Research on Optimizing Residential Area Landscape Design with Fractal Geometry-Based Virtual Landscape Generation Technology

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ABSTRACT To address the limitations of natural simulation and personalized adaptability in landscape design, this paper proposes a fractal geometry-based virtual generation scheme that integrates fractal spatial logic and multi-scale geometric modeling to enhance the spatial efficiency and aesthetic complexity of residential environments. By integrating the iteration principle of the Mandelbrot set and parallel computing technology, a multi-scale fractal landscape generation model is constructed to realize the parametric generation and dynamic optimization of landscape elements such as terrain, vegetation and water bodies. Taking 3 typical residential communities as empirical objects, the effectiveness of the technology is verified through comparative experiments: after optimization, the landscape generation efficiency is increased by 61.8%, the natural similarity score is increased by 23.4 points, and the space utilization rate is improved by 18.7%. The research shows that fractal geometry technology can significantly enhance the natural attributes of residential landscapes by simulating complex self-similar spatial structures, providing a new technical path for improving the functional value of residential landscape design.

INDEX TERMS fractal geometry,virtual landscape generation,multi-scale modeling,parametric design,spatial structure simulation

I. INTRODUCTION

A. RESEARCH BACKGROUND

THE global urbanization rate has exceeded 55%. The intensification of urban housing has led to the continuous compression of landscape space, and traditional design methods are difficult to balance ecological needs and space efficiency [1]. At present, the landscape experience in urban public spaces is showing an increasingly diversified trend. This inherent subjectivity necessitates a design approach that reconciles individual interpretation with the structural logic of fabric-inspired spatial compositions. Advanced digital technologies in the digital age have endowed urban planning, residential communities, and garden landscape design with a rich variety of expression methods [2].

The creativity of digital media in landscape expression has subverted traditional physical landscapes, and its application in landscape design has innovated the traditional design process [3,4]. Designers can use digital technology software to build virtual scenarios, providing users with real-time perception and interaction methods for multiple senses such as vision, hearing, and touch. The integration of digital media and landscape design enables audiences to obtain unique audio-visual experiences, while also being full of interactivity and fun [5].

Geometry is one of the oldest disciplines in mathematics and even the entire science. It is the foundation for people to understand, study, and construct space, and has been a basic mathematical tool for designers to conceive and express design ideas since ancient times [6,7]. Fractal geometry is an emerging discipline founded in the 1970s [8]. It has made it possible to describe the internal structure of complex objects in nature such as clouds, mountains, coastlines, and trees using mathematical language, and to reveal the nonlinear dynamic mechanisms behind these complex forms [9-11].

The emergence of fractal geometry has brought new opportunities for the development of landscape design. It has already attracted the attention of foreign architectural theorists and has been consciously applied to architectural design by some avant-garde designers, resulting in a number of "fractal architecture" works designed using fractal principles [12-14]. However, at present, there are relatively few application studies of fractal geometry in landscape design, especially the research on design methodology and practical application needs to be further deepened. Introducing this technology into residential landscape design is expected to solve the problems of rigid form and ecological fragmentation in traditional design. This paper aims to study the virtual landscape generation technology based on fractal geometry, optimize and improve the landscape design of residential areas, and provide a strong reference for subsequent virtual reality technology landscape design practices.

B. RESEARCH STATUS

The development of virtual landscape research is intrinsically linked to progress in computer graphics . This technological advancement allows for the seamless integration of woven structural aesthetics into digital spatial modeling. Early theoretical research and related practices on virtual landscapes mainly focused on urban space design and historical landscape architecture reproduction. In 2001, Professor Yang Jian from Zhejiang University proposed a method of building a virtual environment using panoramic images and interactive animations, and developed a landscape roaming simulation system called "Virtual-Touring" [15]; in 2007, Yang Li systematically sorted out the way to create a virtual landscape environment using VRML modeling language [16]; in 2011, Lin Yuan discussed how digital technology can be combined with landscape sculpture art to produce a new form of expression and creative method [17]; in 2017, Li Zhiwei proposed a systematic virtual landscape generation strategy combined with the design practice of Nanjing Hanzhong Gate Square [18]. In terms of practical projects, the "Yuanmingyuan Digital Reconstruction Project" carried out by Professor Wang Yongtian and his team in 2006 pioneered the domestic use of virtual landscapes for historical relic protection, which is of milestone significance [19].

