position produces a certain error. When the number of return values of the three methods is 0, the three methods produce errors. The error results are shown in Table 5.

According to the position error results shown in Table 5, the position error generated by the method in reference [6] is 180~200 m, the position error of indoor and outdoor form fractal points in building space is the largest, the position error generated by the method in reference [7] is 120~150 m, the position error of indoor and outdoor form fractal points in actual building space is small, while the position error generated by the design method in this paper is 60~100 m, Compared with the two methods described in the literature, this method is the most accurate for the location of the fractal points of the indoor and outdoor morphology of the actual architectural space.

5. Discussion

The box dimension calculated in this paper is generally high, so the accurate basic data, calculation method, and software design algorithm should be optimized. This is due to the application of building scale data; its distribution is irregular, various types of buildings are scattered, and there is no specific height of buildings, so the accuracy of valuation by floors is not high. This makes the effect of rasterization not ideal; it is difficult to achieve box coverage, and the initial value cannot be displayed, but the horizontal and vertical comparison relationship between box dimension values is completely established, and the conclusion of this paper is tenable. Next, we should accurately process the basic data and supplement it with the optimization calculation formula method and the built-in

FIGURE 3: Test frame structure.

TABLE 4: Fractal point updating parameter results of three methods.

Serial number	Fractal point update parameter(%)		
	Reference [6] methods	Reference [7] methods	Method in this paper
1	43.1	63.4	81.2
2	48.1	66.7	81.5
3	43.8	66.2	80.9
4	42.7	79.8	83.1
5	45.6	64.2	81.8
6	48.4	60.5	84.6
7	46.9	63.7	82.5
8	43.4	68.1	80.2
9	40.5	61.5	83.9
10	46.4	77.1	84.6
11	49.7	79.5	83.4
12	42.4	75.1	80.5
13	42.6	66.8	82.7
14	49.3	62.2	81.5
15	49.3	75.7	84.6

algorithm in ArcGIS software so as to achieve the best coverage in fractal dimension calculation as much as possible.

Standardization of scale-free region recognition methods: the standard setting of index 0.5 in this paper has a certain subjective color. We can refer to the theories and methods of statistics, economics, and other related disciplines, and give a more objective standard combined with computer algorithms.

The improvement of the building data extraction method, as well as the accurate development of the building scale data model, and functional area type categorization basis: the data source's cellular automata model in this paper gives a good idea for building a three-dimensional model of indoor and outdoor space, but there is a discrepancy between the land use type planning of indoor and outdoor space, the type of functional area in the data, and the type of actual functional area, and

FIGURE 4: Correct matching results of three-position tracing models.

TABLE 5: Position error results of three methods.

Location file name	Position error (m)		
	Reference [6] methods	Reference [7] methods	Method in this paper
1	191	131	88
2	182	134	82
3	186	130	68
4	190	143	85
5	187	132	83
6	197	139	53
7	189	143	62
8	185	141	92
9	187	132	99
10	194	129	63
11	180	136	83
12	193	120	62
13	195	131	82
14	185	139	75
15	188	122	86

some plots are greatly divided, so the classified plots should be refined further.

Fractal dimension comparison of multibuilding indoor and outdoor space, a multitime node, and multimethod: the current research is only the box dimension data calculated by the local building data in a certain year. Various fractal dimension calculation methods, such as the radius method, can also be used to analyze the spatial structure of different time nodes in the same area so as to explore the fractal characteristics of indoor and outdoor forms of three-dimensional building space and their theory.

The validity of building data: in the process of the rapid expansion of indoor and outdoor space, there are a large number of practical problems associated with vacant buildings and multiple dwellings, which reduce the actual utilization rate of the building. In the next research, whether the economic parameters or quality expressing each unit or smaller scale can be introduced as a reference to measure the allocation and utilization of indoor and outdoor space will be the focus of the next research.

6. Conclusion

Indoor and outdoor architectural space forms are different when measured in different dimensions, and the structure measured in three-dimensional box dimensions is more realistic. The scale used in this paper, as well as the number of nonempty boxes it corresponds to, are consistent with the episodic relationship. The approach of automatic scale-free area identification by the second derivative is effective, and 95% of them can determine the existence of indoor and outdoor fractals of urban architectural space. The fractal structure of indoor and outdoor architectural space adheres to the idea of fractal dimension inclusion, and the surrounding area's architectural layout is more effective. The fact that the fractal dimension value continuously reduces indicates that the central spread mode is the building's indoor and outdoor space expansion. The degree of integration of the interior and outdoor function space in the Xibuwei building is lower than in the ancient urban area, and the functional spaces

are more concentrated, making it more suited for the functional construction of the building's indoor and outdoor space. This is because the inherent buildings in the old urban area are difficult to control, and there are some phenomena such as villages in the city, multiple address layouts, idle buildings, and so on. Therefore, the rationality of the spatial distribution of functional land is office > entertainment > leisure.

The overall box dimension of the fractal structure of the indoor and outdoor form of the building space is too high, the functional zoning of the building's indoor and outdoor space has to be optimized, and the building's indoor and outdoor space form is showing indications of degradation. On the one hand, the high fractal dimension value may be caused by the basic data, calculation methods, or application software built-in algorithms. However, as a geographic measure index, the most significant feature is comparability, which allows a comparison of values collected in the same scheme unquestionably possible. The high fractal dimension of indoor and outdoor space, on the other hand, reflects the fact that the building's indoor and outdoor space has become similar to the European geometric form, the spatial self-organization relationship is weak, and the distribution of indoor and outdoor space forms is too uniform, resulting in chaos and disorder. It also implies the problems of functional space disorder and disordered near-field expansion of indoor and outdoor space.

The fractal structure of indoor and outdoor architectural space can be used to weigh the intensive and orderly function of indoor and outdoor space with the active and stable development of a self-organizing comprehensive structure, allowing for a reasonable optimization of indoor and outdoor space spatial layout. We reconstruct the space allocation system based on functional zoning and the co-existence of relevant industries, as well as provide supporting logistics support, to improve overall service capacity and avoid excessive separation of indoor and outdoor space and functional space, particularly the separation of work and residence. At the same time, we should pay attention to the optimization and promotion of various types of space, and make it change from the original extensive and disorderly expansion to the development mode of intensive, orderly, and healthy connotation through internal integration. In addition to relying on the government's macrocontrol and guidance of the construction pattern, it also depends on the self-organization optimization of indoor and outdoor space, that is, more fine classification in each plot based on economic and living needs.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest with this study.

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