Research Paper

Construction and Empirical Research on the Optimization Strategy of Urban Green Space Pattern for Noise Prevention and Control

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Abstract

With the acceleration of global urbanization, noise pollution has become a key issue affecting the physical and mental health of urban residents, restricting the improvement of urban spatial quality and hindering the sustainable management of urban environment, which needs to be effectively treated from the planning level. Urban green space can highly adapt to the characteristics of the city, and its spatial layout is easy to adjust and plan, so the green space pattern plays a key role in the prevention and control of noise pollution and the improvement of urban acoustic environment. Although previous studies have shown theoretically that the spatial allocation of urban green space has greater noise reduction benefits than the area and shape of urban green space, there is still a lack of empirical research on the difference of noise distribution before and after the adjustment of green space pattern and its noise reduction effect.

Based on this, this study aims to explore how to use the limited urban green space to play a greater noise reduction benefit. The core issues include: what is the impact mechanism of urban green space pattern on noise distribution? How to propose the adjustment mode of green space pattern optimization based on the results of impact mechanism? How to verify the noise attenuation effect of green space pattern adjustment? Finally, the green space pattern optimization strategy with noise reduction effect is proposed. The research results will provide a solid theoretical basis and practical reference for the important issue of green space pattern optimization process and effect evaluation for noise control.

*In this study, the 2km * 2km area of Lyon center in France was selected as the research sample. The geographic information data and noise data were obtained from the OSM and noise planet platforms respectively. After dividing into 50m * 50m grid units, the noise distribution was simulated by Cadna/A, and the green space pattern index was calculated by FRAGSTATS to build the database. Firstly, the influence mechanism of green space pattern on noise distribution was explored through correlation analysis, geographical detector and geographically weighted regression analysis; Secondly, based on the three results of the impact mechanism, the green space pattern control scheme of "screening optimization index delimiting optimization order selecting optimization area" is constructed in turn, and the spatial allocation of urban green space is further adjusted; Then, Cadna/A was used to simulate the noise distribution before and after the green space pattern adjustment, and the feasibility and applicability of the green space pattern control scheme were tested by counting the noise attenuation area, attenuation level and proportion, and effective attenuation of noise vocal cords; Finally, the optimization strategy of green space pattern for noise control is proposed.*

The results show that in terms of green space pattern optimization process, the impact mechanism can provide a theoretical basis for the determination of green space pattern optimization methods. Specifically, the correlation analysis results show that the correlation between green space pattern index and noise distribution changes dynamically under the

influence of spatial heterogeneity, and the correlation coefficient can increase by 0.18 at most, which provides an important basis for the selection of optimization index; The results of geo detector analysis show that when the aggregation and dispersion index which reflects the characteristics of green space configuration works in concert with other indexes, the impact on the noise distribution can be increased by more than 2.74 times, which provides a scientific basis for the combination selection and order determination of the optimization index; The visualization results of geographically weighted regression analysis can clearly show the regression coefficient of green space pattern index to noise distribution in each grid unit, which provides strong support for the accurate selection of optimized areas. In terms of noise reduction effect evaluation after green space pattern adjustment, the effective attenuation area accounted for 80.25%, which fully proved that green space pattern adjustment had obvious noise reduction effect; The areas with attenuation levels within 1dB, 1-2dB, 2-4dB and 4-12db accounted for 68.94%, 8.63%, 1.50% and 1.19% respectively, and the maximum attenuation value was 10.60db (a). Finally, this study proposed four green space pattern optimization strategies with significant noise attenuation effect, covering the combined regulation of green space density, shape complexity, cohesion, fragmentation, cluster degree and connectivity in different regions. To sum up, this study constructed the proposed process and evaluation method of green space pattern optimization strategy for noise attenuation, and proved that the optimization of green space configuration can significantly reduce the noise level. This can provide theoretical guidance and scientific basis for urban green space pattern planning and urban acoustic environment management at the planning level, and help effectively control noise pollution in the urban green space planning and design stage, so as to build a healthier and more livable sustainable development city.