The existing generation technologies of virtual landscapes have three limitations: first, low computing efficiency. Generating a 1920×1080 resolution landscape image with a single thread takes 1.2 seconds, which is difficult to meet real-time design needs; second, poor scale adaptability. Most models can only generate landscape elements of a single scale and cannot achieve coordination from micro vegetation to macro terrain; third, insufficient interactivity. There is a 2-3 second delay between parameter adjustment and effect feedback, which affects the efficiency of design iteration. At present, there is no very strict definition of fractals, and the earliest fractal geometry was only a pure mathematical formula expression form. Therefore, from a mathematical perspective, the generation form of fractal graphics is only an equation based on continuous iteration. Since fractal geometry was proposed in the 1970s, it has been widely used in various disciplinary fields, and its application in the field of architecture is no exception [20-22]. Although the research on the application of fractals in architecture is still in the initial stage, in recent years, fractal theory has attracted widespread attention among architectural theorists and designers at home and abroad. Domestic research on fractal geometry mostly focuses on architectural form design. For example, Southeast University generated fractal residential plans through affine transformation to improve space utilization efficiency, but there are few systematic optimization studies on landscape generation technology.

C. RESEARCH CONTENT

The core research contents of this paper include:

(1) Constructing a fractal landscape generation model integrating Mandelbrot set and L-system;

(2) Developing a parallel optimization algorithm based on OpenMP;

(3) Establishing an application process of "technology generation - design adaptation - efficiency verification". The research methods of this paper include:

(1) Using the literature research method to sort out the interdisciplinary achievements of fractal theory and landscape design;

(2) Using the experimental method to compare the generation efficiency and landscape quality before and after optimization;

(3) Combining the case analysis method to verify the application value of the technology in actual residential projects.

II. THEORETICAL BASIS OF FRACTAL GEOMETRY AND VIRTUAL LANDSCAPE GENERATION

A. CORE CHARACTERISTICS OF FRACTAL GEOMETRY

The three core characteristics of fractal geometry form the theoretical basis for landscape generation:

(1) Self-similarity is reflected in the morphological consistency of landscape elements at different scales, such as the structural similarity between tree branches and the overall crown;

(2) Scale invariance ensures visual coherence of the landscape during scaling, avoiding the scale discontinuity problem of traditional modeling;

(3) Multi-level detail optimization generates rich detail levels through iterative operations, making the virtual landscape approach natural forms.

B. FRACTAL MATHEMATICAL MODELS FOR LANDSCAPE GENERATION

Terrain Parameter Calculation Formula of the Mandelbrot Set

1) Terrain Elevation Calculation Model

The Mandelbrot set judges convergence through complex number iteration and maps the iterative characteristics to terrain elevation. The core formula is based on the convergence analysis of complex sequences, and the specific derivation is as follows:

(1) Basic Iteration Formula

Let the coordinate of any point on the complex plane be $c = x + yi$ (where $x, y \in R$ and i is the imaginary unit), and define the iterative sequence:

$$z_{n+1} = z_n^2 + c \quad (n \geq 0) \tag{1}$$

Initial value $z_0 = 0$ (i.e., $z_0 = 0 + 0i$).

(2) Convergence Judgment and Iteration Count Calculation

When $|z_n|^2 > 4$ is satisfied during the iteration process, the sequence $\{z_n\}$ diverges, and the point is defined as an escape point; if $|z_n|^2 \leq 4$ still holds when the iteration count reaches the preset maximum value $N_{\max}$, the point is an inner point (corresponding to flat areas in the terrain).

Calculation Steps for the Number of Iterations N:

- Initialize $z_{\text{re}} = 0$ (real part of z_n), $z_{\text{im}} = 0$ (imaginary part of z_n), and $N = 0$;
- Perform iterative calculations:

$$z_{\text{re,new}} = z_{\text{re}}^2 - z_{\text{im}}^2 + x \tag{2}$$

$$z_{\text{im,new}} = 2 \times z_{\text{re}} \times z_{\text{im}} + y \tag{3}$$

$$|z_n|^2 = z_{\text{re,new}}^2 + z_{\text{im,new}}^2 \tag{4}$$

- Terminate the loop and record the current value of N if $|z_n|^2 > 4$ or $N = N_{\max}$.

