RoadNetOpt

A street network optimization tool for urban sustainability

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With the deepening of urban renewal, urban design faces increasingly complex spatial conditions and diverse demands. Promoting sustainability and fairness has become a core goal. Although various digital tools for street design have emerged, most rely on top-down logic and lack parameter flexibility, making them unsuitable for old blocks with complex, dynamic structures. These tools also limit designers' participation and value expression during generation. To address the inefficiency of manual design and the lack of feedback in existing tools, this study proposes a framework for street network generation based on parameterized rules and multi-objective optimization. The framework integrates axis extraction, indicator evaluation, and genetic algorithm optimization, enabling designers to adjust weights and enhance human-computer collaboration and contextual adaptability. Thirty typical blocks in Chinese cities are selected for testing. A nine-indicator evaluation system is constructed, and the entropy weight method is used to determine weights. It also explores differences in network outcomes under different optimization objectives. The final optimization results are compared with manual and original schemes. Results show that the computer-generated schemes have certain advantages in maintaining spatial coherence and improving network accessibility. While reducing redundancy, they enhance overall efficiency, offering feasible design support for optimizing street networks in complex urban environments.

Keywords: *Generative Design, Urban Renewal, Street Network, Design Tool.*

INTRODUCTION

Cities are experiencing a wave of digitalization, and the development and application of digital tools are influencing cities to move towards a knowledge-based future (Ferré-Bigorra et al., 2022). The 2022 United Nations report pointed out ("World Cities Report 2022," n.d.) that cities should improve design capabilities and the application of digital tools, especially in the development of small and emerging cities, emphasizing the sustainability in the process of urban-rural collaboration (Balogun et al., 2020). Generative urban design has become an important research direction in the field of urban design, especially in the process of exploring solutions to complex urban forms (Jiang et al., 2024). It can incorporate the needs and preferences of stakeholders in the initial design stage, making the solutions more adaptable and context sensitive.

As the skeleton structure of urban form, the street network plays a decisive role in the realization of regional functions and spatial organization. At present, the tool frameworks

used for computer-aided road network design can be divided into two categories: The first model based on rule constraints and explicit procedures, such as relying on geometric analysis (Koenig et al., 2013), shape grammars (Feng and Peponis, 2020), direction fields (Beneš et al., 2014) and parametric modeling (Molinero and Hernando, 2020) to generate street networks. The second category comprises data-driven approaches that learn from existing urban forms, such as deep learning methods using convolutional neural networks (Zhang et al., 2023), generative adversarial networks (Hartmann et al.,2017), and graph neural networks (Owaki and Machida, 2020). These methods are increasingly applied in scenarios related to road planning and the optimization of built environments.

This study proposes a street network optimization method based on generative design and multi-objective optimization and develops an interactive design tool. The study applied the tool to the old city renewal in Hexian County, Anhui Province, China, verified its optimizations of connectivity, consistency, complexity and conservation in renewal-required street networks, and compared and analyzed them with traditional methods. This study aims to provide a more adaptable and operational tool framework for street network optimization in urban renewal and explore the application potential of computer-aided design in refined and complex design scenarios.

BACKGROUND

The phenomenon of incoherent hierarchy, complex traffic relations, and lack of street vitality has emerged alongside the rapid development of urban areas (Barrington-Leigh and Millard-Ball, 2019). The spatial pattern of China's historical areas has experienced a process from organic growth to fragmentation and chaos, and then to regular reconstruction, making it present the characteristics of diversity, hybridity and staged differentiation. The spatial structure of these areas is not a one-way shaping from top to bottom but is gradually formed from bottom to top through long-term accumulation, forming a complex adaptive system with a multi-level structure (Song, Zhang and Han, 2022).

Take the road network of Hexian County, Anhui Province as an example. The street network has undergone a significant historical evolution process: from the continuation of the texture of ancient traditional streets and lanes, to the drastic transformation of the scale and structure of the street network under the "giant land use" model under the background of the public land system, and then to the repair, reconstruction and optimization of the existing street network in the process of incremental construction and stock renewal in the market economy stage. Due to the protection of historical and cultural elements, the boundaries of property plots, the existing reserved blocks, rivers and other factors, the problems of uneven street density, narrow road width and many dead-end roads in the historical urban area are particularly obvious.