Keywords

Noise Prevention and Control, Green Space Pattern Optimization, Acoustic Environment Management, Sustainable Urban Development

1. Introduction

With the acceleration of global urbanization, the high-density urban construction and complex traffic network have made noise pollution become a serious source of urban environmental pressure, seriously endangering the physical and mental health of residents (Basner et al., 2014; Fritschi et al., 2011), and restricting the high-quality development of urban spatial quality (Organization, 2018). Under the background of urban sustainable development and "quiet city" construction, how to effectively control noise through planning means has become the focus of academic circles and planning practice. Compared with hard elements such as roads and buildings that are difficult to change, urban green space, as a "soft" element with high adaptability and flexibility in urban ecosystem, not only provides ecosystem services, but also plays an irreplaceable role in noise attenuation (Cohen-Shacham et al., 2016; Kang, 2007). Therefore, from the perspective of landscape architecture and urban planning, it has become an important way to improve the urban acoustic environment by optimizing the urban green space pattern (Dzhambov and Dimitrova, 2015; Liu et al., 2023).

First of all, at the impact mechanism level, the existing research focuses on the "quantity" rather than "shape" of green space, and the understanding of the noise reduction mechanism of green space configuration is not sufficient. The traditional noise control planning often focuses on improving the green space rate or increasing the green coverage area. However, increasing the green space area in the central urban area where land resources are increasingly scarce has great limitations. Existing studies show that the spatial allocation of green space has greater ecological benefits than the area (Margaritis et al., 2018; Reis et al., 2022; Feng et al., 2024; Stuhlmacher et al., 2024). Although some scholars have discussed the relationship between green space form and noise (Margaritis and Kang, 2017; Sakieh et al., 2017), they lack in-depth analysis of the complex spatial heterogeneity and nonlinear synergy between green space pattern index and noise distribution (Han et al., 2018; Wang and Kang, 2011; Yuan et al., 2019). How to accurately explore the impact mechanism of green space pattern on noise distribution is the premise of realizing noise control.

Secondly, at the level of strategy construction, the existing research often stops at "analysis of influencing factors", lacking a systematic transformation method from "mechanism analysis" to "strategy generation". Most of the current studies focus on explaining which factors affect noise, but few studies explore how to translate these statistically significant factors into operable planning and design language. The real pain faced by planners is: which green space indicators should be adjusted first in the face of complex urban texture? Is it a priority to increase plaque density or connectivity? What differentiated control measures should be taken for regions with different characteristics? The lack of a logical and rigorous green space pattern optimization process and control scheme derived from the scientific impact mechanism makes it difficult for the research results to directly guide the planning practice.

Finally, at the level of effect verification, the current researches on the noise reduction benefits of green space are mostly "current situation assessment" or "theoretical deduction", and lack of empirical "comparison before and after optimization" research. Most of the existing work focuses on the assessment of the current acoustic environment, or simulation based on the ideal model, and less on the whole process empirical simulation after the green space pattern adjustment of specific plots. The lack of quantitative test on the noise attenuation effect after the implementation of the optimization strategy makes it difficult to directly verify the actual noise reduction potential of green space pattern optimization, and also limits the promotion and application of relevant strategies in urban renewal and planning management.

Based on this, this study selects the central urban area of Lyon, France, as the empirical object to solve the following three core problems: (1) what is the deep impact mechanism of urban green space pattern on noise distribution? (2) How to build a scientific and systematic urban green space pattern optimization strategy and control scheme based on the impact mechanism? (3) Through empirical simulation, what is the effect of noise attenuation after the adjustment of green space pattern? Through "mechanism exploration strategy construction empirical test", this study aims to build a set of urban green space pattern optimization method system for noise control, and provide a solid theoretical basis and practical reference for mining the noise reduction potential of limited green space at the planning level and improving the management level of urban acoustic environment.