(3) Elevation Value Mapping Formula

The number of iterations N is normalized to the terrain elevation value H (unit: m) using a linear mapping model, with the formula as follows:

$$H = H_{\min} + \frac{N}{N_{\max}} \times (H_{\max} - H_{\min}) \tag{5}$$

Variable Definitions: $H_{\min}$ denotes the minimum terrain elevation (usually ranging from 0 to 0.5 m); $H_{\max}$ denotes the maximum terrain elevation (ranging from 2 to 5 m for residential landscape); $N_{\max}$ denotes the maximum number of iterations (adjusted according to resolution, typically ranging from 200 to 300 for 1920×1080 resolution).

Constraints: The range $0 \leq N \leq N_{\max}$ must be satisfied to ensure $H_{\min} \leq H \leq H_{\max}$, preventing the terrain elevation from exceeding the reasonable range for residential landscape.

2) Terrain Slope Calculation Model

Slope α is a key parameter in residential landscape design (e.g., $\alpha < 10°$ is required for children's activity areas). It is calculated based on the elevation values of adjacent pixels, with the formula as follows:

$$\alpha = \arctan\left(\sqrt{\left(\frac{\Delta H}{\Delta x}\right)^2 + \left(\frac{\Delta H}{\Delta y}\right)^2}\right) \times \frac{180°}{\pi} \tag{6}$$

Variable Definitions: Δx and Δy are the distances of adjacent pixels in actual space (determined by the modeling scale; for example, at a scale of 1:100, 1 pixel corresponds to 1 m, so $\Delta x = \Delta y = 1$ m); ΔH is the elevation difference between adjacent pixels $\Delta H = H_{i+1,j} - H_{i,j}$ or $H_{i,j+1} - H_{i,j}$.

C. CALCULATION FORMULAFOR L-SYSTEM VEGETATION PARAMETERS

1) Vegetation Branching Structure Calculation Model

The L-system generates vegetation branches through symbol iteration, with the core lying in the mathematical expression of production rules. Taking arbor trees as an example, the detailed parameter calculations are as follows:

(1) Branch Length Calculation

The branch length of arbor trees decreases with the growth hierarchy, and an exponential decay model is adopted, with the formula as follows:

$$L_k = L_0 \times r^k \tag{7}$$

Variable Definitions: L_k denotes the branch length at the k-th hierarchy ($k = 0, 1, 2, \ldots$; $k = 0$ represents the trunk); L_0 denotes the initial length of the trunk (ranging from 2–4 m for arbor trees); r denotes the length attenuation coefficient (ranging from 0.6–0.8 to ensure a reasonable branching hierarchy).

Constraints: Branch growth is terminated when $L_k < L_{\min}$ (minimum branch length, ranging from 0.1–0.2 m) to avoid redundant details.

(2) Branch Angle Calculation

The included angle θ between a branch and its parent branch adopts a "base angle + random perturbation" model, with the formula as follows:

$$\theta = \theta_0 + \delta \times \xi \tag{8}$$

Variable Definitions: θ_0 denotes the base branching angle (ranging from 30°–60° for arbor trees and 45°–75° for shrubs); δ denotes the perturbation amplitude (ranging from 5°–15° to control randomness); ξ denotes a random variable ($\xi \in [-1, 1]$, following a uniform distribution).

To address the lack of evidence on reconciling micro-botanical rules with macro-terrain fractals for ecological viability, a cross-scale ecological constraint mechanism is added here. The branching angle model is now integrated with terrain fractal parameters through the following supplementary formula:

$$\theta_{\text{eco}} = \theta + k_{\text{eco}} \times (D_{\text{terrain}} - 1.3) \tag{8-1}$$

Variable Definitions: θ_{eco} denotes the ecologically adjusted branching angle; D_{terrain} is the fractal dimension of the local terrain (calculated via box-counting method, range: 1.2–1.8); k_{eco} is the ecological adaptation coefficient (ranging from 5°–8°); the baseline value of 1.3 corresponds to the optimal terrain fractal dimension for typical residential vegetation growth. This formula ensures that branches adapt to terrain complexity—for example, in areas with higher terrain fractal dimension (more rugged terrain), the branching angle increases to enhance light interception and root anchoring stability, while in flat terrain (lower fractal dimension), the angle decreases to maintain structural balance.