In traditional manual update practices, designers must conduct on-site surveys and data collection, relying on personal experience to identify potential alleys with passable conditions within the intricate existing site conditions. Subsequent models such as Axis Map, sDNA, UNA, and Segment Map have provided a methodological foundation for quantitative analysis (Zheng et al., 2024), with the scope of analysis expanding from material-level geometric and topological characteristics to functional density, neighborhood vitality, street green view ratio, and other indicators in the social, cultural, and economic domains (Mao et al., 2021). Early ArcGIS was a representative of procedural tools that could systematically generate highways and streets based on land-water boundaries and population density (Parish and Müller, 2001). City Engine uses L-system to generate extended street networks using manually defined block rules and

street network patterns (Galin et al., 2010). Some algorithms have been directly integrated into Grasshopper plug-in tools, such as Decoding Spaces Toolbox (Koenig et al., 2013b) provides a Street Network Generation module with analysis, visualization, and geometry processing tools. However, the current design tools have the following challenges:

- Responsiveness: the generation logic is predominantly top-down, overlooking micro-scale, mixed-use, and incremental development characteristics, which limits the tool's responsiveness to complex spatial patterns in historical districts.
- Interpretability: the evaluation method lacks contextual sensitivity, making it difficult to integrate quantitative indicators with designers' subjective insights, thereby weakening the adaptability and interpretability of optimization outcomes in complex renewal scenarios.
- Participation: the generation tool lacks an interactive feedback mechanism, hindering designers' ability to participate in and guide the optimization process, and reducing the fairness and controllability of human-centered decision-making.

Addressing these challenges requires a paradigm shift toward more flexible, context-aware, and Participatory design methodologies, particularly for historically layered urban environments.

METHODOLOGY

This study constructs a comprehensive methodology encompassing four interrelated components. First, it introduces a parameterized technique for extracting street axes that can adapt to diverse morphological patterns within varied block structures. Building upon this, it establishes a set of nine street network indicators derived from Chinese traditional districts using the entropy weighting method. Subsequently, the study develops an optimization model specifically tailored for the renewal of historic urban districts. Utilizing a genetic algorithm, the model supports the automated restructuring and morphological evolution of street networks. Finally, the methodology incorporates an interactive design platform that integrates visualization, indicator-based feedback, and parameter control, allowing designers to adjust preference weights in real time and facilitating iterative collaboration within practical regeneration scenarios.

Evaluation Construction

In constructing an evaluation framework for aging urban districts, this study draws upon multidimensional assessment principles proposed in urban morphology, historic district conservation theory, and space syntax research. (Zheng et al., 2024). The selected indicators cover three fundamental aspects of the street network: spatial structure, network performance, and morphological distribution. A set of nine indicators is developed, organized around four core dimensions: Conservation, Connectivity, Coherence, and Complexity, to comprehensively assess the spatial characteristics and renewal potential of traditional street networks:

• Conservation focuses on the preservation of spatial patterns within historic districts, examining how to retain topological and geometric features during regeneration. This is measured by Axial Continuity (AC) and Path Diversity (PD), which reflect the compatibility between spatial axes and historical textures.

• Connectivity addresses the accessibility of the street network and includes Street Density (SD), Network Density (ND), and Node Density (NoD) to capture different levels of spatial reach and integration.

• Coherence investigates the internal order and continuity of the network, using Permeability (PA) and Street Efficiency (SE) to evaluate the completeness of spatial hierarchies and structural flow.

• Complexity explores the adaptability and flexibility of the network layout, aiming to avoid

Index	Street Density	Network Density	Axial Continuity	Street Bearing
Formulation	$\mathbf{SD} = \frac{L}{A}$	$\mathbf{ND} = \frac{E}{A}$	$\mathbf{AC} = \frac{L_{\text{mean}}}{N}$	$\mathbf{SB} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(b_i - \bar{b})^2}$
Path Diversity	**Permeability**	**Topology Depth**	**Street Efficiency**	**Node Density**
$\mathbf{PD} = \frac{1}{\lvert E\rvert}\sum_{(u,v)\in E} P(u,v)$	$\mathbf{PA} = \frac{\sum_{i\in V}\deg(i)}{N}$	$\mathbf{TD} = \frac{\sum_{i\in V}\sum_{j\in V}\text{steps}(i,j)}{N}$	$\mathbf{SE} = \frac{\sum_{i\in V}\sum_{j\in V} d(i,j)}{N}$	$\mathbf{NoD} = \frac{N}{A}$