2. Methodology

This research system has constructed a research framework (Figure 1). Specifically, let's take a look:

The first step is to determine the research question. What is the impact mechanism of green space pattern on noise distribution? How to optimize the urban green space pattern for noise attenuation? How to verify the noise attenuation effect after adjusting the green space pattern?

Step 2: Select the research area and construct a database of noise distribution and green space pattern index (see 3 for details)

Step three, explore the influencing mechanism from three aspects: influencing factors, degree of influence, and characteristics of influence (see 4.1 for details)

Step four, explore the green space pattern control plan from three aspects: optimization indicators, optimization sequence, and optimization methods (see 4.2 for details)

The fifth step is to test the noise attenuation effect of the green space pattern control, and propose optimization strategies for urban green space patterns aimed at noise attenuation (see 4.3 for details).

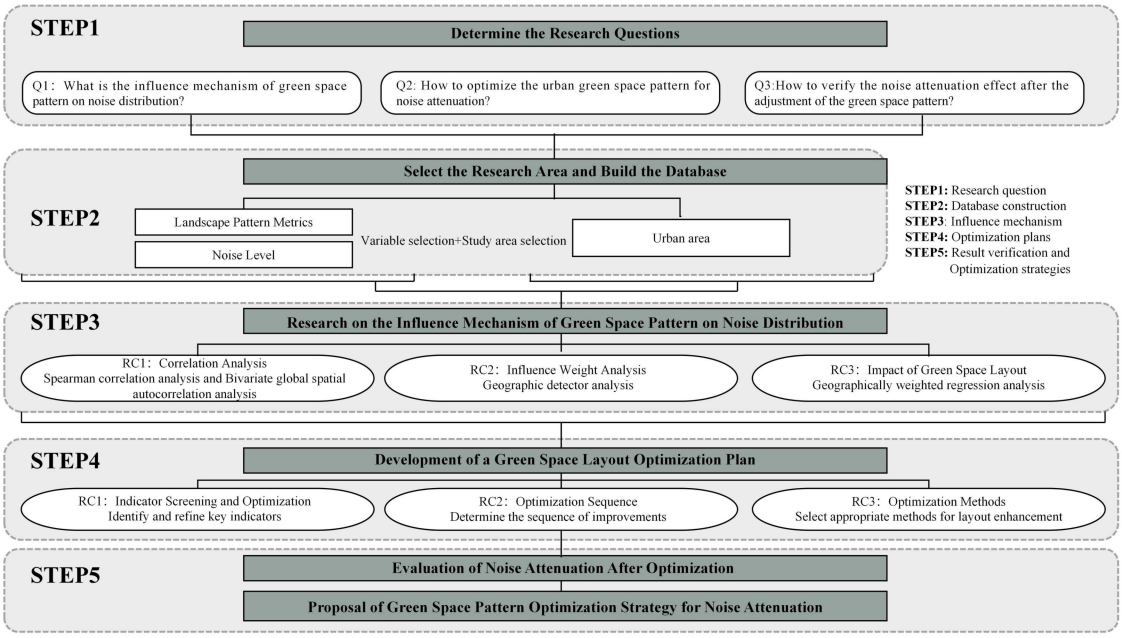


Figure 1. Research framework (Source: Created by the authors.)

3. Study Area Selection and Data Processing

3.1. Study Area

This study selected a 2km x 2km plot of land within the administrative region of Lyon, France as the research area (Figure 2). Due to its location at the intersection of major trade routes, it has highly operational road, river, railway, and aviation infrastructure, with a particular focus on developing multimodal transport, which has led to increased industrial and transportation noise.