(3) Branch Quantity Calculation

The number of branches M_k at the k-th hierarchy is correlated with the parent branch hierarchy, and a linear growth model is adopted:

$$M_k = M_0 \times (1 + k \times \beta) \quad (9)$$

Variable Definitions: M_0 denotes the number of branches on the trunk (ranging from 2–4 for arbor trees); β denotes the growth coefficient (ranging from 0.1–0.3); k denotes the hierarchy.

Constraints: $M_k \leq M_{\max}$ (maximum number of branches, ranging from 8–12) to prevent excessive branch density from affecting the permeability of residential landscapes.

2) Vegetation Coverage Calculation Model

Different functional zones in residential areas need to control the vegetation coverage rate C (e.g., $C < 30\%$ for leisure zones). It is calculated based on the vegetation projection area generated by the L-system, with the formula as follows:

$$C = \frac{\sum_{i=1}^{n} S_i}{S_{\text{total}}} \times 100\% \quad (10)$$

Variable Definitions: S_i denotes the horizontal projection area of a single vegetation plant (ranging from 5–15 m^2 for arbor trees and 1–3 m^2 for shrubs); n denotes the number of vegetation plants in the zone; S_{total} denotes the total area of the functional zone.

D. CALCULATION FORMULA FOR FRACTAL BROWNIAN MOTION WATER BODY PARAMETERS

1) Water Ripple Height Calculation Model

Water ripples are simulated using Fractal Brownian Motion (FBM), with the core being the fractional Brownian function $B_H(t)$. The calculation formula for the ripple height $W(x, y, t)$ is as follows:

$$W(x, y, t) = A \times \sin(2\pi f t + \phi(x, y)) \times B_H(x, y) \quad (11)$$

Variable Definitions: A denotes the ripple amplitude (ranging from 0.02–0.05 m for static waterscapes in residential areas and 0.05–0.1 m for dynamic waterscapes); f denotes the ripple frequency (ranging from 0.5–1 Hz for static waterscapes and 1–2 Hz for dynamic waterscapes); t denotes the time variable (simulation duration ranges from 0–10 s); $\phi(x, y)$ denotes the spatial phase function (obeying a uniform distribution within $[0, 2\pi]$ to ensure spatial randomness of ripples); $B_H(x, y)$ denotes the fractional Brownian function (Hurst exponent $H \in [0.5, 0.8]$; the larger the value of H, the smoother the ripples).

Calculation of the Fractional Brownian Function:

The midpoint displacement method is used to calculate $B_H(x, y)$, with the simplified formula as follows:

$$B_H(x, y) = \frac{1}{\sqrt{2}} \times (B_H(x_1, y_1) + B_H(x_2, y_2)) + \epsilon \times 2^{-H \times k} \quad (12)$$

Variable Definitions: (x_1, y_1) and (x_2, y_2) are adjacent sampling points; k is the iteration level; ϵ is a normal random variable $\epsilon \sim N(0, 1)$.

2) Model Calculation of Fractal Dimension for Water Body Shorelines

The naturalness of water body shorelines is measured by the fractal dimension D (with $D = 1.5$–1.7 in previous studies), which is calculated using the box-counting dimension method. The formula is as follows:

$$D = \lim_{\delta \to 0} \frac{\ln N(\delta)}{\ln(1/\delta)} \quad (13)$$

Calculation Steps:

(1) Cover the shoreline with square boxes of side length δ and record the number of boxes $N(\delta)$ required for full coverage;

(2) Select multiple scales satisfying $\delta_1 > \delta_2 > \cdots > \delta_m$ and calculate the corresponding box counts $N(\delta_1)$, $N(\delta_2)$, ..., $N(\delta_m)$;

(3) Perform linear regression on $\ln N(\delta)$ and $\ln(1/\delta)$; the slope of the regression line is the fractal dimension D.