Table 1
Nine indicators and formulas

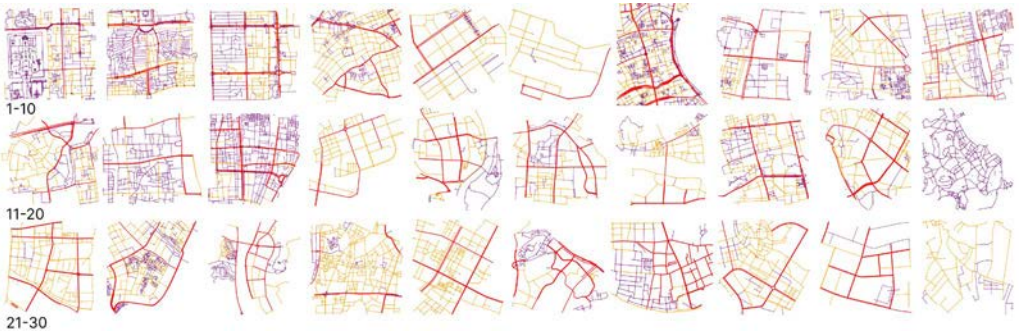

Figure 1
30 street block samples of Chinese officially designated historic and cultural districts

overly uniform interventions. It is represented by Topological Depth (TD) and Street Bearing (SB), indicating directional richness and configurational variety.

To ensure the reliability and representativeness of the evaluation system, this study selects 30 cities from the first batch of Chinese officially designated Historic and Cultural Districts, published by the Ministry of Housing and Urban-Rural Development in 2015 (Wikipedia, n.d.). These traditional districts have undergone various degrees of renewal over the past decade, providing a valuable empirical foundation for building a generalizable indicator system. Street network data were sourced from the open-source platform OpenStreetMap, and each sample was defined as a 1,000m × 1,000m patch. In total, 30 street block samples were extracted, and values for all nine indicators were computed.

All indicator calculations were implemented within a customized C#-based computational graphics library, enabling seamless integration with visualization and evaluation tools. To determine the weights for the multi-objective fitness function, normalization intervals were defined for each indicator based on theoretical knowledge and expert input. The indicators were then standardized, and the entropy weighting method was applied to compute the final entropy weight matrix:

$$W = [\omega_{SD,}\omega_{ND}, \omega_{AC}, \omega_{SB}, \omega_{PD}, \omega_{PA}, \omega_{TD}, \omega_{SE}, \omega_{ToD}]$$

$$W = [\,0.16, 0.15, 0.10, 0.08, 0.05, 0.03, 0.10, 0.09, 0.23\,] \quad (1)$$

Axial Line Extraction

This study combines axis generation (Li, Ma and Li, 2016) with the Delaunay triangulation algorithm (Liu, C. et al., 2016) to explore an innovative axis generation strategy. This strategy extracts axes from complex convex polygons. Its core concept is to use the connection of the midpoints of adjacent edges instead of the traditional triangle center point connection method to construct the skeleton. On this basis, the axis screening method and design rule constraints are used to screen and optimize, to obtain a preliminary solution set of road networks

that meet the basic rule requirements in the selected plot (refer to figure 2).

Analyzing complex site conditions, this study uses the drawing exchange format (DXF) as the main data carrier. The program needs to extract three types of key data from the imported DXF file: building outlines, impassable areas and existing regional road network structures. Based on the block partitioning theory (Marshall, 2004), the urban spatial element map is divided into independent block units, each of which has a set of spatial attributes specific to street network generation. Users can customize road nodes to divide block units or use the program to automatically identify block units. By removing buildings and impassable areas within each unit, continuous vacant spaces are delineated.