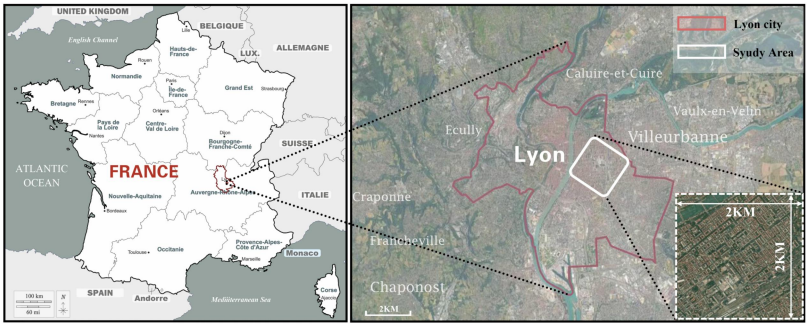


Figure 2. Research area (Source: Created by the authors.)

3.2. Data Processing

This study obtained geographic information data and noise data from the OSM and Noise Planet platforms, respectively (Bocher et al., 2017; Picaut et al., 2021). Firstly, select CadnaA to simulate the noise distribution in the study area (Zhou et al., 2024), use the default international standard ISO9613 to calculate the configuration (Ray, 2004), set a 50m × 50m grid and a 1.5m ear height for simulation, and export the simulation results in Ascii Grids format for subsequent processing. Secondly, this study selected 12 green space pattern indices that can reflect the quantity, shape, structural composition, and spatial configuration of green spaces, namely Class Area(CA),Largest Patch Index(LPI),Contiguity index distribution(CONTIG), Shape index distribution (SHAPE),Euclidean nearest neighbor distance distribution(ENN), Clumpiness index(CLUMPY),Aggregation index(AI),Patch Cohesion Index(COHESION), Landscape division index(DIVISION) ,Split index(SPLIT) ,Patch density(PD) and Connectance Index (CONNECT). Use Fragstats to calculate the green space pattern index (McGarigal and Marks, 1995) and perform subsequent processing in ArcGIS. In the end, among the 1600 grids in the study area, there was one noise value and 12 green space pattern index values. Based on this, an accurate database can be provided for the study of optimization strategies after the impact mechanism.

4. Results

4.1. The Influence Mechanism of Green Space Pattern on Noise Distribution

4.1.1. Analysis of Influencing Factors

The Spearman correlation analysis results showed that, except for CONTIG, ENN, and CONNECT, all other green space pattern indices were significantly correlated with Leq ($-0.09 \leq r \leq 0.27$). Among them, COHESION had the strongest positive correlation with noise level (Figure 3, upper part). The global spatial autocorrelation analysis results showed that, except for CONNECT, all other green space pattern indices were significantly correlated with Leq ($-0.15 \leq$ MoranI ≤ 0.19), with COHESION showing the strongest negative correlation with Leq and PD showing the strongest positive correlation with Leq (Figure 3, lower

part). Overall, when considering spatial factors, the correlation between green space pattern index and noise level will change, mainly manifested in the strength and positivity of the correlation. This is because Spearman correlation analysis only calculates the numerical correlation between two variables, while global spatial autocorrelation analysis considers the influence of spatial distribution and geographical location.

Green Space Pattern Index	CA	LPI	CONTIG	SHAPE	ENN	CLUMPY
Numerical correlation (r value)	0.05*	0.13**	0.02	0.15**	0.04	0.10**
Green Space Pattern Index	AI	COHESION	DIVISION	SPLIT	PD	CONNECT
Spatial correlation (r value)	0.12**	0.17**	-0.09**	-0.09**	-0.08**	0.02