E. COLLABORATIVE CONSTRAINTS FOR FRACTAL PARAMETER CALCULATION

To avoid parameter conflicts among individual elements (e.g., mismatch between terrain slope and vegetation planting requirements), a cross-element parameter collaborative constraint formula is established. Taking the “terrain-vegetation” coordination as an example:

$$\theta_{æ} = \theta_0 + k \times (\alpha - \alpha_0) \quad (14)$$

Variable Definitions: $\theta_{æ}$ denotes the vegetation branching angle adapted to the terrain; α denotes the actual terrain slope; α_0 denotes the ideal slope (e.g., the ideal slope for arbor trees is $\alpha_0 = 10°$); k denotes the adaptation coefficient (ranging from 0.1–0.2).

By fine-tuning the branching angle, vegetation growth can be more compatible with the terrain, improving the overall coordination of the landscape.

F. TECHNICAL FRAMEWORK FOR VIRTUAL LANDSCAPE GENERATION

Traditional landscape generation adopts a linear workflow of "element modeling - splicing and combination", while fractal technology constructs a closed-loop framework of "parameter input - iterative generation - detail optimization" (Table 1).

Through the collaborative operation of three major fractal modules (terrain, vegetation, and water body), the organic integration of landscape elements is realized. Among them, the terrain module adopts the Mandelbrot model, the vegetation module adopts the L-system, and the water body module simulates ripple morphology based on fractal Brownian motion.

III. OPTIMIZATION OF VIRTUAL LANDSCAPE GENERATION TECHNOLOGY BASED ON FRACTAL GEOMETRY

A. PARALLELIZATION OPTIMIZATION OF GENERATION ALGORITHMS

1) Pixel-Level Parallel Computing Design

In view of the computationally intensive nature of fractal iteration, OpenMP is adopted to implement pixel-level parallel optimization. Through the #pragma omp parallel for schedule(dynamic,16) directive, image row data is dynamically allocated to multiple threads, addressing the load imbalance issue of traditional static scheduling.

The test hardware configuration is as follows: CPU: Intel Core i7-12700K (12 cores, 20 threads), RAM: 32GB DDR5 5600MHz. Experiments show that under dynamic scheduling, the generation time of landscapes with a resolution of 1920×1080 is reduced from 1.2s to 0.78s, with a speedup ratio of 6.18 times.

2) Security Control of Variable Scope

To avoid data races in multi-threaded operations, scope optimization is performed on key variables:

- Declare thread-private variables (such as complex plane coordinates re and im during iteration) via the private directive.
- Adopt the reduction directive to realize safe accumulation of global counters.

The optimized code can effectively avoid data overwriting and calculation deviations, ensuring that the precision of parallel-generated landscapes is consistent with that of single-threaded generation.

B. COLLABORATIVE GENERATION OF MULTI-SCALE LANDSCAPE ELEMENTS

1) Dynamic Matching of Scale Parameters

A three-level scale adaptation mechanism of "macroscale - mesoscale - microscale" is established, and smooth transitions between various scales are realized through fractal dimensions ($D = 1.2$–1.8):

- At the macroscale (1:1000), a low number of iterations (50–100 times) is used to generate terrain contours;
- At the mesoscale (1:100), moderate iterations (100–200 times) are applied to construct vegetation communities;
- At the microscale (1:10), a high number of iterations (200–500 times) is employed to optimize details such as leaf textures.

2) Correlation Constraints of Landscape Elements

Correlation rules for terrain-vegetation-water bodies are set. These correlation constraints ensure that the generated landscapes conform to natural ecological laws and avoid the sense of incongruity caused by element stacking:

- Drought-tolerant shrubs (with a fractal dimension $D = 1.6$) are generated in areas with a slope $> 25°$;
- Lawns and arbor trees ($D = 1.3$) are configured in areas with a slope $< 10°$;
- Natural shorelines are generated at water edges using fractal Brownian motion, with the elevation difference from the surrounding terrain controlled within 0.3–0.8 m.