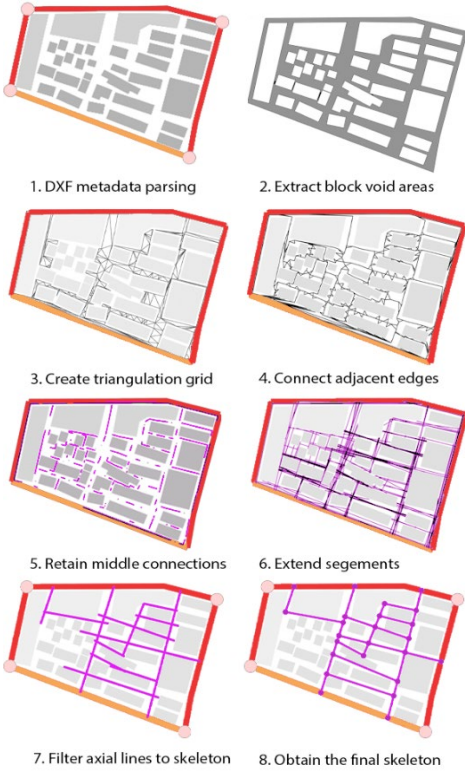

Figure 2
Explanation of axis extraction process

To accommodate varying setback distances during urban renewal, it treats buildings within the same property parcel as a unified base unit. These are used to generate convex polygons for Delaunay triangulation, from which a basic point set is derived. The point set is extended into axial lines, producing an initial axial map that aligns with the existing street morphology. To ensure compliance with geometric logic and road design standards, the generated axial lines are refined through a two-stage process: noise reduction and rationality filtering.

In the first stage, geometric noise is minimized via similarity and length-based filtering. This is followed by a comprehensive refinement based on four adjustable rules: angle thresholding, intersection avoidance, isolation detection, and proximity filtering. All parameters are user-defined to accommodate varying site conditions. After extracting, splitting, and deduplicating intersections, the resulting axial network achieves high connectivity and planning compliance, providing a robust foundation for subsequent optimization and extension.

Genetic Algorithm

This study uses the Genetic Sharp framework to implement a multi-objective genetic algorithm. Users can customize the maximum and minimum population size according to their needs. When initializing the population, each chromosome represents a potential road network configuration scheme. The genetic code on everyone corresponds to a minimum generation block, and its storage content is the axis result of the block. As shown (refer to figure 3), this study proposes the following genetic algorithm encoding scheme:

- Chromosome encoding structure: where Gi represents the i gene, corresponding to a block unit, and n is the number of block units in the population;

$$RoadChromosome = \{G1, \dots, Gn\} \qquad (2)$$

- Gene structure definition: The coding of each gene is specifically expressed as:

$$Gi = (Li, Fi, Bi),$$
$$Li = \{Li1, Li2, \ldots, Lim\} \quad (3)$$

Wherein Li: represents the state of the axis in the block unit, m is the number of axes contained in the generated unit; Fi: fitness score, used for fitness evaluation; Bi : Boolean flag, used to determine whether the block unit participates in the optimization calculation;

- Fitness function definition: The fitness function in the genetic algorithm is constructed based on the indicators in Evaluation Construction. Convert the above indicators into a scoring function.

$$F = \omega_1 \cdot X_1^{norm} + \ldots + \omega_9 \cdot X_9^{norm} \quad (4)$$

Finally, the street configuration scheme with the highest fitness, Best Chromosome, is output according to the default number of iterations or the number of iterations customized by the user.

- Fitness Evaluation of Computational Units: To improve efficiency, the system employs parallel computing. Each unit is initialized with a copy of the map data and independently performs street network analysis and evaluation. A locking mechanism ensures synchronization and consistency across units.