Note:**represents $p<0.01$.*represents $p<0.05$

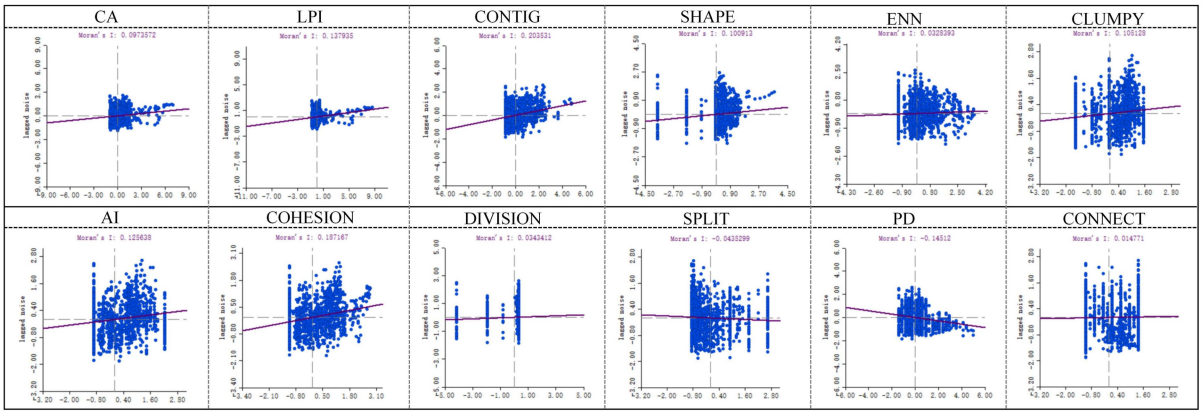


Figure 3. Results Correlation analysis (Source: Created by the authors.)

4.1.2. Analysis of Influence Degree

The differentiation and factor detection results show that only CONTIG, AI, DIVISION, SPLIT, and PD can affect the spatial distribution of noise to a certain extent, with PD having a greater impact (q=7.00%) (Figure 4, left). The interaction detection results show that almost all indices have a non-linear increase in their impact on the noise distribution when they work together. Among them, when LPI and PD work together, they can have the greatest impact on the spatial distribution of noise (q=19.02%) (Fig. 3, right). The ecological detection results show that there are significant differences in the impact of most indices on noise distribution (Figure 4, right). This indicates that the entry point for improving the urban sound environment is available, that is, to reduce noise under the same conditions, the green space pattern index that has a similar impact on noise distribution can be adjusted according to the actual situation.

Factor detector

Metric	q value
CA	0.0175
LPI	0.0608
CONTIG	0.0502
SHAPE	0.0439
ENN	0.0184
CLUMPY	0.0475
AI	0.0503
COHESION	0.0607
DIVISION	0.0452
SPLIT	0.0391
PD	0.0697
CONNECT	0.0397

Interaction detector and Ecological detector

	CA	LPI	CONTIG	SHAPE	ENN	CLUMPY	AI	COHESION	DIVISION	SPLIT	PD	CONNECT
CA		0.1337	0.1539	0.1427	0.1368	0.1175	0.1248	0.136	0.1104	0.1015	0.1409	0.1059
LPI	Y		0.1516	0.1293	0.152	0.1495	0.1469	0.1355	0.158	0.1146	0.1902	0.1521
CONTIG	Y	Y		0.1448	0.1631	0.1109	0.1013	0.0874	0.1407	0.1454	0.165	0.1465
SHAPE	Y	Y	Y		0.1312	0.1226	0.1404	0.1099	0.1321	0.1255	0.1511	0.1337
ENN	N	Y	Y	Y		0.1615	0.1522	0.1402	0.1523	0.1488	0.1623	0.1094
CLUMPY	Y	Y	N	Y	Y		0.0679	0.1292	0.1389	0.1388	0.1415	0.1334
AI	Y	Y	N	Y	Y	N		0.1159	0.1347	0.1235	0.1571	0.1538
COHESION	Y	N	Y	Y	Y	Y	Y		0.1305	0.1369	0.1605	0.1421
DIVISION	Y	Y	Y	N	Y	N	Y	Y		0.0856	0.1474	0.1215
SPLIT	Y	Y	Y	Y	Y	Y	Y	Y	Y		0.1501	0.1129
PD	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y		0.1212
CONNECT	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	Y	

Interaction detector: **The blue font** represents Enhance,bi-; **The black font** represents Enhance,nonlinear
Ecological detector: **Y** represents a significant difference; **N** represents that there is no significant difference

Figure 4. Results of the geographic detector (Source: Created by the authors.)