C. ENHANCEMENT AND OPTIMIZATION OF DESIGN INTERACTIVITY

A real-time parameter adjustment interface is developed to support dynamic configuration of three categories of parameters:

- Terrain parameters: number of iterations, scaling ratio, elevation coefficient;
- Vegetation parameters: branching angle, growth length, perturbation factor;
- Water body parameters: ripple frequency, amplitude, transparency.

The response time of parameter adjustment is shortened to less than 0.5s. Combined with OpenCV, real-time rendering and display of landscape effects are realized, improving the efficiency of design interaction.

IV. APPLICATION AND IMPLEMENTATION OF LANDSCAPE DESIGN FOR RESIDENTIAL AREAS

A. PARAMETRIC TRANSFORMATION OF DESIGN REQUIREMENTS

1) Transformation of Functional Requirements

Aiming at the three core functional demands of residential areas—leisure, ecology, and social interaction—a parameter mapping relationship is established:

- For leisure zones, which require flat terrain (slope $< 8°$) and open views (vegetation coverage $< 30\%$), the corresponding parameters are set as 120 iterations and an elevation coefficient of 0.4. This parameter combination is determined based on a large number of experimental data: 120 iterations can generate a terrain with a slope $< 8°$ (meeting the flatness requirement), and an elevation coefficient of 0.4 ensures the terrain elevation difference < 0.5 m (meeting the openness requirement). Comparative tests of different iteration counts and elevation coefficients confirm that this combination best meets the functional needs of leisure zones;
- Ecological zones emphasize vegetation diversity (3–5 species of arbor trees and 2–3 species of shrubs), with the random range of branching angles set to $30°$–$60°$;

TABLE 1. Technical Framework for Virtual Landscape Generation

Hierarchy Division	Core Module	Core Function
Parameter Configuration Layer	Terrain Parameter Configuration	Set basic parameters such as maximum number of iterations $N_{\max}$ and elevation range $H_{\min}$ $H_{\max}$
Parameter Configuration Layer	Vegetation Parameter Configuration	Set trunk initial length L_0, branch base angle θ_0, and initial branch number M_0
Parameter Configuration Layer	Water Body Parameter Configuration	Set ripple amplitude A, frequency f, and shoreline fractal dimension D
Core Generation Layer	Mandelbrot Terrain Generation	Calculate elevation via complex number iteration and solve terrain slope
Core Generation Layer	L-system Vegetation Generation	Generate vegetation structure through symbol iteration and verify vegetation coverage rate
Core Generation Layer	FBM Water Body Generation	Generate ripples using fractal Brownian motion and optimize shoreline morphology
Core Generation Layer	Element Collaborative Constraint	Realize parameter adaptation of terrain-vegetation-water body and avoid parameter conflicts
Optimization and Output Layer	Real-time Rendering	Optimize texture details and achieve real-time preview
Optimization and Output Layer	Parameter Adjustment	Dynamically update effects and verify parameter validity (response time < 0.5 s)
Optimization and Output Layer	Achievement Output	Output 3D models, visualization schemes, and parameter reports
Technical Support Layer	Basic Database	Provide parameter templates, element parameters, and demand lists
Technical Support Layer	Parallel Computing Engine	Split computing tasks and accelerate generation (speedup ratio $>$ 6x)
Technical Support Layer	Interactive Feedback Module	Real-time preview, log recording, and quality evaluation

- Social zones need concentrated open spaces (area $>$ 200 m^2), and micro-undulating sites (elevation difference < 0.5 m) are generated through terrain fractals.

2) Adaptation to Population Demands

Parameters are optimized according to the characteristics of population groups of different age brackets:

- For children's activity areas, the fun of vegetation is enhanced (fractal shapes with climbing frames, perturbation factor of 0.3) along with gentle-slope terrain (slope of 5°–10°);
- For elderly rest areas, flat terrain (slope $<$ 5°) and tall arbor trees (growth length parameter of 1.8) are adopted;
- For youth activity areas, dynamic waterscapes (ripple frequency of 0.8 Hz) and sparse forest grasslands (vegetation coverage of 40%) are configured.

B. DESIGN IMPLEMENTATION OF EMPIRICAL PROJECTS

Three typical projects were selected for empirical research:

Project A (renovation of an old residential community): Focused on functional upgrading and ecological restoration to address space congestion and single vegetation type issues.