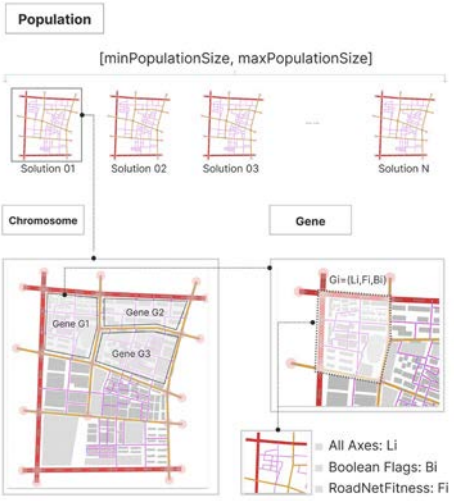

Figure 3
Genetic algorithm coding

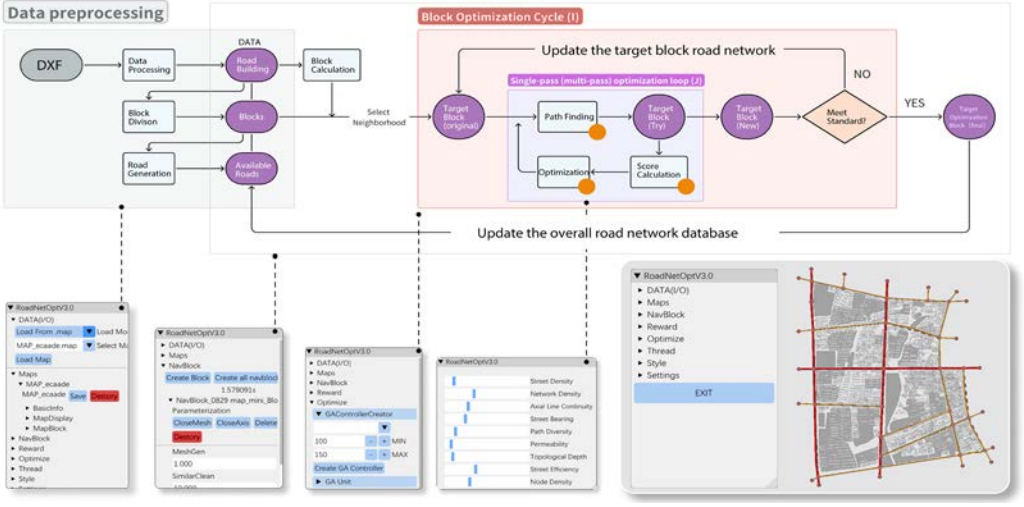

Figure 4
Optimization framework and interactive flowchart

User Interactive

The interactive interface is built on the GUI platform of the Unity engine and uses the HCL (Human-Computer Interaction) framework to provide designers with professional interactive tools in the early design stage (refer to figure 4). The tool includes the following core interactive contents:

Users can upload vector map data to define the target area for optimization. The system then generates an initial street network based on axis extraction rules, allowing users to adjust parameters and make custom modifications through an interactive GUI. Road network optimization is carried out by adjusting index weights to produce multiple alternative solutions. The generated outcomes can be evaluated and visualized to assess their effectiveness. This interactive workflow integrates automated computation with user input, enhancing the flexibility and controllability of the design process.

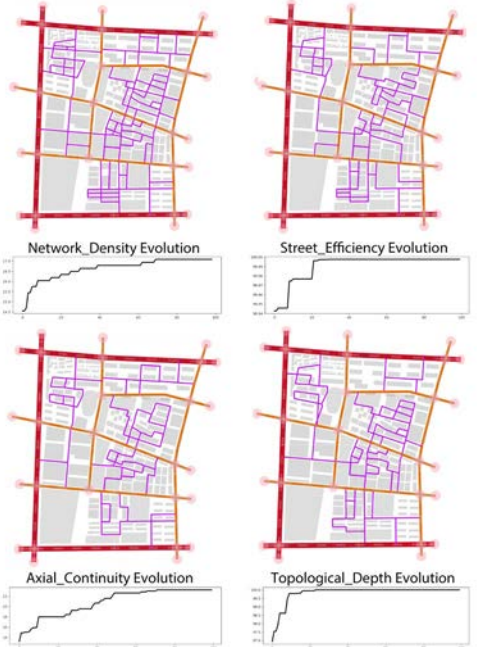

Figure 5
Results for the four individual indicators and iterative curves

IMPLEMENTATION

The experiment relies on the Unity platform and uses the C# programming language to implement the calculation process of various optimization indicators. The experimental parameters are set as follows: the population size is 50, the number of iterations is 100, the mutation rate is 0.25, and the crossover rate is 0.75.

Analysis of Weight Sensitivity

This experiment investigates how different weight configurations in the objective function influence the generative outcomes of street networks, with the aim of validating the feasibility and necessity of interactive weight adjustment. By assigning maximal weight to individual indicators, the study compares street generation behaviors under four distinct dimension-led priorities. The experiment was conducted on a simplified and boundary-defined virtual site, using four representative indicators: Axial Continuity (Conservation), Network Density (Connectivity), Street Efficiency (Coherence), and Topological Depth (Complexity). The running time for each axial extraction was 1.5 seconds, with a total optimization iteration time of 197 seconds.

The experimental results indicate that when optimizing network density, the evolutionary process progresses slowly yet steadily, producing more secondary streets that connect major roads and increasing local spatial coverage and overall structural density. When targeting street efficiency, the optimization converges rapidly in early generations, yielding smoother street layouts with stronger accessibility. Optimization is based on axial continuity results in a staircase-like evolutionary curve, generating longer continuous main axes with fewer internal branches. In the case of topological depth, initial improvement is rapid, but the overall range of change is limited; the resulting networks exhibit dense intersections and compressed average access distances through more direct and interwoven street connections.