4.1.3. Analysis of Influence Characteristics

Before conducting Geographically Weighted Regression (GWR), this study excluded green space pattern indices with collinearity based on the results of ordinary least squares regression analysis. After running the GWR model, effective regression coefficients (βn) were generated for each green space pattern index in the grid cells of low, medium, and high-density areas. This study visualized these coefficients (Figure 5). Through this visualization method, the spatial distribution characteristics of the impact of different green space pattern indices on noise can be clearly displayed. At the planning level, the impact mode, degree, and hotspot areas of each green space pattern index on noise distribution can be intuitively judged, thereby formulating more accurate sound environment management strategies.

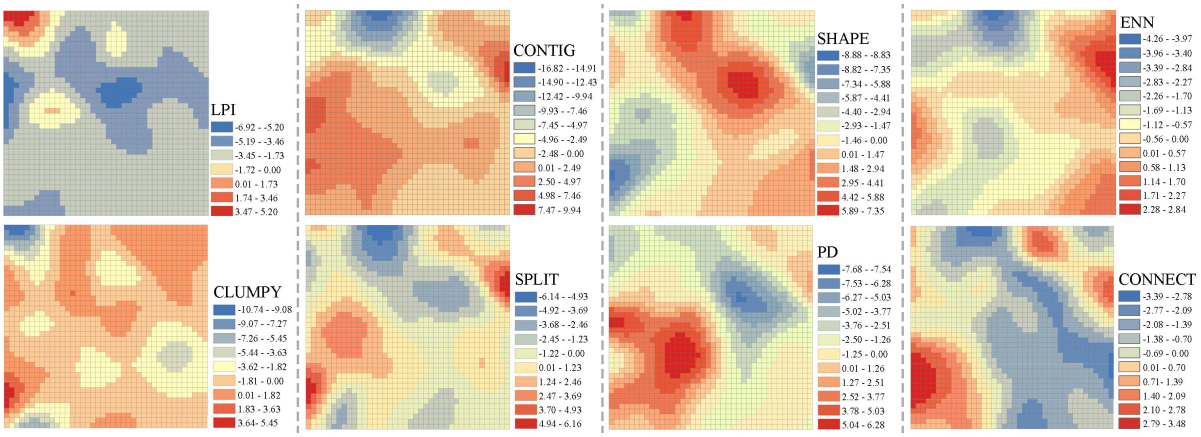


Figure 5. Results of Geographically Weighted Regression analysis (Source: Created by the authors.)

4.2. Construction of Green Space Pattern Regulation Schemes

4.2.1. Screening Optimization Indices

By comparing the results of Spearman correlation analysis and bivariate global spatial autocorrelation analysis in Section 3.1, a total of 7 green space pattern indices were selected that showed an increase in correlation with noise distribution due to spatial heterogeneity. This study further calculated the growth value of the absolute correlation value (Table 1). This means that these indices can be given priority consideration when controlling green spaces.

Table 1 Comparison of Spearman correlation results and global autocorrelation results (Source: Created by the authors.)

Green Space Pattern Index	PD	CA	LPI	CONTIG	CLUMPY	AI	COHESION
Numerical correlation	-0.08**	0.05*	0.13**	0.02	0.10**	0.12**	0.17**
Spatial correlation	-0.15**	0.10**	0.14**	0.20**	0.11**	0.13**	0.19**
Correlation growth value	0.07	0.05	0.01	0.18	0.01	0.01	0.02

Note:**represents $p<0.01$.*represents $p<0.05$

4.2.2 Determining Optimization Sequence

Based on the results of differentiation and factor detection, six green space pattern indices (Table 2, left) that have an impact on the spatial distribution of noise were selected in descending order of influence and significance (6.97% ≥ q ≥ 3.91%). Based on the interaction detection results, select the index that can significantly increase the impact on noise distribution when synergistically working with these six

indices as the bivariate green space pattern index group for improvement control (Table 2, right). In addition, decision-makers can also select replaceable indices based on ecological detection results.

Table 2 The degree of influence of green space pattern index and index group on noise distribution (Source: Created by the authors.)