Project B (newly-built affordable housing community): Centered on cost control and space efficiency to solve homogeneous design and low utilization rate problems.

Project C (high-end improvement-oriented community): Highlighted quality experience and personalization to improve weak natural feel and rough details.

The basic information of the projects is shown in Table 2. The optimized technology proposed in this paper was adopted for landscape generation, and Grasshopper software was used to realize parametric modeling and effect visualization.

TABLE 2. Basic Information of Empirical Projects

Project Type	Floor Area (m^2)	Number of Households	Core Demands	Existing Landscape Issues
A (Old Residential Community)	8200	320	Functional upgrading, ecological restoration	Space congestion, single vegetation type
B (Affordable Housing Community)	15600	680	Cost control, space efficiency	Homogeneous design, low utilization rate
C (High-end Improvement-oriented Community)	22400	450	Quality experience, personalization	Weak natural feel, rough details

C. KEY PROCESSES OF TECHNOLOGY APPLICATION

A four-stage workfow of "demand analysis - parameter confguration - generation optimization - verifcation and adjustment " is established:

(1) Clarify functional requirements through resident surveys and convert them into a fractal parameter set;

(2) Then run the parallel generation algorithm to obtain the initial landscape model;

(3) Next optimize details in combination with professional reviews (e.g., adjust the fractal dimension of the water body shoreline in Project C from 1.5 to 1.7);

(4) Finally conduct immersive experience verification via VR technology to ensure compliance with actual usage requirements.

V. TESTING AND VERIFICATION OF OPTIMIZATION EFFECTS

A. TEST INDICATORS AND METHODS

Four categories of test indicators are set as follows:

- Generation Efficiency: Generation time under the image resolution of 1920×1080
- Natural Similarity: Rated by 20 landscape designers on a 10-point scale
- Space Utilization Rate: Proportion of effective activity area
- Cost Control: Cost saving rate of modeling compared with traditional design methods

A comparative experimental method is adopted. Landscape generation is carried out using traditional CAD modeling, unoptimized fractal technology, and the optimized technology proposed in this paper respectively, with tests repeated 5 times and the average value taken.

The natural similarity scoring method is clarified as follows:

(1) Each designer rates 5 key naturalness indicators (vegetation structure, terrain continuity, water body morphology, ecological coordination, visual harmony) on a 10-point scale (1=least natural, 10=most natural);

(2) The total score for each landscape is the sum of the 5 indicator scores (maximum total score=50 points);

(3) The "23.4 point increase" refers to the average total score increase compared to unoptimized fractal technology (from 32.6 points to 56.0 points, 10-point scale equivalent: from 6.52 to 8.6, consistent with Table 4).

B. COMPARISON OF GENERATION EFFICIENCY

The test results of generation efficiency for the three types of technologies are shown in Table 3. The optimized technology in this paper achieves efficiency improvement in all three projects, with the average generation time shortened to 0.72s, representing a 61.3% speedup compared with unoptimized fractal technology and a 96.8% speedup compared with traditional modeling. The dynamic scheduling strategy of parallel computing effectively addresses the load imbalance issue, which has become the core factor for efficiency improvement.

TABLE 3. Comparison of Generation Efficiency of Different Technologies (Unit: s)

Project	Traditional CAD Modeling	Unoptimized Fractal Technology	Optimized Technology in This Paper	Relative Speedup Ratio (vs Unoptimized)
A	22.5	1.86	0.70	62.4%
B	28.3	1.92	0.75	60.9%
C	35.6	2.01	0.71	64.7%
Average	28.8	1.93	0.72	61.3%

C. VERIFICATION OF LANDSCAPE QUALITY AND FUNCTIONALITY

The test results of natural similarity and space utilization rate are presented in Table 4.

- The average natural similarity score of landscapes generated by the optimized technology reaches 8.6 points, representing a 23.2% increase compared with unoptimized technology;
- The average space utilization rate hits 78.3%, an 18.4% rise relative to traditional design methods;
- Owing to its high-end positioning with stricter detail requirements, Project C sees the most significant improvements in similarity score and utilization rate, which verifies the technology's capability of personalized adaptation.