Figure 6
Original, manual, and computed street networks of Hexian

	SD	ND	AC	SB	PD	PA	TD	SE	NoD
Original Street	6.842	49.550	138.089	57.099	2.038	2.551	7.495	233.853	38.797
Manual Design	7.368	45.544	161.789	55.288	2.718	2.842	7.664	193.015	32.049
Computed Design	9.490	96.992	97.842	55.594	2.580	2.949	11.760	394.233	65.786

Table 2
Comparison of nine indicators

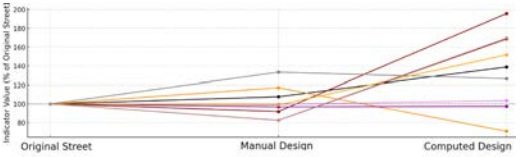

Figure 7
Relative change of indicators compared to original street

Case Application to Hexian County

This experiment aims to test the adaptability of the constructed generation and optimization framework in real blocks and evaluate its performance differences with manual design schemes in multiple performance indicators. Through field application and multi-indicator comparison of historical blocks, the generalization ability and local refinement of the method in complex urban contexts are verified. The experimental data comes from the old blocks in Hexian County, Anhui Province, and 10 sample areas are selected for optimization experiments. Under the initial weight combination, the experiment first examines the convergence behavior of optimization. The optimization process tends to be stable between the 70th and 80th generations, and the fitness value reaches a balanced state.

By comparing the original road network, the manually designed layout, and the algorithm-generated results (refer to figure 6, Table 2), it shows that the computed design successfully

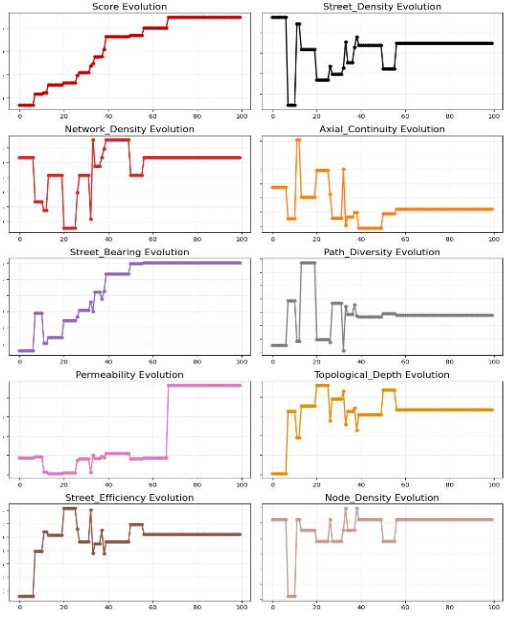

Figure 8
Convergence trends of metrics scores

reproduces the overall structural intent of the manual design while demonstrating superior performance across multiple key dimensions. For instance, it achieves varying degrees of improvement in eliminating dead-end streets, increasing network density and street efficiency, and reducing directional disorder. In terms of local connectivity and path organization, the manual design tends to prioritize straightened axial lines and visual regularity, whereas the computational approach places greater emphasis on path diversity and permeability, often introducing more branch streets to enhance spatial accessibility. Additionally, the computational model provides more precise control over street access points, enabling finer-grained and more rule-compliant network configurations.

From the iteration curves of the nine performance indicators and the total score (refer to figure 8), it can be observed that network density fluctuates significantly but eventually stabilizes, indicating the need to balance trade-offs between this and other objectives during the optimization process. Road diversity shows dramatic changes in the early stages but tends to stabilize in the middle and later stages, suggesting that the algorithm explores different structural combinations at first and maintains consistency after identifying relatively stable forms. Street orientation and integration exhibit clear step-like improvements in the later stages of iteration, indicating significant progress in these two dimensions during the optimization process.

CONLUSION

This study developed a parametric, multi-objective street network generation framework tailored to the complex requirements of urban renewal. By integrating axis extraction, multi-index evaluation, and genetic algorithm optimization, the tool enhances computational efficiency and local precision control. Through parameter tuning and interactive feedback, designers can dynamically guide outcomes during optimization. Compared to the original and manual designs, the optimized solutions show improvements in spatial coherence, connectivity, and overall efficiency.

However, the limitations remain current implementation do not fully account for road grade and width differences, parameter interdependence may cause instability under constraints, and computation time remains high for large-scale cases.

Future research will focus on improving runtime efficiency, parameter coupling, and road semantic integration to enhance adaptability to urban renewal. Beyond computational optimization, the framework also aims to support multi-stakeholder participation. By integrating object-oriented interaction and collaborative editing, policymakers, designers, and community members can engage in real-time dialogue and joint decision-making during renewal processes, evolving the tool into an open, inclusive, and sustainable urban design platform.

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