Green Space Pattern Index and q Value (%)		Green Space Pattern Index Group and q Value (%)			
PD	6.97	PD+LPI	19.02	PD+CONTIG	16.50
AI	5.03	AI+PD	15.71		
CONTIG	5.02	CONTIG+ENN	16.31		
DIVISION	4.52	DIVISION+LPI	15.80		
CONNECT	3.97	CONNECT+LPI	15.21	CONNECT+CONTIG	14.65
SPLIT	3.91	SPLIT+PD	15.01	SPLT+ENN	14.88

4.2.3 Selecting Optimization Methods

Screen out AI, COHESION, DIVISION, and CA based on whether they have collinearity. Based on this, 7 sets of green space pattern index control schemes can be determined (Table 3). Specifically, firstly, based on the spatial correlation results, the control method is selected. If the correlation is negative, it indicates that an index needs to be added to control the green space pattern and attenuate noise; If the correlation is positive, then it is opposite. Furthermore, based on geographically weighted regression analysis, the control area is selected. For example, for the first set of schemes, it is necessary to find an area in the visualization results that satisfies both index regulation modes simultaneously. In this area, PD and Leq show a negative correlation, while LPI and Leq show a positive correlation.

Table 3 Green space layout Index control plan (Source: Created by the authors.)

Green space pattern index and spatial correlation			Green space layout Index control plan
1	PD[-]	LPI[+]	Increase PD while reducing the LPI
2	PD[-]	CONTIG[+]	Increase PD while reducing the CONTIG
3	CONTIG[+]	ENN[+]	Reduce CONTIG while reducing the ENN
4	CONNECT[+]	LPI[+]	Reduce CONNECT while reducing the LPI
5	CONNECT[+]	CONTIG[+]	Reduce CONNECT while reducing the CONTIG
6	SPLIT[-]	PD[-]	Increase SPLIT while increasing PD
7	SPLIT[-]	ENN[+]	Increase SPLIT while reducing the ENN

4.3. Analysis of Noise Attenuation Effects After Pattern Control

4.3.1 Simulation and Attenuation Analysis

After adjusting the green space pattern based on the control plan, in order to test whether the noise level has decreased, this study used the noise simulation software Cadna/A to simulate the noise distribution after control and compared it with the initial noise level. Specifically, this study calculated the noise

attenuation values in each grid and divided them into intervals of less than 1dB (A) and 2dB (A), further calculating the number and proportion of grids in each attenuation interval (Table 4). The results showed that 80.25% of the areas had varying degrees of noise attenuation, with 68.94% of the areas mainly concentrated within 1dB (A) attenuation. In addition, 8.63%, 1.50%, 0.31%, 0.06%, and 0. 19% of the areas had noise levels attenuated by 1-2dB (A), 2-4dB (A), 4-6dB (A), 6-8 dB (A), 8-10 dB (A), and 10-12 dB (A), respectively. In addition, in this area, the noise level decreased by a maximum of 10.60dB (A). This proves that regulating green spaces based on influence mechanisms has a significant noise attenuation effect.

Table 4 Noise Attenuation Results after the control of Green Space Layout (Source: Created by the authors.)

The attenuation situation of noise decibel values								
Total attenuation		<1dB	1-2dB	2-4dB	4-6dB	6-8dB	8-10dB	10-12dB
Total number of grids	1284	1103	138	24	10	5	1	3
Proportion	80.25%	68.94%	8.63%	1.50%	0.63%	0.31%	0.06%	0.19%

4.3.2 Proposal of Optimization Strategies

Due to the overlapping regulatory regions of the seven indices, four green space pattern optimization strategies for noise attenuation were ultimately proposed by integrating them within the study area. Specifically, in areas where the green spaces on the west side are relatively evenly distributed, the proportion of the main green spaces in the area should be reduced, and the connectivity and spacing between the main green spaces should be reduced while evenly dispersing small green spaces near the transportation network. At the location where the green space is distributed in a strip on the northwest side, reduce the proportion of the main green space in the area and divide the long strip green space into several small green spaces. In the sparse distribution and small area of green spaces on the northeast side, it is necessary to reduce the adjacency between green spaces. Compared to the initial green space pattern, it is necessary to make them more dispersed and reduce the spatial characteristics of their clustered distribution. In areas where the green space on the south side is loosely distributed and has a relatively large area, it is necessary to increase the density of patches without changing the area and reduce the degree of adjacency between small green spaces.