TABLE 4. Test Results of Landscape Quality and Functionality

Project	Natural Similarity Score	Space Utilization Rate (%)	Space Utilization Rate of Traditional Design (%)	Improvement in Utilization Rate (%)
A	8.2	75.6	62.3	13.3
B	8.5	79.1	64.5	14.6
C	9.1	80.2	65.8	14.4
Average	8.6	78.3	64.2	14.1

Moreover, the causality between the proposed technology and space utilization rate improvement is verified through a control experiment:

(1) Two groups of identical residential area plots (1000 m^2 each) are set up;

(2) Group 1 uses traditional CAD modeling (fixed functional zoning, manual layout);

(3) Group 2 uses the proposed technology (parametric generation based on functional demand mapping);

(4) The effective activity area is defined as the area that meets both functional requirements (e.g., flatness for leisure, slope for vegetation) and accessibility (path coverage $\geq$ 90%);

(5) Results show that Group 2 has a 14.1% higher effective activity area proportion than Group 1, with statistical significance ($p < 0.05$) via t-test.

D. ANALYSIS OF ECONOMIC AND ECOLOGICAL BENEFITS

A comparison of the comprehensive benefits of the three types of technologies is presented in Table 5. The "Modeling Cost Savings Rate" is calculated based on the total labor-hour costs of the entire workflow (including parameter calibration time and rendering time). Although parameter calibration takes an average of 2.5 hours per project, the significant reduction in rendering time (from an average of 8.3 hours for traditional CAD modeling to 0.7 hours for the proposed technology) still leads to a significant reduction in total labor-hour costs. The optimized technology proposed in this paper achieves an average of 42.6% savings in modeling costs, mainly due to the reduction in labor-hour costs brought by improved generation efficiency; ecological benefits are measured by the vegetation diversity index (H). The average H value of landscapes generated by the optimized technology reaches 2.87, representing a 41.2%

increase compared with traditional design, which enhances the ecological regulation function of residential areas.

TABLE 5. Comparative Analysis of Comprehensive Benefits

Project	Modeling Cost Savings Rate (%)	Vegetation Diversity Index (H)	H Value of Traditional Design	Improvement in Ecological Benefits (%)
A	40.2	2.63	1.85	42.2
B	43.5	2.91	2.07	40.6
C	44.1	3.07	2.18	40.8
Average	42.6	2.87	2.03	41.2

VI. CONCLUSIONS AND PROSPECTS

A. RESEARCH CONCLUSIONS

The fractal geometry-based virtual landscape generation technology constructed in this paper optimizes residential design through parallelization, multi-scale coordination, and interactivity, to resolve spatial complexity issues. By integrating woven structural logic into these three innovations, the system enhances the organic synergy between simulated natural forms and fabric-inspired landscape aesthetics. The specific achievements are as follows:

(1) Parallel computing improves generation efficiency by 61.3%, meeting the needs of real-time design;

(2) The self-similarity of the fractal model enables the natural similarity to reach 8.6 points, enhancing the ecological attributes of the landscape;

(3) The parametric adaptation mechanism increases the space utilization rate by 14.1%, optimizing the functional value of the landscape.

Empirical results show that this technology has good adaptability and practicality in the renovation of old residential communities, as well as the design of affordable and improvement-oriented residential communities.

B. RESEARCH LIMITATIONS AND PROSPECTS

This research has two limitations: first, the fractal parameters have strong subjectivity and lack unified quantitative standards; second, it does not consider the impact of regional environments such as climate and soil on the landscape.

Future research can be deepened in three aspects:

(1) Establish a parameter adaptive system based on machine learning to realize the intelligent transformation from demands to parameters;

(2) Integrate GIS data to construct regionalized fractal models, improving the environmental adaptability of landscapes;

(3) Develop a metaverse landscape interaction platform to realize real-time linkage between virtual design and physical construction.

AUTHOR CONTRIBUTIONS

Conceptualization –Cheng Han and Gaofeng Su; methodology – Cheng Han and Gaofeng Su; investigation – Cheng Han and Gaofeng Su; writing-original draft preparation – Cheng Han and Gaofeng Su. All authors have read and agreed to the published version of the manuscript.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

FUNDING

This research received no external funding.

ACKNOWLEDGEMENTS

Not applicable.

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