5. Conclusion

Aiming at the practical problems of limited green space resources in urban high-density built-up areas and the difficulty of traditional extensive greening to meet the demand for noise reduction, this study built a closed-loop research system of "mechanism exploration strategy generation empirical test" from the perspective of "green space pattern". By integrating multi-dimensional spatial analysis method and noise simulation technology, this study not only quantifies the nonlinear influence mechanism of green space pattern index on noise distribution, but also confirms the noise reduction potential based on pattern optimization, which provides a scientific basis for urban acoustic environment planning from "passive protection" to "active regulation".

Firstly, this study reveals the mechanism of the impact of urban green space pattern on noise distribution. The study found that the impact of green space pattern on noise has significant spatial heterogeneity and synergistic effect. Specifically, considering the spatial autocorrelation factor, the correlation between some pattern indexes and noise is significantly enhanced (the maximum increase of correlation

coefficient is 0.18), which proves the limitation of only analyzing from the level of numerical statistics. The geo detector analysis further shows that the aggregation and dispersion index (such as AI and cohesion) reflecting the "spatial configuration" characteristics of green space is the key "synergy factor". When it works in synergy with other indexes, the explanatory power of noise distribution can be increased by more than 2.74 times. This discovery explains why, on the premise of constant green quantity, the spatial configuration of green space can achieve better noise reduction effect.

Secondly, this study established a reproducible and quantifiable green space pattern control method system of "screening optimization index delimiting optimization order selecting optimization area", and verified its effectiveness through empirical simulation. Compared with the theoretical deduction of previous studies, the empirical simulation results of this study based on Cadna/a show that after the application of the control scheme, the noise attenuation is achieved in 80.25% of the study area, and the maximum attenuation value is 10.60db (a). This quantitative evidence strongly proves that under the background of stock planning, fine adjustment of the spatial configuration of green space is a low-cost and high-yield technical path to improve the quality of urban acoustic environment.

Thirdly, based on the results of empirical analysis, this study summarizes four green space pattern optimization strategies with clear spatial orientation, which provides specific guidance for planning practice. For urban areas with different texture characteristics, noise reduction strategies should focus on different aspects: in areas with homogeneous distribution of green space, emphasis should be placed on "reducing connectivity and dispersion", reducing the proportion of main green space and distributing it along the road network; In the zonal green space distribution area, we should adopt the strategy of "cutting long strips and zeroing"; In the sparse and small green areas, it is necessary to further "reduce adjacency and de cluster" and increase dispersion; However, in the area with loose green space and large scale, it should "increase density and reduce fragmentation" on the premise of keeping the area unchanged. These strategies go beyond the general planning principles and provide differentiated management and control schemes based on the characteristics of land plots.

Although this study confirmed the noise reduction potential of green space pattern optimization, there are still some limitations to be deepened. Firstly, in the index dimension, the landscape pattern index mainly focuses on the two-dimensional plane, and the vertical structure of plant communities and the three-dimensional blocking effect of three-dimensional green quantity on sound propagation have not been fully considered; Secondly, in terms of influencing factors, multiple variables such as the level of economic development, geographical and topographical characteristics, population distribution density and climatic and meteorological conditions are not fully included. These macro factors may act on the urban acoustic environment together with the micro form; Finally, in terms of sample breadth, the empirical object is limited to the specific region of a single city, and future research should be expanded to more regions with different geographical backgrounds and city types for comparative analysis, so as to verify the universality and effectiveness of this paradigm.

6. Acknowledgments

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